

ABSTRACT

SHIN, GWANSEOB. The effects of sloped ground on the hip, knee, and ankle joint kinetics and kinematics during manual lifting tasks. (Under the direction of Dr. Gary A. Mirka.)

The biomechanical effects of sloped ground on hip, knee, and ankle joint moments and lifting posture during sagittally symmetric manual lifting were investigated using a two-dimensional five-segment dynamic biomechanical model. Subjects' motions were traced and recorded at 60Hz by Flock of Birds magnetic tracking system as they lifted a 10 kg cubic box on five sloped grounds; two declined slopes (-20° , -10°), two inclined slopes ($+20^{\circ}$, $+10^{\circ}$), and flat ground (0°), using three lifting techniques; back lift, freestyle lift, and leg lift. Fifteen trials were tested and each trial involved repetitive lifting (6 to 9 lifts per trial) for 50 seconds. The kinetic and kinematic effects were examined by computing the peak net reactive moments at the hip, knee, and ankle joints, and measuring peak segment flexion angles of the trunk, thigh, and leg (shank).

Results indicated that the peak joint moments and peak segment angles were significantly affected by slope angle and lifting technique ($\alpha = 0.05$). The inclined slope angles

(10° and 20°) caused up to 6.8 % and 14.3 % larger peak hip moments than flat ground during the freestyle and leg lifts, respectively. The lowest peak hip moment (236.48 Nm) was observed during the leg lift on flat ground and the largest peak hip moment (302.62 Nm) occurred during the back lifts on flat ground. The components contribution analyses showed that the two static components (vertical reaction static force on the shoulder joint and the trunk mass) were main contributors to the responses of peak hip moment to changes in slope angle. The leg lift technique produced significantly less peak joint moments than other lifting techniques regardless of slope angle. The mean peak hip moment was 16.0 % and 10.5 % less in the leg lift technique (251.0 Nm) than in the back (298.8 Nm) and freestyle lift (280.4 Nm) respectively. Specifically, trunk angular acceleration acted as a major contributor to the significant difference in peak hip moments between the back lift and the leg lift. The trunk angular acceleration, peak flexion angles of the trunk, thigh, and shank separated the leg lift from the back lift.

**The effects of sloped ground on the hip, knee, and ankle joint
kinetics and kinematics during manual lifting tasks.**

by

GWANSEOB SHIN

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Industrial Engineering

Raleigh
2002

APPROVED BY :

Chair of Advisory Committee

BIOGRAPHY

Gwanseob Shin was born on May 20, 1973 in Seoul, Korea. He received the Bachelor of Engineer degree with a major in mechanical engineering from the Korea University in Seoul, in 1996.

From 1996 to 1999 he was employed with the Hanjin Heavy Industries Co., Ltd. of Pusan, Korea as a researcher performing structure analysis of industrial facilities.

In August 2000 he began working on the graduate degree in the department of Industrial Engineering at North Carolina State University.

His areas of interests are biomechanical modeling and analysis and ergonomic product design.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to the Chairperson of my advisory committee, Dr. Gary Mirka for all the support and guidance throughout the carrying out this study.

I also sincerely thank to my other committee members, Dr. Carolyn Sommerich and Dr. Eric Klang for their great assistance throughout my graduate education.

Special thanks to all of my subjects and to my lab colleagues who have advised and helped me for this study.

Finally, thank you my sister and her family, and my fiance Jihye for their patience, support, and understanding throughout this study.

TABLE OF CONTENTS

	Page
LIST OF TABLES	vii
LIST OF FIGURES	ix
1. INTRODUCTION	1
1.1. Basic LBP Epidemiology	1
1.2. Physical Risk Components for LBP	2
1.2.1. Lifting and Forceful Movements	2
1.2.2. Heavy Physical Load	3
1.2.3. Frequent Bending and Twisting	4
1.2.4. Whole Body Vibration	5
1.2.5. Static Work Posture	5
1.3. Lifting Technique	7
1.4. Biomechanical Modeling	9
1.4.1. Biomechanical Models for Lifting	9
1.4.2. Static vs. Dynamic Model	10
1.4.3. Relationship Between Moments at the L5/S1, Hip, Knee, and Ankle Joint	11
1.5. Biomechanical Studies on Sloped Ground	13
1.6. Specific Aims	14
2. METHODOLOGY	16
2.1. Subjects	16
2.2. Apparatus	18
2.3. Independent Variables	22
2.4. Dependent Variables	22
2.5. Experimental Procedure	22
2.6. Biomechanical Model	23
2.7. Data Processing	28

2.7.1.	Data Collection	28
2.7.2.	Statistical Analysis	31
3.	RESULTS	33
3.1.	Verification of Statistical Assumptions	33
3.2.	Variation Between and Within Subjects, and Between Repetitions	40
3.3.	Peak Joint Moment	43
3.3.1.	Interaction Effect on Peak Joint Moment	43
3.3.2.	Slope Angle Effect on Peak Joint Moments	47
3.3.3.	Lifting Technique Effect on Peak Joint Moments	49
3.4.	Peak Segment Angle	51
3.4.1.	Interaction Effect on Peak Segment Angle	51
3.4.2.	Slope Angle Effect on Peak Segment Angle	55
3.4.3.	Lifting Technique Effect on Peak Segment Angle	57
3.5.	Components Analyses of the Peak Joint Moments Within Technique	60
3.5.1.	Component Analysis of Peak Hip Moment Across Slope angles	60
3.5.2.	Component Analysis of Peak Knee Moment Across Slope angles	65
3.5.3.	Component Analysis of Peak Ankle Moment Across Slope angles	70
3.6.	Components Analyses of the Peak Joint Moments Between Technique	75
3.6.1.	Component of Peak Hip Moment Across Lifting Techniques	75
3.6.2.	Component of Peak Knee Moment Across Lifting Techniques	77
3.6.3.	Component of Peak Ankle Moment Across Lifting Techniques	78
4.	DISCUSSION	79
4.1.	Variation Between and Within Subject	79
4.2.	The Slope Angle effects on the Peak Joint Moments and Peak Segment Angles	79
4.3.	Lifting Technique	83
4.4.	Limitations	85
4.5.	Recommendations	86
4.6.	Future Work	86

5.	CONCLUSIONS	88
6.	REFERENCES	90

LIST OF TABLES

	Page
Table 2.1 Subjects' Anthropometry	17
Table 2.2 Weights and Center of Gravity of Body Segments	19
Table 3.1 ANOVA results testing the effect of slope angle, technique, and interaction on peak joint moments	44
Table 3.2 ANOVA results testing the effect of slope angle on peak hip moment while controlling for lifting technique	48
Table 3.3 ANOVA results testing the effect of slope angle on peak knee moment while controlling for lifting technique	48
Table 3.4 ANOVA results testing the effect of slope angle on peak ankle moment while controlling for lifting technique	48
Table 3.5 Tukey's grouping of mean peak joint moments by lifting technique	49
Table 3.6 ANOVA results testing the effect of lifting technique on peak hip moment while controlling for slope angle	50
Table 3.7 ANOVA results testing the effect of lifting technique on peak knee moment while controlling for slope angle	50
Table 3.8 ANOVA results testing the effect of lifting technique on peak ankle moment while controlling for slope angle	50
Table 3.9 Tukey's grouping of mean peak joint moments by slope angle	51
Table 3.10 ANOVA results testing the effect of slope angle, technique, and interaction	

on peak segment angle	52
Table 3.11 ANOVA results testing the effect of slope angle on peak trunk angle while controlling for lifting technique	56
Table 3.12 ANOVA results testing the effect of slope angle on peak thigh angle while controlling for lifting technique	56
Table 3.13 ANOVA results testing the effect of slope angle on peak shank angle while controlling for lifting technique	56
Table 3.14 Tukey's grouping of mean peak segment angles by lifting technique	57
Table 3.15 ANOVA results testing the effect of lifting technique on peak trunk angle while controlling for slope angle	58
Table 3.16 ANOVA results testing the effect of lifting technique on peak thigh angle while controlling for slope angle	58
Table 3.17 ANOVA results testing the effect of lifting technique on peak shank angle while controlling for slope angle	58
Table 3.18 Tukey's grouping of mean peak segment angles by slope angle	58
Table 3.19 Components of hip moment	61
Table 3.20 Components of knee moment	66
Table 3.21 Components of ankle moment	71

LIST OF FIGURES

	Page
Figure 2.1 Sensor locations	20
Figure 2.2 Wooden platform (10° inclined slope) and weight box	21
Figure 2.3 Horizontal and vertical distances between weight box and foot	21
Figure 2.4 Five-segment two-dimensional (sagittally symmetric) model	26
Figure 2.5 Hip moment and trunk angle during a freestyle lift at 0° slope	30
Figure 3.1 Plot of residuals vs. predicted peak hip moment	34
Figure 3.2 Plot of residuals vs. predicted peak knee moment	34
Figure 3.3 Plot of residuals vs. predicted peak ankle moment	35
Figure 3.4 Plot of residuals vs. predicted peak trunk (T9) angle	35
Figure 3.5 Plot of residuals vs. predicted peak thigh angle	36
Figure 3.6 Plot of residuals vs. predicted peak shank angle	36
Figure 3.7 Plot of residuals of peak hip moment vs. time	37
Figure 3.8 Plot of residuals of peak knee moment vs. time	37
Figure 3.9 Plot of residuals of peak ankle moment vs. time	38
Figure 3.10 Plot of residuals of peak trunk angle vs. time	38
Figure 3.11 Plot of residuals of peak thigh angle vs. time	39
Figure 3.12 Plot of residuals of peak shank angle vs. time	39
Figure 3.13 Box plot of peak hip moment by ‘subject’	41
Figure 3.14 Box plot of peak trunk (T9) angle by ‘subject’	41
Figure 3.15 Box plot of peak hip moment by ‘repetitions’	42

Figure 3.16 Box plot of peak trunk angle by ‘repetitions’	42
Figure 3.17 Mean peak hip moments	45
Figure 3.18 Mean peak knee moments	46
Figure 3.19 Mean peak ankle moments	47
Figure 3.20 Mean peak trunk (T9) angle	53
Figure 3.21 Mean peak thigh angle	54
Figure 3.22 Mean peak shank angle	55
Figure 3.23 Component analysis of peak hip moment in the back lift	62
Figure 3.24 Component analysis of peak hip moment in the freestyle lift	63
Figure 3.25 Component analysis of peak hip moment in the leg lift	64
Figure 3.26 Component analysis of peak knee moment in the back lift	67
Figure 3.27 Component analysis of peak knee moment in the freestyle lift	68
Figure 3.28 Component analysis of peak knee moment in the leg lift	69
Figure 3.29 Component analysis of peak ankle moment in the back lift	72
Figure 3.30 Component analysis of peak ankle moment in the freestyle lift	73
Figure 3.31 Component analysis of peak ankle moment in the leg lift	74
Figure 3.32 Component analysis of peak hip moments at 0° slope	76
Figure 3.33 Component analysis of peak knee moments at 0° slope	77
Figure 3.34 Component analysis of peak ankle moments at 0° slope	78
Figure 4.1 Moment profiles during the leg lift	83

1. INTRODUCTION

1.1. Basic LBP Epidemiology

Musculoskeletal disorders (MSDs) account for nearly 70 million physician office visits in the United States annually (National Research Council, 2001) and the economic burden from MSDs is as high as \$215 billion based on data collected in 1995 (Praemer, 1999). Low back pain (LBP) is one type of MSD and is recognized to be one of the most common medical conditions in the western world, affecting up to 85 % of the population sometime during their lifetime (Korff, 1988; Andersson, 1998). LBP is the second most frequently reported reason for a physician visit, the fifth most frequent cause of hospitalization, and the third most frequent reason for a surgical procedure (Andersson, 1998). In the workplace, work related MSDs have been an important and costly problem both in terms of health care costs and lost productivity. In 2000, nearly 5.7 million cases were reported as nonfatal occupational injuries and illnesses in private industry. The number of cases involving days away from work was over 1.6 million and 25.5 % were back and spine injuries (Bureau of Labor Statistics, 2000). Because the BLS method omits any absence days beyond one calendar year, depending on the date of injury, the BLS method may underestimate the duration of disability (Hashemi et al., 1997). For decades, LBP cases have been the most common category of workers' compensation losses, accounting for 15 % to 25 % of all claims and up to 86 % of costs (Spengler et al., 1984; Webster and Snook, 1994; Hashemi et al., 1997). Also, the disability associated with LBP increased 14 times faster than the rate of population growth from 1977 to 1981 (Frymoyer, 1991). The direct costs (treatment costs, lost wages, disability costs) paid annually in the United States for workers' compensation benefits for work-related LBP was estimated to be over \$11 billion during 1989 (Webster and Snook, 1994),

and the total economic impact including non-work related back pain contribution has been estimated up to \$100 billion per year (Frymoyer, 1991).

The etiology of low back pain is not clear because LBP is multifactorial in origin and may be associated with both occupational and non-occupational factors. The non-occupational factors may include age, gender, smoking status, physical fitness level, anthropometric measures, lumbar morbidity, strength, medical history, and structural abnormalities (Garg and Moore, 1992). The occupational factors are often grouped into two major categories: psychosocial exposures and physical exposures. The psychosocial risk factors for work-related back pain are high job demands, low decision control, low stimulus from work, low social support at work, low job satisfaction, high perceived stress, high perceived emotional effort, perceived ability to return to work, and perceived work dangerous to back (National Research Council, 2001). The risk factors of physical load that are consistently thought to be associated with low back pain are lifting and forceful movements, heavy physical load, frequent bending and twisting (awkward posture), whole body vibration (WBV), and static work posture (NIOSH, 1997).

1.2. Physical risk factors for LBP

1.2.1. Lifting and forceful movement

The NIOSH (1997) defined lifting as “moving or bringing something from a lower level to a higher one”, and forceful movements as “movement of objects in other ways, such as pulling, pushing, or other efforts.”

Waters et al. (1999) cross-sectional study examined the correlation between the prevalence of low back pain and exposure to manual lifting stressors. Fifty jobs were evaluated with the NIOSH lifting equation, and a symptom and occupational history questionnaire was

administered to 204 people employed in lifting jobs and 80 people employed in non-lifting jobs. As the lifting index increased from 1.0 to 3.0, the odds ratio of low back pain increased, with a peak and statistically significant odds ratio occurring in the $2 < LI \leq 3$ category (odds ratio = 2.45, 95 % CI 1.29-4.85). Kraus et al. (1997) performed a cohort study of about 31,000 material handlers employed in Home Depot, Inc., stores from 1990 through 1994. With over 87 million work hours, incidence rates were calculated overall and according to age, sex, length of employment, and job-lifting intensity. The unadjusted low back injury rate was 1.6 times higher for men than women, and rates were highest for those less than 25 years of age, those with less than 2 years of current job experience, and employees with the greatest materials lifting and handling job requirements. The incidence rate of low back injury increased with increasing lifting intensity. The incidence rate for high lifting intensity was 5.8 times higher than incidence rate for low lifting intensity.

1.2.2. Heavy physical load

Heavy physical work has been defined as “work that has high energy demands or requires some measure of physical strength” (NIOSH, 1997) or “jobs that impose large compressive forces on the spine” (Marras et al., 1995).

Xu et al. (1997) cross sectional study investigated the associations between the prevalence of low back pain and occupational activities by interviews of a random sample of 5185 Danish employees. The level of exposure was measured by evaluating the duration of daily exposure. A multiple logistic regression model demonstrated that those with intensively hard physical work in their jobs had more low back pain than those with light physical work (OR = 1.28, 95 % CI 1.08-1.52). Videman et al. (1984) performed a cross sectional study of Finnish

nurses to examine the relationship between physical loading factors and LBP. Exposures were reclassified as “heavy”, “intermediate”, and “light” based on questionnaire responses. A dose-response was observed between prevalence of previous LBP and workload category in younger women (77 %, 79 %, and 83 % for light, intermediate, and heavy categories).

1.2.3. Frequent bending and twisting (awkward posture)

NIOSH (1997) defined bending as flexion of the trunk, usually in the forward and/or lateral directions and twisting refers to trunk rotation or torsion. Awkward postures include non-neutral trunk postures (related to bending and twisting) in extreme positions or at extreme angles.

Liira et al. (1996) used the Ontario health survey that was conducted in 1990 to provide data on the relationship of work exposures to long-term back problems in a population survey (sample number = 61,239). The prevalence of long-term back problems was 7.8 % in working-age adults and it generally increased with age. Physical work exposures (awkward working position, working with vibrating vehicles or equipment, and bending and lifting) were all associated with a greater risk of back problem. The OR of ‘working with back in an awkward position’ was 1.66 (95 % CI 1.13-2.44) in white-collar occupations and 2.33 (95 % CI 1.72-3.15) in blue-collar occupations. Punnet et al. (1991) case-control study analyzed the jobs in auto assembly work to examine the possible causal relationship between back pain and various occupational risk factors. Back pains were determined by interview and medical examinations. Risk factors were analyzed by videotaping and postural analysis. Exposures included time spent in various awkward postures. In multivariate analyses, time in non-neutral postures in mild or severe flexion and bending were strongly associated with back disorder (OR = 8.0, 95 % CI 1.0-4.7). Xu et al. (1997) also found epidemiologic evidence for an association between frequent

twisting and bending and low back pain. They observed increasing odds ratio with increased duration of frequent twisting or bending exposure (peak OR = 2.02).

1.2.4. Whole body vibration (WBV)

Whole body vibration refers to “mechanical energy oscillations which are transferred to the body as a whole, usually through a supporting system such as a seat or platform. Typical exposure includes driving automobiles and trucks, and operating industrial vehicles” (NIOSH 1997).

Magnusson et al. (1996) investigated the physical factors affecting back, neck, and shoulder pain in a two-country cohort study of bus and truck drivers and sedentary workers. Vibration exposure was obtained by directly measuring the vibration imposed on the driver during a typical work day. Cumulative exposure was computed based on work history and musculoskeletal health information was based on questionnaires. Of the sample, 50 % reported LBP, with no difference between countries. The highest risk factors for back and neck pain were long-term vibration exposure (OR = 2.0, 95 % CI 0.98-4.1), heavy lifting (OR = 1.86, 95 % CI 1.2-2.8), and frequent lifting (OR = 1.55, 95 % CI 1.01-2.39). A combination of long-term vibration exposures and frequent lifting carried the highest risk of low back pain (OR = 2.1, 95 % CI 1.3-3.3). The study with the Ontario Health Survey, by Liira et al. (1996), also showed the effect of WBV on long-term back problem. The odds ratio in white collar occupations requiring operation of vibrating vehicles or equipment was 1.71 (95 % CI 1.09-2.67) and it was greater in blue collar occupations (OR = 1.84, 95 % CI 1.25-2.72).

1.2.5. Static work postures

Static work postures are defined as “ isometric positions where very little movement occurs, along with cramped or inactive postures that cause static loading on the muscles. These include prolonged standing or sitting and sedentary work. In many cases, the exposure is defined subjectively and/or in combination with other work-related risk factors” (NIOSH 1997).

Svensson and Andersson (1989) examined the association between LBP and different work factors in a retrospective cross sectional study of a random sample of 1,760 women. The life-time incidence of LBP was 66 % and the prevalence was 35 %. Burdorf et al. (1993) studied the relationship of LBP and sedentary work in a cross sectional study. They compared 86 crane operators, 95 straddle-carrier drivers, and 86 office workers as a control group. LBP history and working conditions were obtained by interview, and exposures were measured according to level of WBV and postural load. The 12-month prevalence of LBP among crane operators was 50 %; among straddle-carrier drivers, 44 %; and among office workers, 34 %. However, the daily exposure to WBV in the first two occupations was low, and the results suggested that sustained sedentary work in a forced non-neutral trunk posture was a risk factor for LBP. ‘Standing up’ for long period of time also proved to be a risk factor for the occurrence of LBP. Xu et al. (1997) analyzed the interviews of a random sample of 5185 workers and found that standing up all the time increased the risk of LBP (OR = 1.20).

The reviews of previous studies suggest that these five physical risk factors (lifting and forceful movements, heavy physical load, frequent bending and twisting, whole body vibration, and static work posture) have moderate or strong causal relationship with back pain or disorder in the workplace. The NIOSH (1997) reviewed over 40 articles which provide evidence regarding the relationship between low back disorder and the physical workplace factors. In their review,

the heavy physical work and awkward postures had moderate positive relationship with low back disorders, and the static work postures showed relatively weak positive relationship. Strong evidence was observed in the studies of the lifting and forceful movement, and the whole body vibration. In the studies of lifting and forceful movements the odds ratio ranged from 2.2 to 11. Of eighteen studies that were reviewed, thirteen studies were consistent in demonstrating positive relationships. This data motivates the further study of manual material handling tasks.

1.3. **Lifting techniques**

Individual variations of work technique in the performance of a work task have been observed among workers and these variations have been shown to be related to musculoskeletal disorders (Kilbom and Persson, 1987). As one part of work technique, lifting technique has been studied.

To investigate the relationship between lifting techniques and biomechanical loading, various lifting techniques have been examined and the most commonly studied techniques are the leg lift and the back lift. During a leg lift the knees are flexed and back remains erect, while during a back lift the knees remain straight and back is bent.

The commonly recommended technique is the leg lift because a leg lift is assumed to be less hazardous to the low back. However, the advantage of the leg lift in view of net moment at L5/S1 or hip joint has not been proved. Kjellberg et al. (1998) examined the differences between back and leg lifts with fast and slow lifting speed using dynamic biomechanical model. Twelve female subjects lifted an 8.7 kg box from floor to a waist level table. The distance between the rear of box and ankle was 30 cm. The lifting techniques varied between the subjects to a greater extent than the individual variability over repetitions of a lift task. A larger inter-individual

variability for kinematic variables was mostly shown in leg lifts compared with back lifts. The mean peak L5/S1 net moments were higher for the fast lifts than the slow lifts ($p < 0.0001$). However, no statistically significant difference was observed between back and leg lift techniques.

To assess the biomechanical evidence supporting the leg lift technique, van Dieën et al. (1999) reviewed previous papers that compared the back and the leg lift techniques. Among 27 studies comparing leg and back lifting with respect to the mechanical load on the back, eight studies suggested the positive effects of leg lift. However, six of those eight studies allowed subjects to change the horizontal distance between the load and the feet. So, only two studies observed the positive effect of leg lift with constant horizontal distance between the load and foot. However, the positive effects of one of those two were lost when analyzing with a dynamic biomechanical model. From this review, the authors could find the positive effects of leg lift only when leg lift allowed for lifting from a position between the feet.

From the physiological view point, negative effects of leg lift have been observed. Kumar (1984) performed an experimental study in which physiological cost and ventilation rates were studied during lifting activities. Twelve subjects lifted and lowered a 10 kg basket from floor to 91 cm above the floor in sagittal and two lateral planes by the back, leg, and freestyle techniques six times per minute for a period of 4 minutes. The steady-state values of oxygen consumption during lifting activities were measured and subjects reported the relative degree of tiredness of the tasks. Results showed that the back lifts required the least amount of oxygen and had the lowest per-minute inspiratory ventilation volume. The leg lifts required the highest oxygen consumption and inspiratory ventilation volume. Subjects assessed the leg lift technique as most tiring, and freestyle technique as least tiring.

1.4. Biomechanical modeling

1.4.1. Biomechanical models for lifting.

In general, occupational biomechanical models are used to estimate forces or moments acting on different musculoskeletal components of the human body, to predict the maximum allowable magnitude in manual material handling activities, and to find the least stressful configuration of the workplace. Also, biomechanical models can be used to simulate hazardous work situations in which a real human experiment is very difficult to perform. For these reasons, many biomechanical models have been developed and applied to the analysis of human body in work situations.

Net joint moments and forces are often used to quantify the loading of musculoskeletal structures in the analysis of manual lifting tasks. In most models, the human body is represented as a multiple body-segment link model. Each body segment is represented as a rigid body and adjacent segments are linked by a simple hinge joint. Forces in static biomechanical models are vector quantities and have four characteristics; magnitude, direction, line of action, and point of application (Chaffin et al., 1999). Usually, external forces are considered to act through the center of gravity of the hand, and segments' weights are assumed to act through the center of gravity of each segment. In static models, the direction of force is always downward because the active acceleration is gravity only. In the dynamic model, the vertical and horizontal accelerations of a segment mass and an external load are added to the static model. Thus, the weight of body segment and external load may be reduced or increased depending on the acceleration. The net joint moments are calculated by multiplying force vectors by perpendicular distances from the point of application of force to the joint.

1.4.2. Static vs. dynamic model

Most early biomechanical models were static in nature (e.g. Bejjani et al., 1984; Chaffin, 1969). These models assume that lifting tasks can be represented by a static analysis and only include force due to gravity, neglecting the effects of velocity and acceleration. Although static models have limitations, many studies have used static models because static models are able to be employed in surveillance studies simply by visual observation, such as videotaping, in work environments. The results from static analyses are often used to establish lifting guidelines (e.g. NIOSH lifting equation). The basis of the NIOSH lifting equation is that predicted maximum compressive forces on the L5/S1 disc should not exceed 3400 N for nominal risk to most workers, while 6400 N of compressive force is defined as the maximum permissible limit during lifts. These recommendations were based on results from compressive tolerance cadaver studies and force predictions made by means of a static biomechanical model (Lindbeck and Arborelius, 1991).

Many dynamic biomechanical models, however, have predicted compression forces far beyond the NIOSH maximum permissible limit during lifts which, in static models, were below the limit (Freivalds et al., 1984). The inertial effects produced in momentary jerking might result in the increase of the compressive force in dynamic models and potentially injurious overloads on the low back that were not identifiable in a static analysis which might underestimate the risks of hazardous work tasks. These circumstances have emphasized the role of dynamic analysis.

To investigate the dynamic effects in lifting tasks, many comparisons of static and dynamic models have been reported. Freivalds et al. (1984) developed a seven rigid-link dynamic model and analyzed lifting motions using force plate and stroboscopy (20Hz). Six subjects lifted boxes from floor to a table height, and L5/S1 compressive forces were calculated.

They observed dynamic effects to increase the effect of the static load by as much as 40 %.

Leskinen (1985) evaluated the L5/S1 compression when 20 subjects lifted a 15 kg box from floor to knuckle height. The acceleration of the load was more than 0.5g on average and the increase due to inertial factors was 33 %~60 % depending on lifting technique. Bush-Joseph et al. (1988) emphasized the effect of dynamic components on calculating L5/S1 moment by changing lifting speed. Ten subjects performed lifts from the floor to a 1 m high shelf (150N box) with three speeds (slow, normal, and fast). The peak moment increased linearly with increasing lifting speed. Lindbeck and Arborelius (1991) analyzed four lift conditions (back and leg, slow and fast) with static, dynamic, and semi-dynamic methods. Ten subjects lifted a 12.8 kg box from the floor to 61 % of the stature. Ground reaction forces and body movements were measured with a sampling frequency of 100Hz. The results from dynamic and semi-dynamic analysis were, on average, 100 % larger than static peak moment on L5/S1. They also analyzed the inertial effects of each segment and observed the significant contribution of vertical directional acceleration of the trunk only in the fast leg lift task.

1.4.3. Relationship between moments at the L5/S1, hip, knee, and ankle joint

Manual material handling is a complex dynamic task involving the lower extremities as well as the trunk. The effects of lifting on the trunk or spine have been studied by examining the electromyographic activity of trunk muscles (e.g. Granata & Marras, 1995), by measuring intra-abdominal pressure (e.g. McGill et al., 1990), and by computing the forces acting on the trunk using biomechanical models (e.g. Lavender et al., 1999). However, the roles that lower extremities play in supporting the loads and selecting lifting technique have received less attention.

The effects on lower extremities of manual lifting are often examined together with the effects of lifting techniques (Toussaint et al., 1992; Schipplein et al., 1990). Toussaint et al. (1992) calculated the net moments of L5/S1, hip, knee, and ankle joints during back lift and leg lift by means of a linked-segment dynamic biomechanical model. Eight subjects performed repetitive lifting with a 13.5 kg barbell using two different lifting techniques (back lift and leg lift) and their motions and foot reaction forces were recorded. The relative distance between the body and the barbell was constant for all lifts. In results, the net moment at knee joint was significantly reduced by shifting lifting technique from the back lift to the leg lift. Net moments at other joints were not significantly different. Their results contradicted the generally held view of advocating leg lift to reduce the compressive force on the low back and to shift the stresses on the body from the low back to the legs. Schipplein et al. (1990) investigated the influence of load magnitude on the self-selected lifting technique using a dynamic biomechanical model. They hypothesized that with heavier weights a tendency would occur to lift more with the back and less with the legs. Flexion-extension moments at the L5/S1 level, hip, and knee joints were calculated for subjects when lifting boxes weighing from 50 to 250 N with freestyle technique at normal speed. The results showed an inverse relationship between the moment at the hip joint and knee joint moment. The moment at the hip joint increased with increasing weight, however, the corresponding knee moment decreased. To determine the relationship between knee and back forces during freestyle lifting, Bejjani et al. (1984) performed an experimental study with a static biomechanical model. Net joint reaction forces for the knee and the back, along with their compressive and shear components, were calculated for each subject, as a function of the knee, back and ankle angles. Their results showed a strong inverse correlation between the back and the knee forces for all subjects.

1.5. **Biomechanical studies on sloped ground**

Effects of sloped ground on human biomechanical performance have received little attention. Some published studies have focused on slipping effects due to sloping ground during manual material handling. Zhao et al. (1987) observed the potential risks of slipping during manual material handling in agriculture industry, especially manual lifting in fruit and vegetable growing fields. To investigate the risks of slipping associated with lifting on inclined surfaces, they conducted laboratory experiments. Eight subjects performed leg lift and back lift on the two inclined surfaces (15° and 25°), and the path of the weighted box and foot reaction force were recorded during lifting. Subjective ratings of risk were reported for all tasks. In their results, the method of lifting appeared to be important. When subjects used the back lift, their center of gravity changed less than when they used the leg lift. The slipping risk was significantly higher ($\alpha = 0.05$) in the leg lift than in the back lift due to the larger change of motion in the leg lift. Also, the increase in the slope angle (from 15° to 25°) increased the risk of slipping significantly. In the analyses of subjective rating scale, subjects assessed that the lifting on the 25° inclined slope was more risky than the lift on 15° inclined slope significantly.

Another area of research related to the biomechanics on sloped surfaces is the literature related to the standing or walking with high-heeled shoes. Opila et al. (1987) studied the postural difference in barefoot and high-heeled shoes in order to quantify segmental alignment with respect to the line of gravity in standing posture, and to assess structural compensation for external stresses (high-heeled shoes). The intra-subject comparison of barefoot and high-heeled shoes showed that the wearing of high heels caused lumbar flattening, a backward tilting pelvis, a reduction of the distance of the knee and ankle from the line of gravity, and a posterior

displacement of the head and thoracic spine. They assumed the flattened lordosis with high-heeled shoes might be due to a tendency to overcompensate for the sensation of falling forward caused by the raised heels. Lateur et al. (1991) measured 16 subjects' back, hip, knee, and ankle angles while they were standing on negative heels, barefoot, and positive heels. A significant trend was found toward decreasing lumbar lordosis only among male subjects with positive high heels. Similarly, Franklin et al. (1995) investigated the postural changes when women subjects were standing with zero and 5 cm heel inclination. Results indicated positive heel inclination caused significantly lower anterior pelvic tilt, lumbar lordosis, and sacral base angles when compared with zero heel inclination. Recently, Lee et al. (2001) studied the biomechanical effect of high-heeled shoes using EMG and still photographs. They found decreased trunk flexion angle and increased low back EMG signal when subjects walked with high-heeled shoes (8 cm).

From these results, it could be assumed that, in addition to the shift of center of body mass, the magnitude and direction of reaction force vector on foot might be changed during manual lifting on sloped surface. Further, friction force due to slipping force might produce positive or negative moment on body joints during lifting. Thus, it is hypothesized that the biomechanical load on musculoskeletal structure might be affected by changing ground angle in sagittal plane during manual lifting.

1.6. Specific Aims

The main objective of this study was to examine the kinetic and kinematic effects of slope angle during sagittally symmetric manual lifting tasks. The detailed objectives are,

- To investigate the effect of ground slope angle, lifting technique, and their interaction on

net moment at the hip, knee, and ankle joints. It is hypothesized that the net moment on sloped ground will be different from on flat ground.

- To observe the postural change resulting from sloped ground. It is hypothesized that segment postures will change to compensate for the shift of center of gravity with slope angle changes.
- To investigate the inter-relationship between the moments of the hip, knee, and ankle joints as a function of slope angle and lifting technique.
- To investigate the contribution of individual biomechanical forces to the total joint moments and find which components are impacted by lifting technique or slope angle.

2. METHODOLOGY

2.1. Subjects

Thirteen subjects (seven males and six females) were recruited from the university community and participated voluntarily. Age range for all subjects was from 23 to 34 years, with a mean of 28.5 years. Each subject was free from chronic and current problems of the back and knees, and gave written informed consent after being introduced to the nature of the study. To prevent slips and reduce the effect of heel height, all subjects wore sneakers during the experiment. Subjects' stature, mass, ankle to knee length, knee to hip length, hip to shoulder length, and right arm length were measured by anthropometer and scale (Table 2.1).

Table 2.1 Subjects' anthropometry

No.	gender	stature (m)	mass (kg)	ankle to knee (m)	knee to hip (m)	hip to shoulder (m)	arm length (m)
1	female	1.610	50.0	0.348	0.358	0.483	0.623
2	female	1.610	52.0	0.355	0.361	0.470	0.611
3	male	1.810	68.0	0.412	0.415	0.535	0.730
4	male	1.678	70.0	0.394	0.389	0.482	0.654
5	male	1.766	69.0	0.431	0.380	0.498	0.739
6	female	1.709	60.0	0.393	0.368	0.469	0.697
7	male	1.686	65.0	0.423	0.380	0.464	0.678
8	female	1.554	60.5	0.355	0.390	0.470	0.636
9	male	1.785	111.0	0.460	0.426	0.540	0.746
10	female	1.701	63.0	0.405	0.386	0.490	0.687
11	male	1.761	62.0	0.387	0.413	0.493	0.692
12	male	1.704	63.0	0.399	0.400	0.502	0.678
13	female	1.586	50.5	0.374	0.378	0.436	0.685

2.2. Apparatus

Body movements during the lifting task were captured by means of the Flock of Birds magnetic motion tracking system (Ascension Technology Corporation). Four 6-DOF (x, y, z coordinate and 3 angles around x, y, z, axes) magnetic sensors were placed on the right-hand side of the body at the sagittal plane projection of center of gravity of right shank of leg, center of gravity of right thigh, on the back at level T9, and center of gravity of right arm. The sensors were held in place by hypoallergenic adhesive tape and elastic straps. The locations of center of gravity of body segments were defined and are shown in Table 2.2. Additionally, one sensor was placed on right side of center of gravity of lifted box. All sensors were positioned when the subjects were standing upright on flat surface (Figure 2.1).

A cubic shape (35cm x 35cm x 30cm) wood box with weighting block inside was used as weight object (Figure 2.2). The box had two cut-out handles placed 25cm above the base. The total weight of box with block was 10 kg. A wooden platform was developed that could be adjusted to create an inclined or declined standing work surface. High-friction material was installed on top plate to prevent slipping on surface. The initial horizontal and vertical distance from subjects' feet to the box was constant for all lifts throughout the study. The vertical distance from ankle to box handle was 21.5 cm, and horizontal distance from foot anterior end to center of box was 21.3 cm (Figure 2.3). All tasks were recorded by a video camera located at the left side of subject for the purpose of checking possible interruption and unpredictable movements from motion data.

Table 2.2 Weights and center of gravity of body segments (P133, Pheasant 1986)

Segment	Weight (% body weight)	Location of center of gravity
Head and neck and trunk	58.4	40 % of distance from hip to vertex of head
Upper arm	2.8	48 % of distance from shoulder to elbow joints
Forearm	1.7	41 % of distance from elbow to wrist joint
Hand	0.6	40 % of hand length from wrist joint (at the center of an object gripped)
Thigh	10.0	41 % of distance from hip to knee joints
Lower leg	4.3	44 % of distance from knee to ankle joint

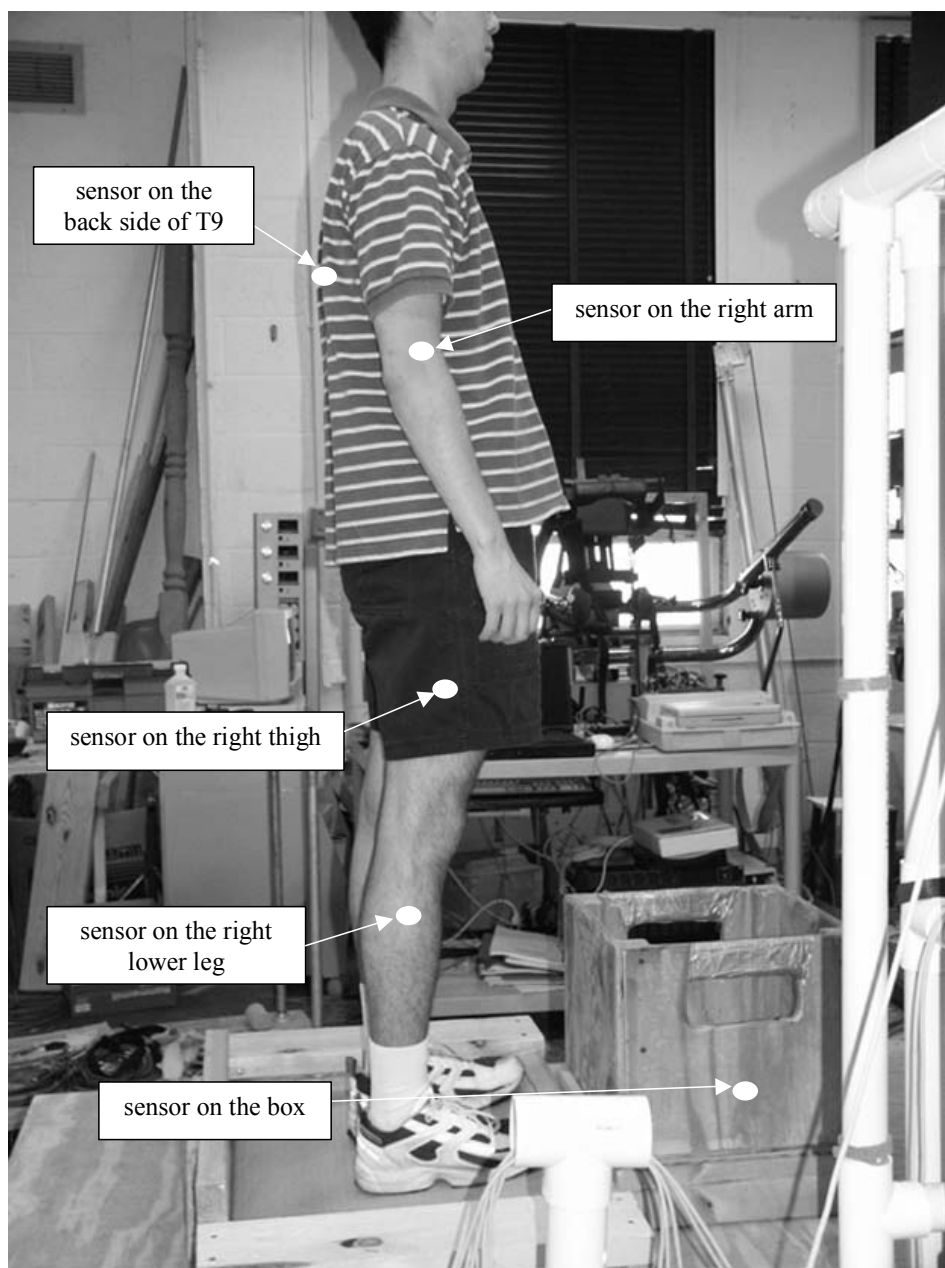


Figure 2.1 Sensor locations



Figure 2.2 Wooden platform (10° inclined slope) and weight box

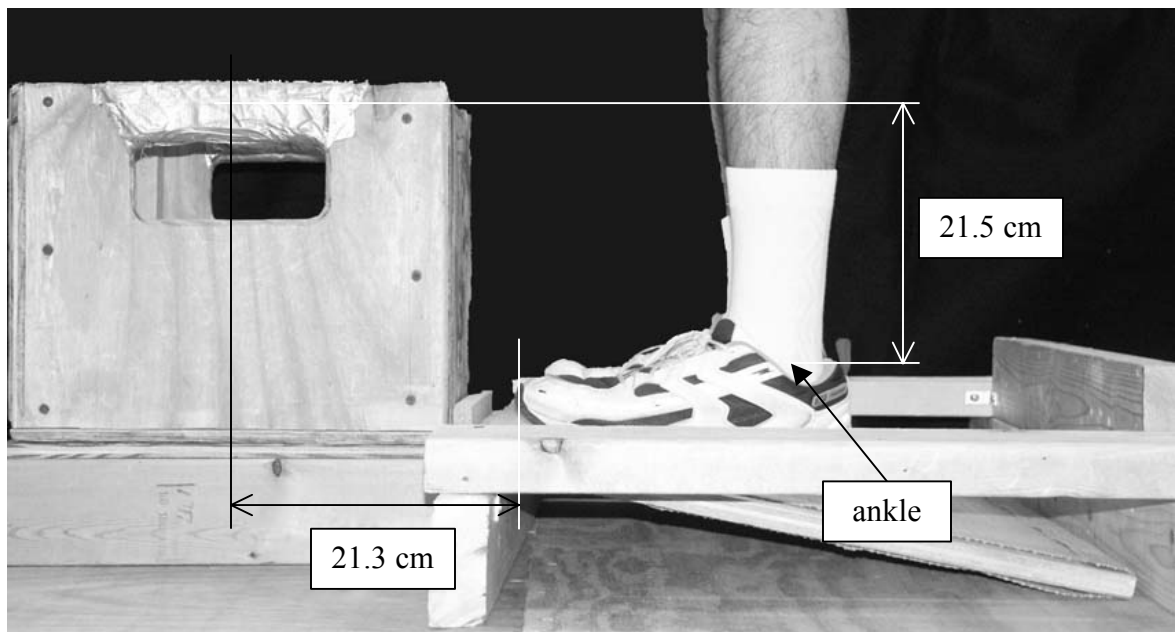


Figure 2.3 Horizontal and vertical distances between weight box and foot

2.3. **Independent variables**

Independent variables were slope angle and lifting technique. A slope angle for each trial was chosen from five angles; two inclined slope angles (20° , 10°), two declined slope angles (-20° , -10°), and flat ground (0°). On each of the five different slope angles subjects were asked to perform lifts with one of three lifting techniques (leg lift, back lift, and freestyle lift). In the leg lift technique the subjects were asked to keep their backs as erect as possible and flex the knees during lift. During the back lift subjects were asked to keep their legs as straight as possible and flex the back. Freestyle lift technique was self-selected and not constrained. Subjects could choose any type of technique including leg and back lift. All lifts were sagittally symmetric and lifting motions were continuous. The order of conditions was random and there were fifteen trials (5 slope angles $\times$ 3 lifting techniques).

2.4. **Dependent variables**

Dependent variables in this study were peak net reactive moment at the hip, knee, and ankle joints as computed from a dynamic biomechanical model, and the peak angle (deviation from vertical, refer to Figure 2.4) of the trunk (T9), thigh, and shank (leg).

2.5. **Experimental Procedures**

After informed consent was obtained, anthropometry measurements were taken and a brief warm-up stretching period was given to all subjects in order to reduce potential risks from the experiment. Subjects performed 15 half squat exertions followed by simple stretching motions (neck, shoulder, back, hamstring, and achilles). More stretching was allowed if subject desired. With all sensors in place, subjects stood on flat platform and performed two or three

freestyle lifts while movements were collected and analyzed briefly to verify sensor assignment and orientations. All subjects participated in a brief training period to be familiarized with the experimental procedures and lifting techniques. Subjects performed five to ten lifts on flat ground with three lifting techniques for practice until they understood each method and procedures correctly. Subjects did not perform practice on sloped grounds. After 1- minute break on flat ground, the data collection session began.

This experiment consisted of fifteen lifting bouts (trials) and each trial began with examiner's notice ('begin'). Subjects started from standing vertical position and bent down to grab the box. Each lift ended when the subjects returned to their original standing position with the box in their hands. When the subjects' body was stable, the box was taken by the examiner and returned to the original position. After four-second pause, the examiner gave a signal and the subjects performed another lift under the same condition (same lifting technique and slope). Each lifting bout continued for 50 seconds. A 60 second break was given between consecutive bouts. During the break period, subjects could take a rest standing on flat ground or sitting in a chair. During this break, the experimenter adjusted the platform slope angle to the next setting. Before each bout, the subjects were instructed which of three different lifting techniques (back lift, leg lift, and freestyle lift) to use for next bout. For all lifts, subjects were asked to lift the box at what they considered a normal speed for work that continues for 8 hours a day.

2.6. Biomechanical Model

The biomechanical model used in this study was a two-dimensional (sagittally symmetric), five-segment dynamic model (Figure 2.4). The body was divided into segments describing the feet, legs (shanks), thighs, head-neck-trunk, and arms-hands. All segments were

considered rigid bodies, connected by frictionless, simple hinge joints. The ankle was assumed to remain in a fixed position, and wrist and elbow were not treated as joints because very little wrist and elbow action was observed in the pilot experiment. Arms were assumed to be straight during lift. The biodynamic model of this study added the linear acceleration effects to the static effects, plus the rotational moment-of-inertia effect of the segment in computing the net moment acting at the joints. Net moments were calculated by examining the segments one at a time by means of force vectors and position vectors of each segment, starting with the arm segment.

The net moment at joint j is the sum of six terms which are,

- moment at upper joint
- vertical reaction force on upper joint $\times$ horizontal distance from upper joint to joint j
- horizontal reaction force on upper joint $\times$ vertical distance from upper joint to joint j
- vertical inertial force of segment $\times$ horizontal distance from COG of segment to joint j
- horizontal inertial force of segment $\times$ vertical distance from COG of segment to joint j
- moment-of-inertia about joint $j \times$ angular acceleration of segment about j

The equations for net moments of shoulder (Ms), hip (Mh), knee (Mk), and ankle (Mak) joints are,

$$\begin{aligned} Ms = & F_{o,y} \times D_{h,s} \times \cos(Sd) + F_{o,z} \times D_{h,s} \times \sin(Sd) + F_{a,y} \times D_{a,s} \times \cos(Sd) \\ & + F_{a,z} \times D_{a,s} \times \sin(Sd) + (I_a + m_a \times (D_{a,s})^2) \times \alpha_a \end{aligned} \quad (1)$$

$$Mh = Ms + R_{s,y} \times D_{s,h} \times \cos(T9) + R_{s,z} \times D_{tr,h} \times \sin(T9) + F_{tr,y} \times D_{tr,h} \times \cos(T9)$$

$$+ F_{tr,z} \times D_{tr,h} \times \sin(T9) + (I_{tr} + m_{tr} \times (D_{tr,h})^2) \times \alpha_{tr} \quad (2)$$

$$\begin{aligned} Mk = & Mh + R_{h,y} \times D_{h,k} \times \cos(Th) + R_{h,z} \times D_{h,k} \times \sin(Th) + F_{th,y} \times D_{th,h} \times \cos(Th) \\ & + F_{th,z} \times D_{th,h} \times \sin(Th) + (I_{th} + m_{th} \times (D_{th,k})^2) \times \alpha_{th} \end{aligned} \quad (3)$$

$$\begin{aligned} Mak = & Mk + R_{k,y} \times D_{k,ak} \times \cos(Sh) + R_{k,z} \times D_{k,ak} \times \sin(Sh) + F_{sh,y} \times D_{sh,h} \times \cos(Sh) \\ & + F_{sh,z} \times D_{sh,h} \times \sin(Sh) + (I_{sh} + m_{sh} \times (D_{sh,ak})^2) \times \alpha_{ah} \end{aligned} \quad (4)$$

The locations and terminology of forces and moments of biomechanical model are shown in Figure 2.4.

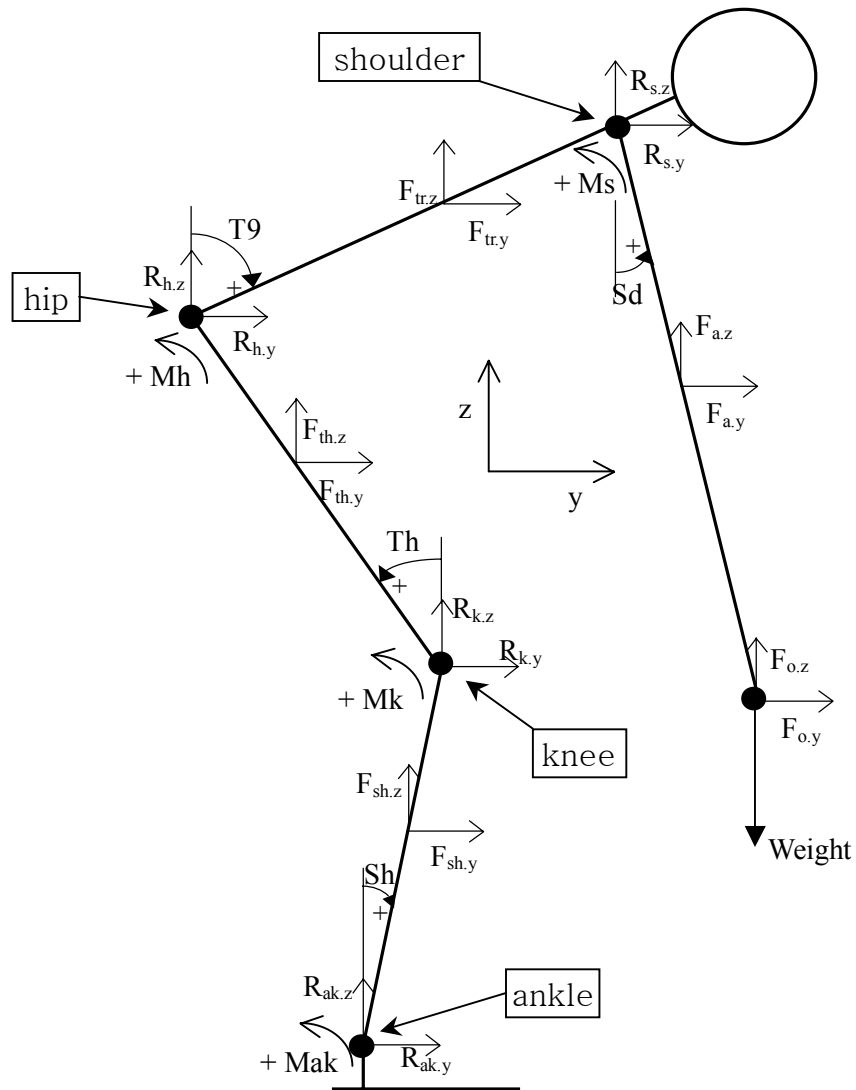


Figure 2.4 Five-segment two-dimensional (sagittally symmetric) model

M_s = net moment at shoulder joint (Nm)

M_h = net moment at hip joint (Nm)

M_k = net moment at knee joint (Nm)

M_{ak} = net moment at ankle joint (Nm)

S_d = shoulder flexion angle (deg)

T_9 = trunk flexion angle (deg)

T_h = thigh flexion angle (deg)

S_h = shank flexion angle (deg)

m_a = mass of arms (kg)

m_{tr} = mass of trunk-neck-head (kg)

m_{th} = mass of thighs (kg)

m_{sh} = mass of shanks (kg)

I_a = moment of inertia of arms (m^4)

I_{tr} = moment of inertia of trunk-neck-head (m^4)

I_{th} = moment of inertia of thighs (m^4)

I_{sh} = moment of inertia of shanks (m^4)

W = mass of box (kg)

$F_{o,y}$ = inertial horizontal force of object (weight) (N)

$F_{o,z}$ = inertial vertical force of object (weight) (N)

$F_{a,y}$ = inertial horizontal force of arms (N)

$F_{a,z}$ = inertial vertical force of arms (N)

$F_{tr,y}$ = inertial horizontal force of trunk-neck-head (N)

$F_{tr,z}$ = inertial vertical force of trunk-neck-head (N)

$F_{th,y}$ = inertial horizontal force of thighs (N)

$F_{th,z}$ = inertial vertical force of thighs (N)

$F_{sh,y}$ = inertial horizontal force of shanks (N)

$F_{sh,z}$ = inertial vertical force of shanks (N)

$R_{s,y}$ = horizontal reaction force at shoulder joint (N)

$R_{s,z}$ = vertical reaction force at shoulder joint (N)

$R_{h,y}$ = horizontal reaction force at hip joint (N)

$R_{h,z}$ = vertical reaction force at hip joint (N)

$R_{k,y}$ = horizontal reaction force at knee joint (N)

$R_{k,z}$ = vertical reaction force at knee joint (N)

$R_{ak,y}$ = horizontal reaction force at ankle joint (N)

$R_{ak,z}$ = vertical reaction force at ankle joint (N)

$D_{h,s}$ = distance between hand and shoulder joint (m)

$D_{a,s}$ = distance between center of gravity of arm and shoulder joint (m)

$D_{s,h}$ = distance between shoulder joint and hip joint (m)

$D_{tr,h}$ = distance between center of gravity of trunk-neck-head and hip joint (m)

$D_{h,k}$ = distance between hip joint and knee joint (m)

$D_{th,k}$ = distance between center of gravity of thigh and knee joint (m)

$D_{k,ak}$ = distance between knee joint and ankle joint (m)

$D_{sh,ak}$ = distance between center of gravity of shank and ankle joint (m)

α_a = angular acceleration of arm at shoulder joint (deg/sec²)

α_{tr} = angular acceleration of trunk-neck-head at hip joint (deg/sec²)

α_{th} = angular acceleration of thigh at knee (deg/sec²)

α_{sh} = angular acceleration of shank at ankle (deg/sec²)

2.7. Data processing

2.7.1. Data collection

Subjects' anthropometric data were collected at the beginning of the experiment. The body weight, stature, ankle (lateral malleolus) to knee (lateral collateral ligament at the height of the joint cleft) distance of right leg, knee to hip (greater trochanter) distance of right leg, hip to shoulder (acromion) distance or right lateral side, and right arm length (from the acromion to the tip of the middle finger) were measured by scale and anthropometer. The mass of segments, the

location of COG (center of gravity) of segments, and the moment-of-inertia of arm-hand, trunk-head-neck, thigh, and ankle were calculated from measured anthropometric data, based on Pheasant (1986) and McConville et al. (1980).

The x-y-z coordination and angles about three axes from magnetic sensors were recorded 60 times per second (60 Hz). The raw data were then low-pass filtered by the Butterworth filter with an effective cut-off frequency of 20 Hz. The sampling frequency and filter frequency were decided from pilot study. The second derivative (9-point differentiation method, (Lanczos, 1956)) of raw data yielded angular and linear accelerations. The recording, filtering, and derivation of acceleration were carried out using the Motion MonitorTM Ver.4.0 (Innovative Sports Training, Inc) software. Then, the filtered raw data were exported to Microsoft Excel spreadsheet and the imported data were processed by biodynamic equations which were programmed in the Excel spreadsheet to compute the moment at joints. The first two lifts within each bout were not included in the statistical analyses because pilot tests showed large variability in the first couple of lifts as the subjects developed their strategy for a given condition. An example of the profiles of hip moment and trunk angle (T9 level) with lifting time is displayed in Figure 2.5. The 'sd_vrs' means the moment at hip joint due to the vertical reaction static force on shoulder joint and 'lift off' was defined by checking for an abrupt change of this factor. The maximum moment value between 'lift off' point and 'end of lift' was defined as the peak joint moment, and the maximum segment angle value between 'start of lift' and 'end of lift' was identified as the peak segment angle. That is, the peak joint moments were analyzed only when subjects were holding the box.

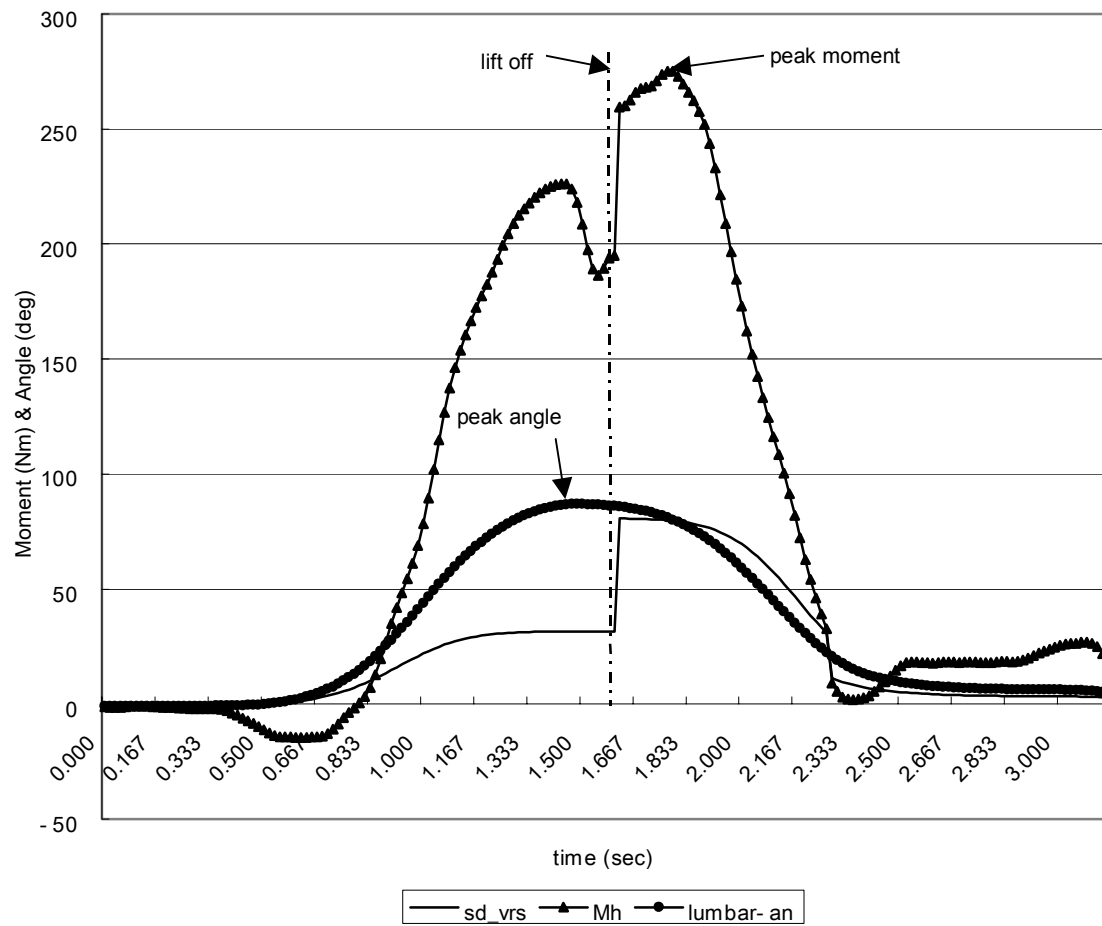


Figure 2.5 Hip moment and trunk angle (labeled 'lumbar-an' in figure) during a freestyle lift at 0° slope.

2.7.2. Statistical analysis

The assumptions of the ANOVA technique were first tested by plotting the residuals as a function of the predicted values and as a function of time to see if any trends existed indicating a violation of these basic assumptions (Montgomery, 2001).

The Analysis of variance (ANOVA) for the two-factor (5×3) randomized block design was performed to test the differences due to three lifting styles and five slope angles. In addition to slope angle and lifting techniques, the inter-subject variability (blocking variable) had an effect on the response (refer to results section). To prevent the inflation of error term from inter-subject variability, this variation was factored out of the error term by putting it in the model as a block.

The effect model for this design is,

$$y_{ijk} = \mu + \beta_i + \tau_j + (\beta\tau)_{ij} + \delta_k + \varepsilon_{ijk}$$

where y_{ijk} = observation at the i th level of factor A and j th level of factor B for k th block.

μ = the overall mean

β_i = the effect of i th level of factor 'slope angle' ($i = 1, 2, 3, 4, 5$)

τ_j = the effect of j th level of factor 'lifting technique' ($j = 1, 2, 3$)

$(\beta\tau)_{ij}$ = the effect of the interaction between τ_j and β_i

δ_k = the effect of k th block 'subject' ($k = 1, 2, \dots, 13$)

ε_{ijk} = the random error component associated with observation y_{ijk}

The model assumed that interaction between blocks (subject) and treatments (slope angles or lifting techniques) was negligible. The error term in this model consisted of the $(\tau\delta)_{ik}$, $(\beta\delta)_{jk}$, and

$(\tau\beta\delta)_{ijk}$ interactions that represent random variation of subjects across treatments. To test the slope angle effect, the interaction between 'slope angle' and 'subject' was used as the error term. Similarly, the interaction between 'lifting technique' and 'subject' was an error term of ANOVA for the 'lifting technique' effect, and the interaction between 'lifting technique', 'slope angle', and the 'subject' was an error term of the ANOVA for the interaction effect between 'lifting technique' and 'slope angle' (Montgomery, 2001). The differences of means of each dependent variable between slope angles or lifting techniques were compared by the Tukey's multiple comparison test when any significant difference was found by ANOVA ($\alpha = 0.05$).

3. RESULTS

3.1. Verification of statistical assumptions

An examination of residuals was performed to investigate the basic assumptions of ANOVA and model adequacy. Figure 3.1 ~ 3.6 display the residuals versus the predicted values $\hat{y}_{ijk}$. These plots indicate a weak tendency for the variance of the residuals to increase as the dependent variables increase and no unusual structure is apparent. Figure 3.7 ~ 3.12 display the residuals of dependent variables in time order of data collection. No apparent tendency is observed, implying that the residuals are not correlated with each other.

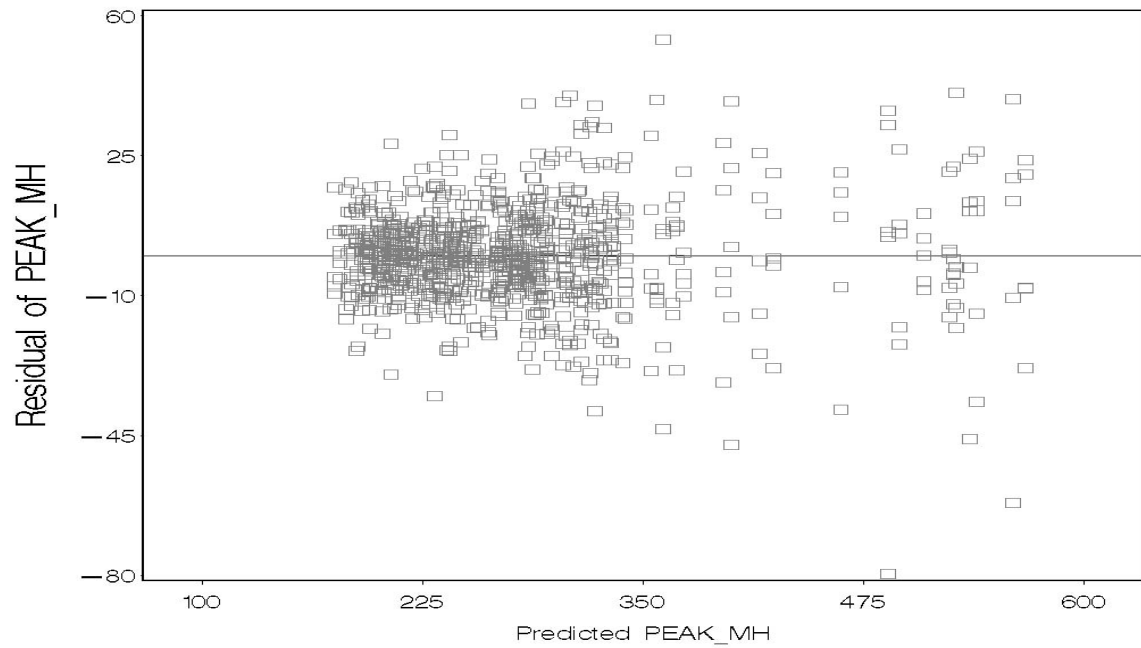


Figure 3.1 Plot of residuals vs. predicted peak hip moment

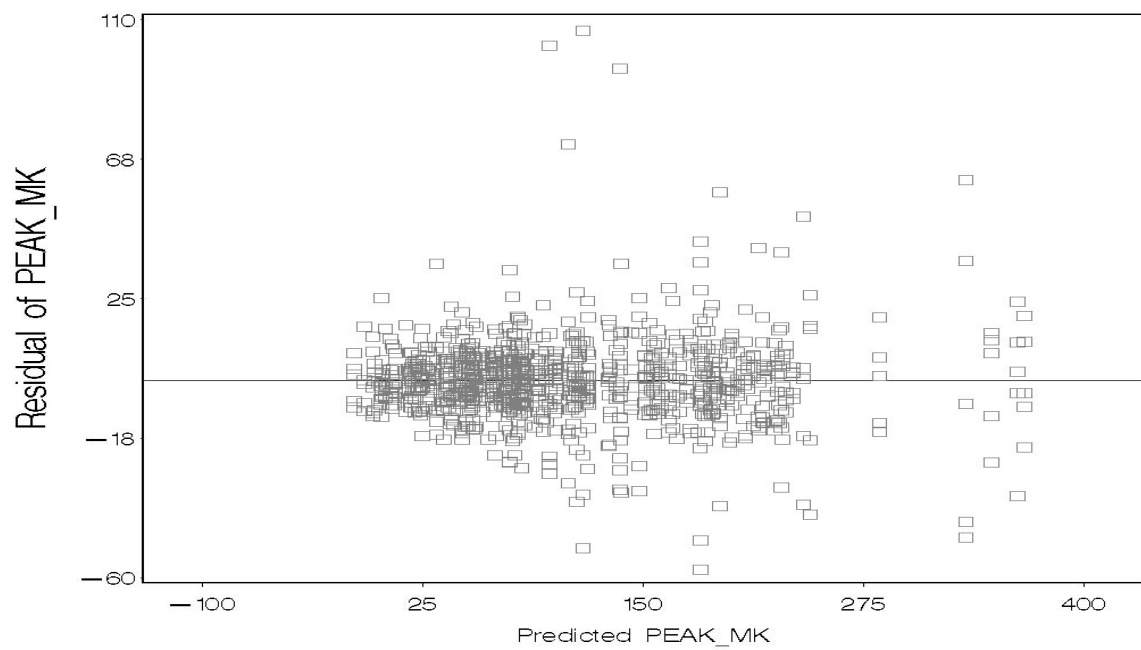


Figure 3.2 Plot of residuals vs. predicted peak knee moment

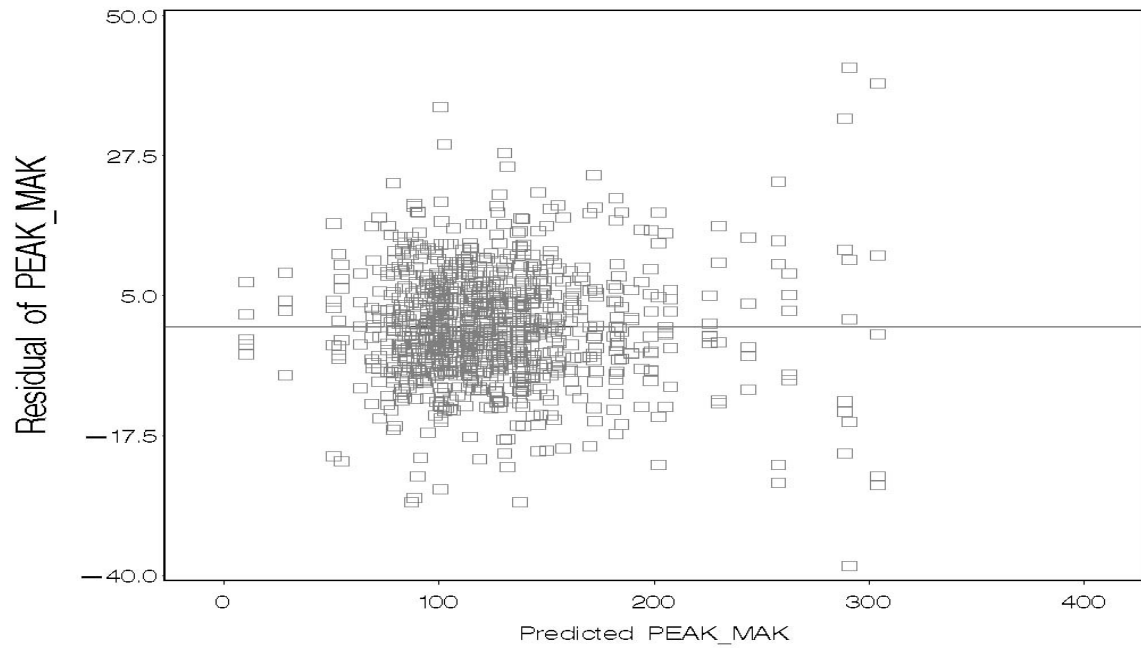


Figure 3.3 Plot of residuals vs. predicted peak ankle moment

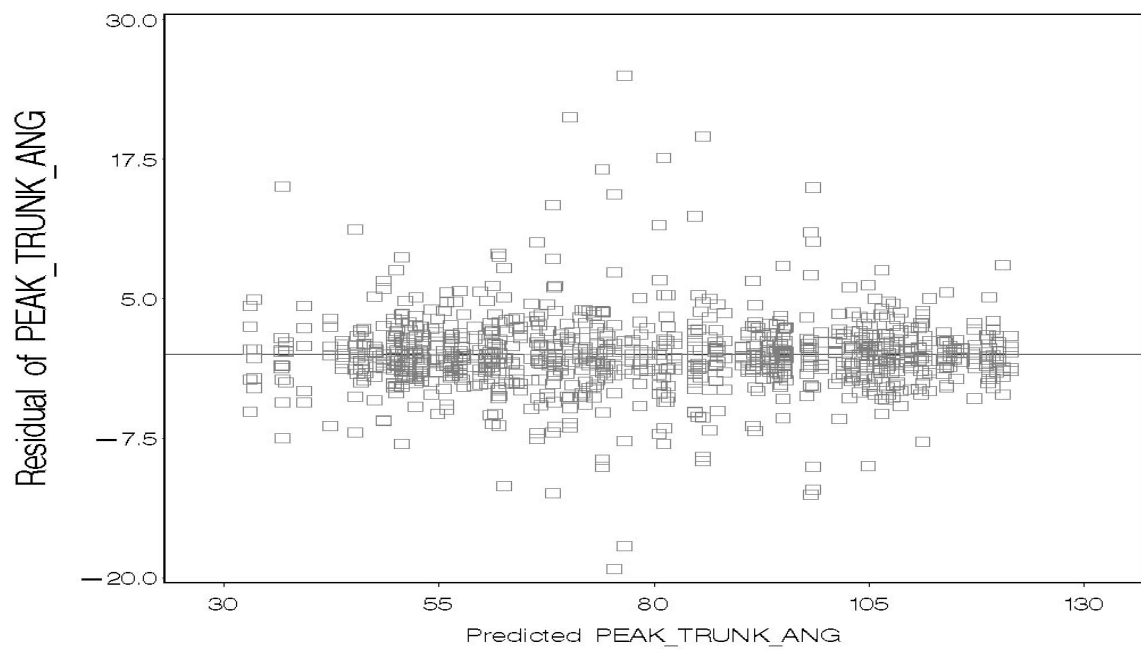


Figure 3.4 Plot of residuals vs. predicted peak trunk (T9) angle

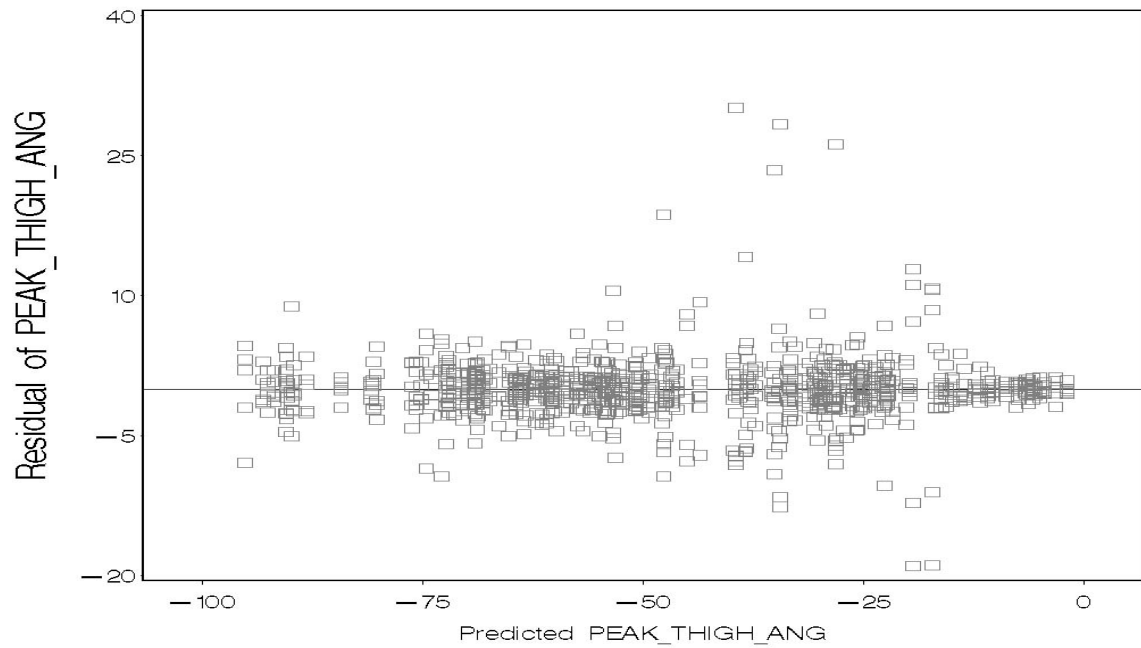


Figure 3.5 Plot of residuals vs. predicted peak thigh angle

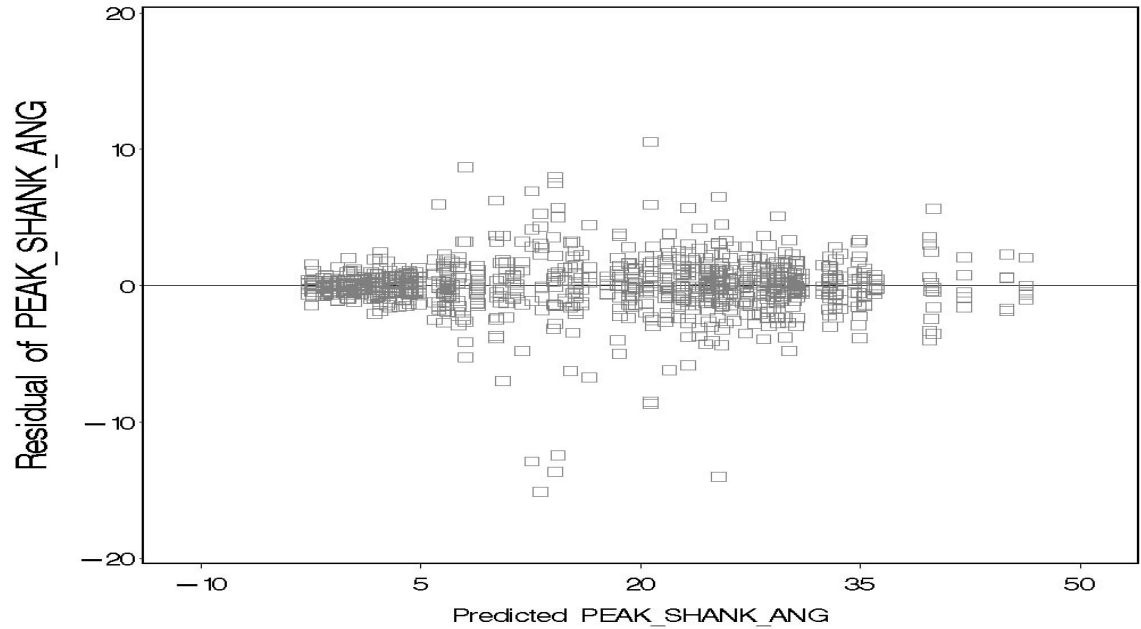


Figure 3.6 Plot of residuals vs. predicted peak shank angle

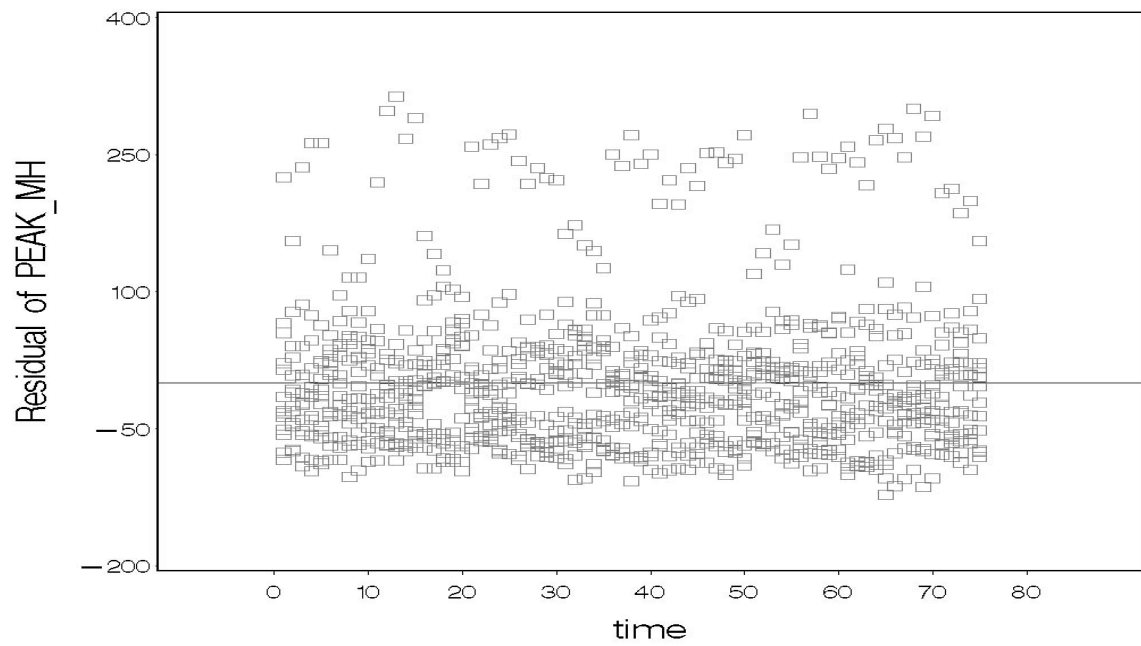


Figure 3.7 Plot of residuals of peak hip moment vs. time

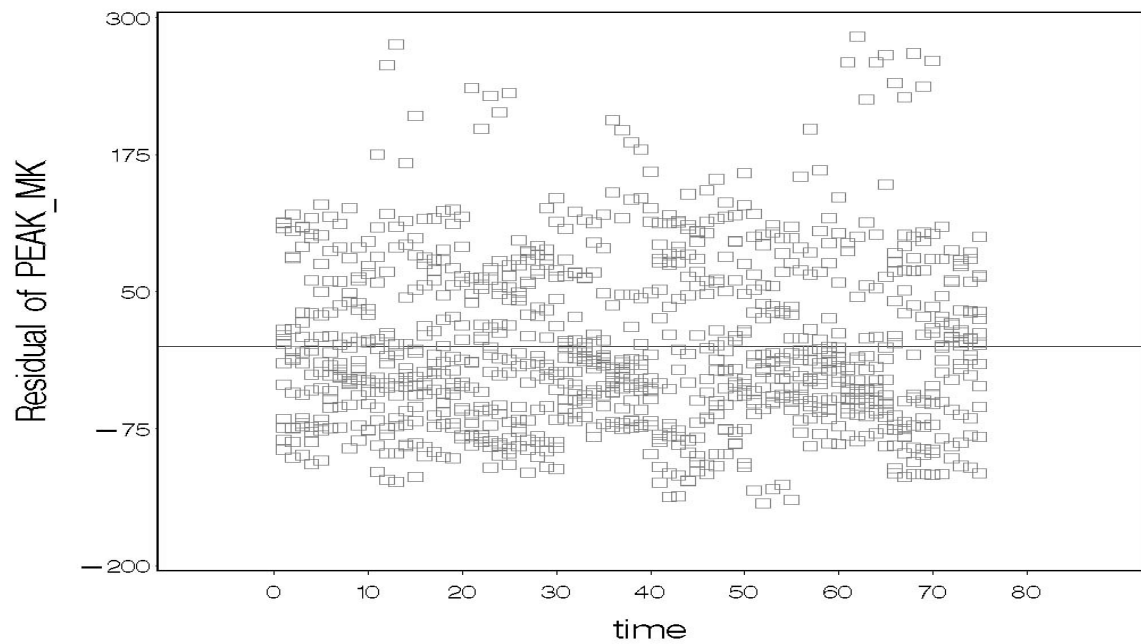


Figure 3.8 Plot of residuals of peak knee moment vs. time

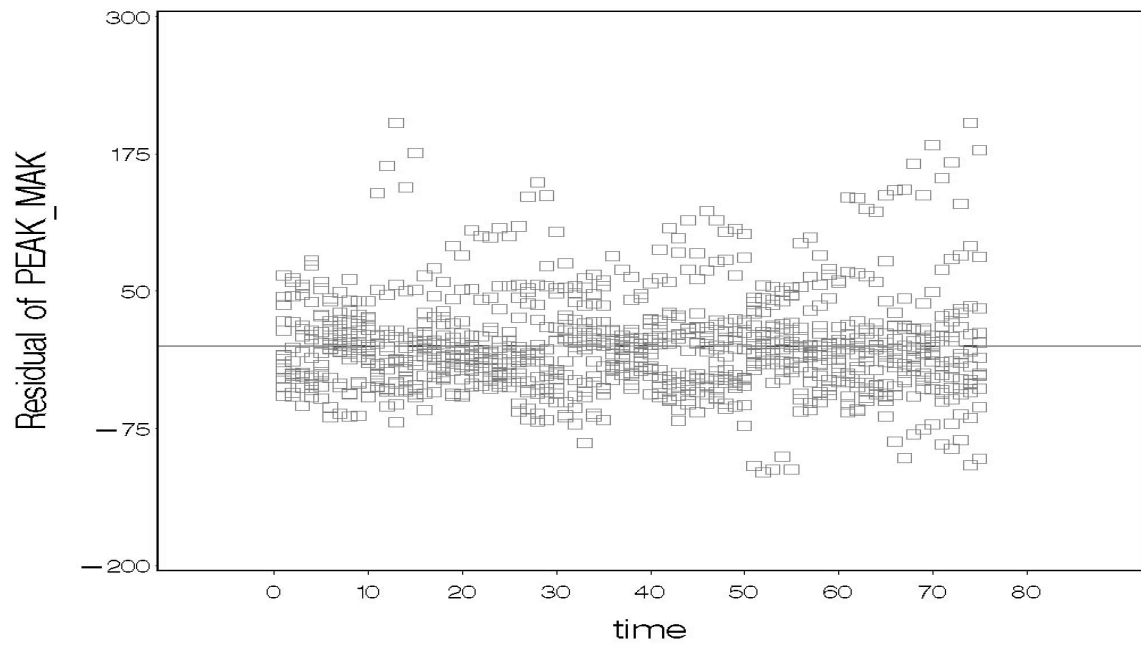


Figure 3.9 Plot of residuals of peak ankle moment vs. time

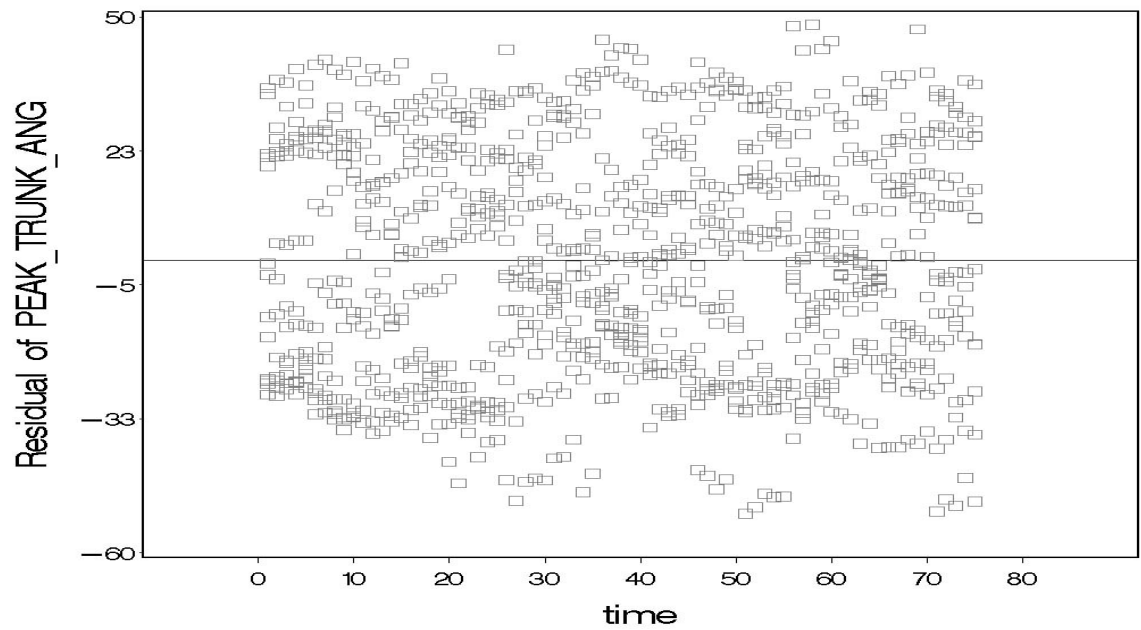


Figure 3.10 Plot of residuals of peak trunk angle vs. time

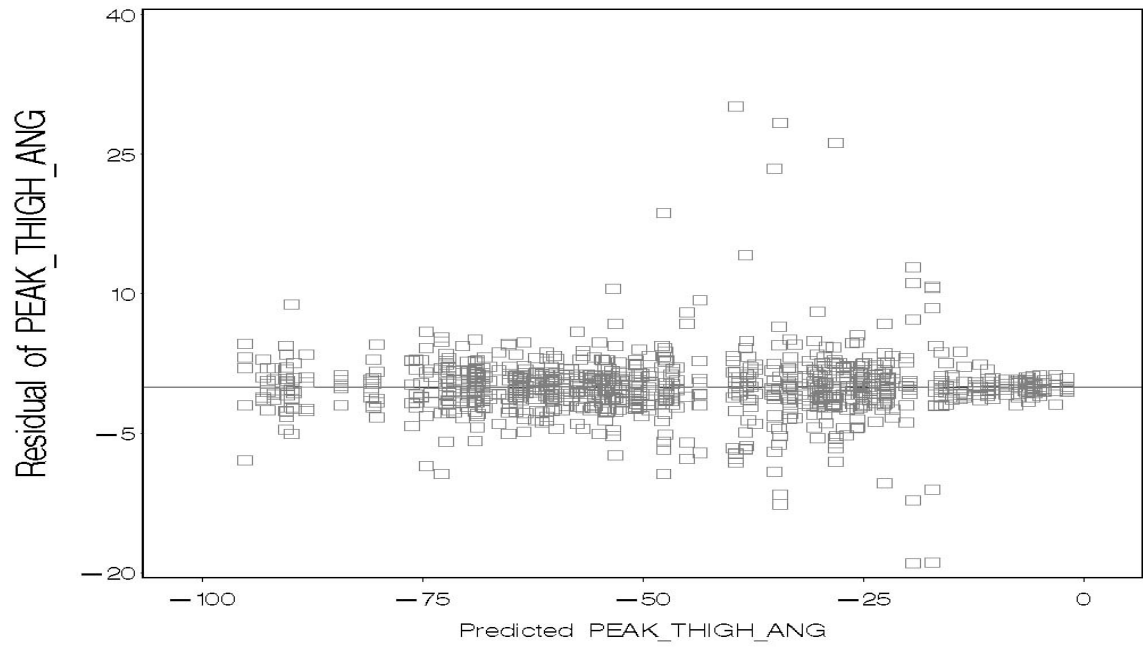


Figure 3.11 Plot of residuals of peak thigh angle vs. time

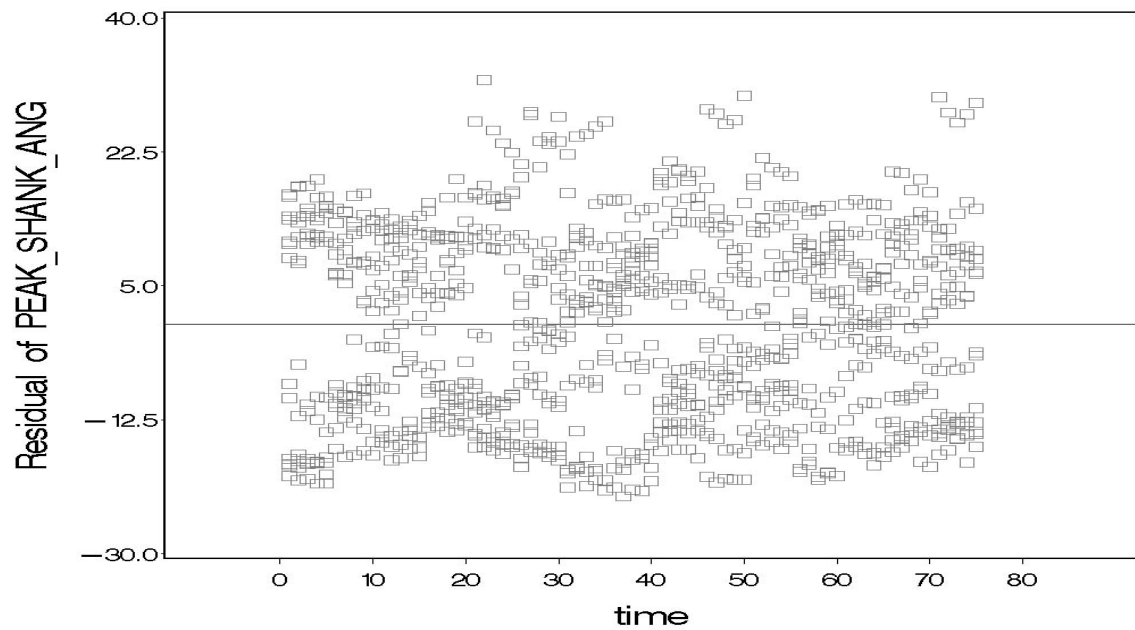


Figure 3.12 Plot of residuals of peak shank angle vs. time

3.2. **Variation between and within subjects, and between repetitions**

The box plots of peak hip moments and peak trunk angles by ‘subjects’ and ‘repetitions’ are displayed in Figure 3.13 ~ 3.16. The horizontal line inside the box represents the median, and the top and bottom of the box represent the 3rd quartile and the 1st quartile, respectively. The whiskers are drawn to the maximum and minimum observations. Mean is represented as ‘+’ within box.

The variation of peak hip moment between subjects was larger than within subject variations (Figure 3.13). The same results were observed at other dependent variables. The variation between repetitions was low in peak hip moment and peak trunk angle (Figure 3.15, 3.16). Other dependent variables showed similar results.

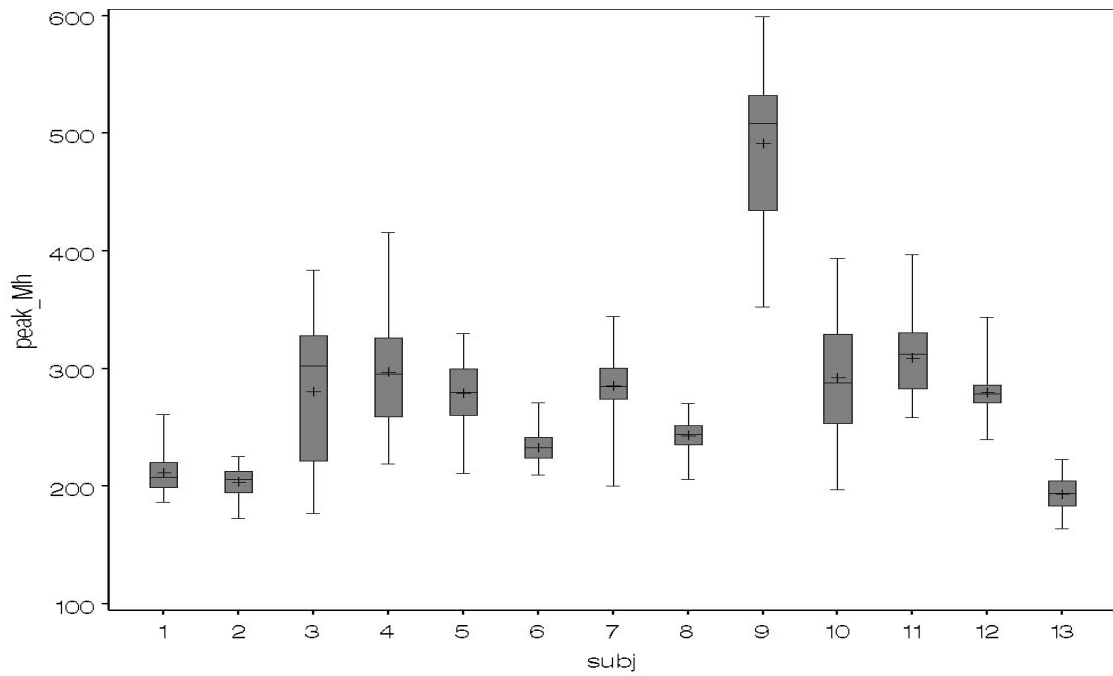


Figure 3.13 Box plot of peak hip moment by 'subject'

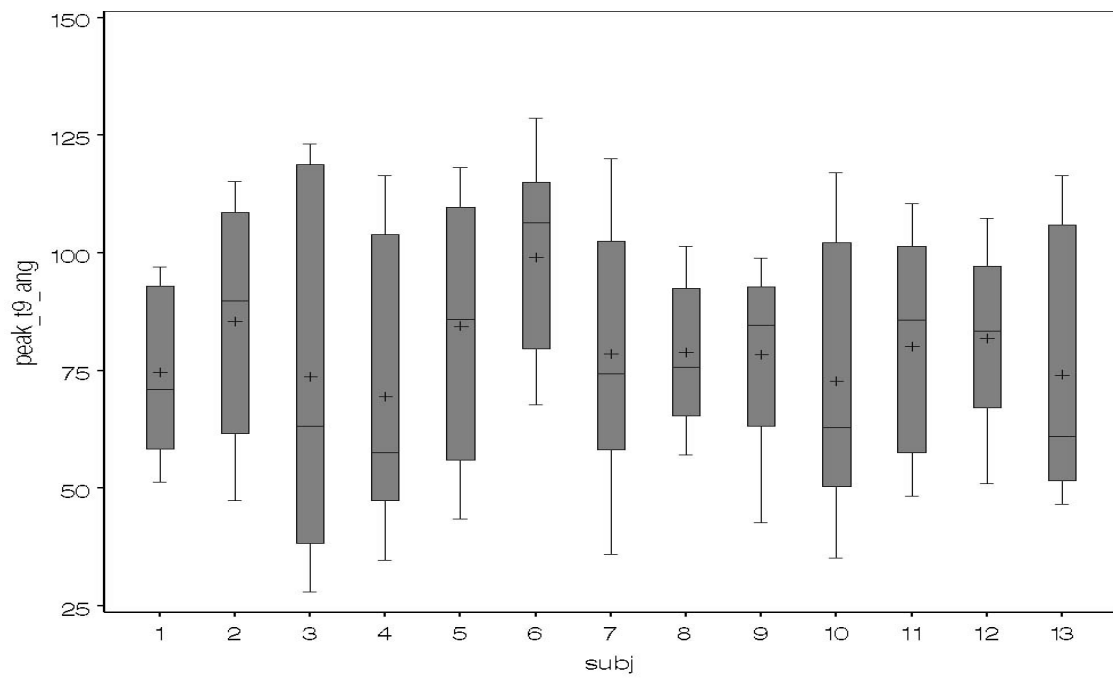


Figure 3.14 Box plot of peak trunk (T9) angle by 'subject'

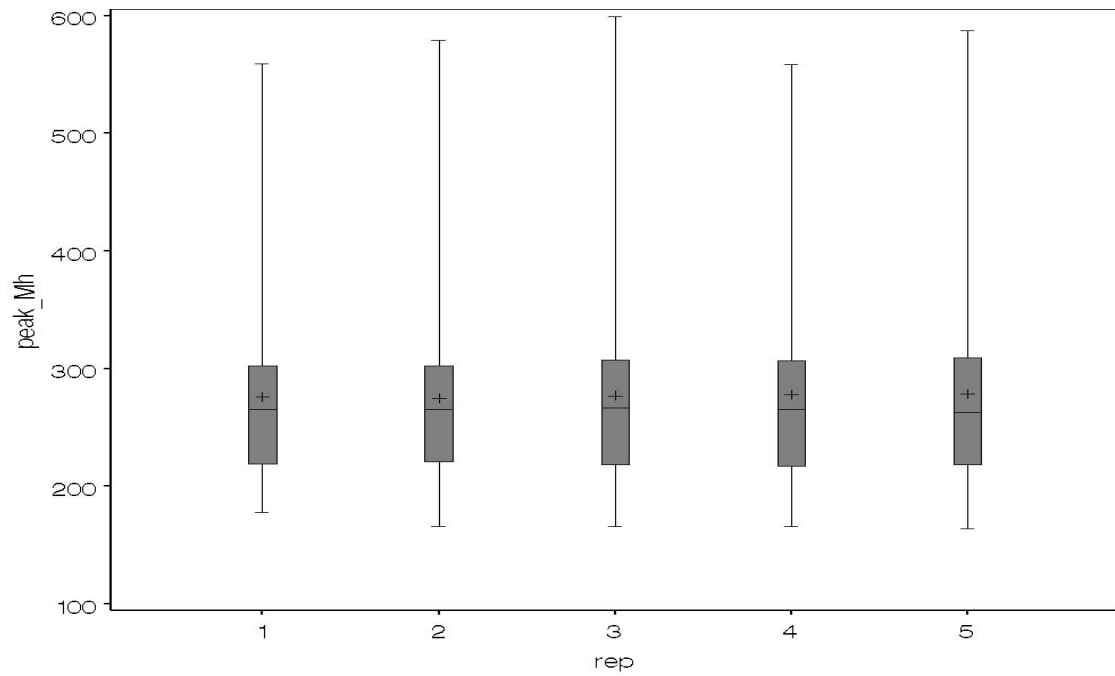


Figure 3.15 Box plot of peak hip moment by 'repetitions'

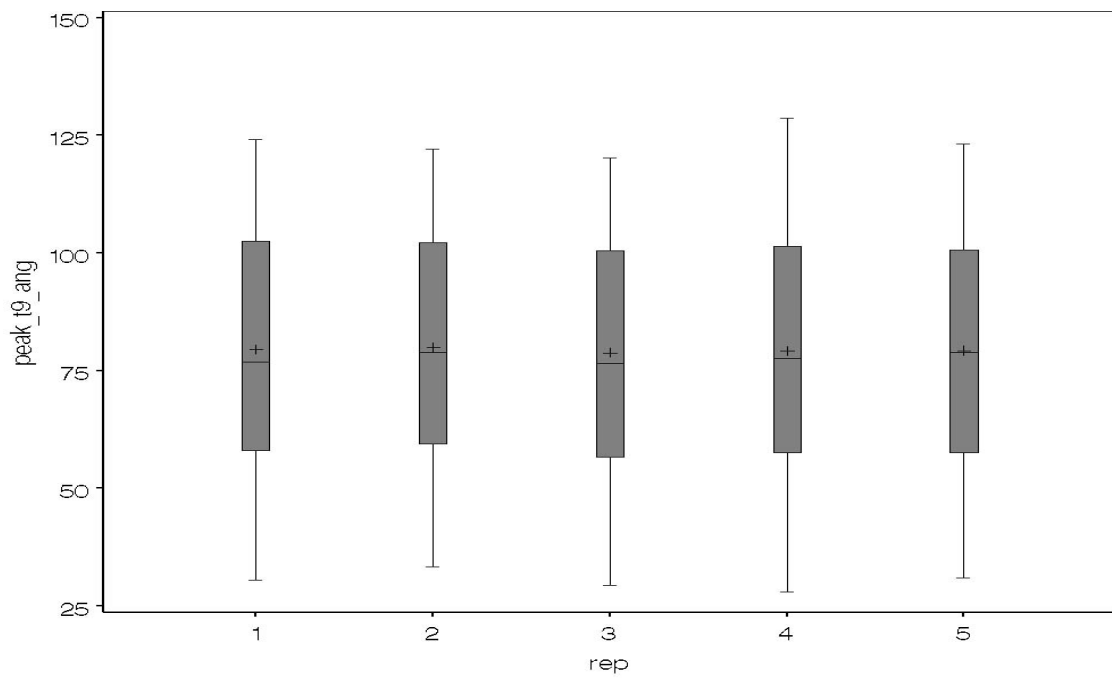


Figure 3.16 Box plot of peak trunk angle by 'repetitions'

3.3. Peak joint moment

3.3.1. Interaction (slope angle $\times$ lifting technique) effect on peak joint moments

Since this study used the two-way ANOVA, three possible null hypotheses were tested. A first null hypothesis stated that the peak joint moments were identical across five slope angles, controlling for the lifting technique. The second null hypothesis stated that the peak joint moments were identical across three lifting techniques, controlling for the slope angle. The last null hypothesis states that there was no strong interaction in the effects of the two independent variables (slope angle and lifting technique) on the responses (peak joint moments).

Table 3.1 displays the results of the ANOVA for each peak joint moment. The null hypotheses for the interactions are rejected ($p < 0.05$). The p-values of all tests are less than 0.05 for all dependent variables. These interactions can be observed in Figures 3.17 ~ 3.19. Figure 3.17 plots the mean peak hip moments of three lifting methods across five slope angles. The difference in means between lifting techniques depends on the slope angle, and the slope angle effect on peak hip moment differs for lifting techniques (lines are not parallel). Similarly, the plots of mean peak knee moment (Figure 3.18) and mean peak ankle moment (Figure 3.19) show interactions between slope angle and lifting technique.

Because the interaction between slope angle and lifting technique was statistically significant for all three peak joint moments, further analysis was necessary to assess the main effects. Specifically, the data set was partitioned such that the effects of one independent variable could be considered while the other was controlled. Therefore, when assessing the effects of slope angle, the data set was partitioned into three sets, one for each lifting technique. The effect of slope angle was then assessed for each lifting technique (Tables 3.2 ~ 3.4). Likewise, when assessing the effects of lifting technique, the data set was partitioned into five sets, one for each

slope angle. The effect of lifting technique was then assessed for each slope angle (Tables 3.6 ~ 3.8). Finally, the Tukey's post-hoc multiple comparison test was used to further describe the significant main effects of slope angle (Table 3.5) and lifting technique (Table 3.9).

Table 3.1 ANOVA results testing the effect of slope angle, technique, and interaction on peak joint moments

Dep. variable	Source	Error Term	DF	Type III SS	Mean Square	F - Value	Pr > F
Mh	angle	angle*subject	4	44085.19	11021.30	6.73	0.0002
	technique	technique*subject	2	377681.67	188840.83	15.77	<.0001
	angle*technique	angle*technique*subject	8	25924.61	3240.58	2.21	0.0327
Mk	angle	angle*subject	4	79452.65	19863.16	13.88	<.0001
	technique	technique*subject	2	3225818.71	1612909.36	71.48	<.0001
	angle*technique	angle*technique*subject	8	30051.47	3756.43	2.66	0.0111
Mak	angle	angle*subject	4	325729.19	81432.30	37.88	<.0001
	technique	technique*subject	2	106792.70	53396.35	9.20	0.0011
	angle*technique	angle*technique*subject	8	18907.31	2363.41	2.46	0.0181

Mh : peak hip moment (Nm)

Mk : peak knee moment (Nm)

Mak : peak ankle moment (Nm)

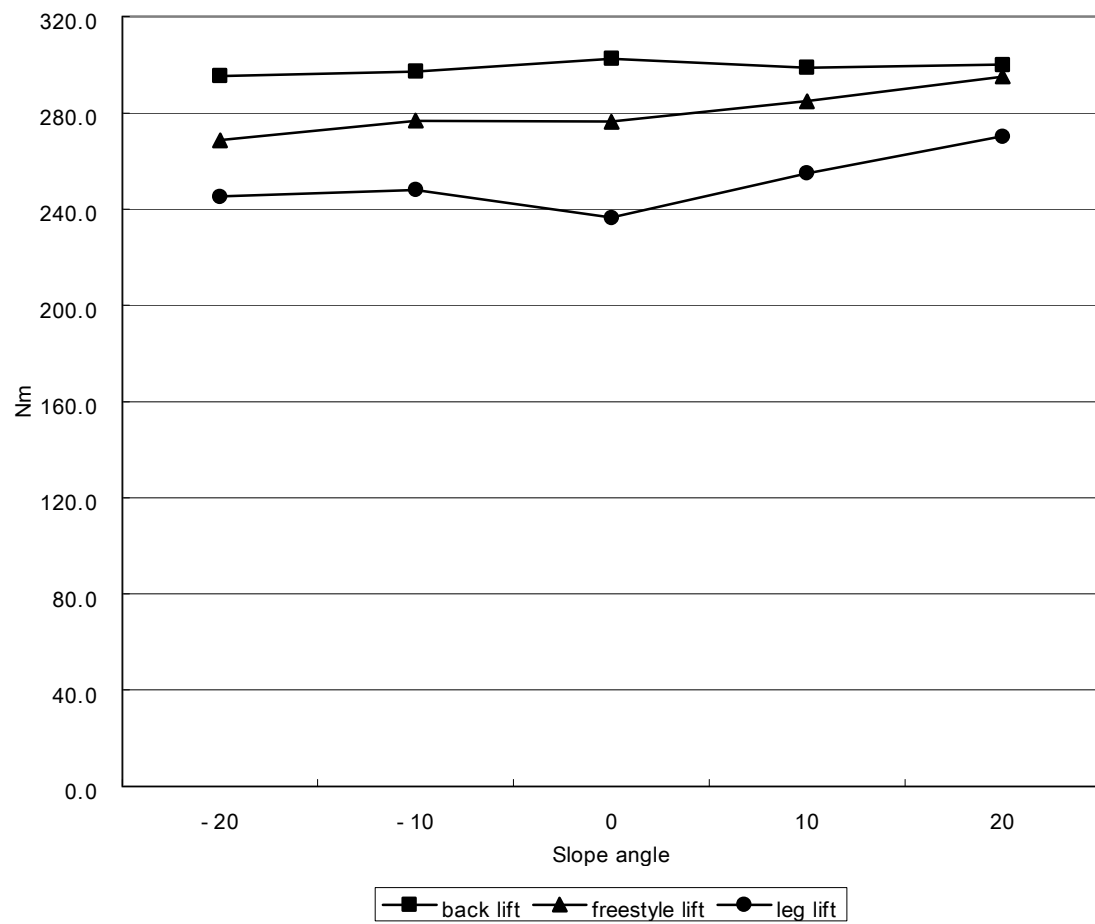


Figure 3.17 Mean peak hip moments

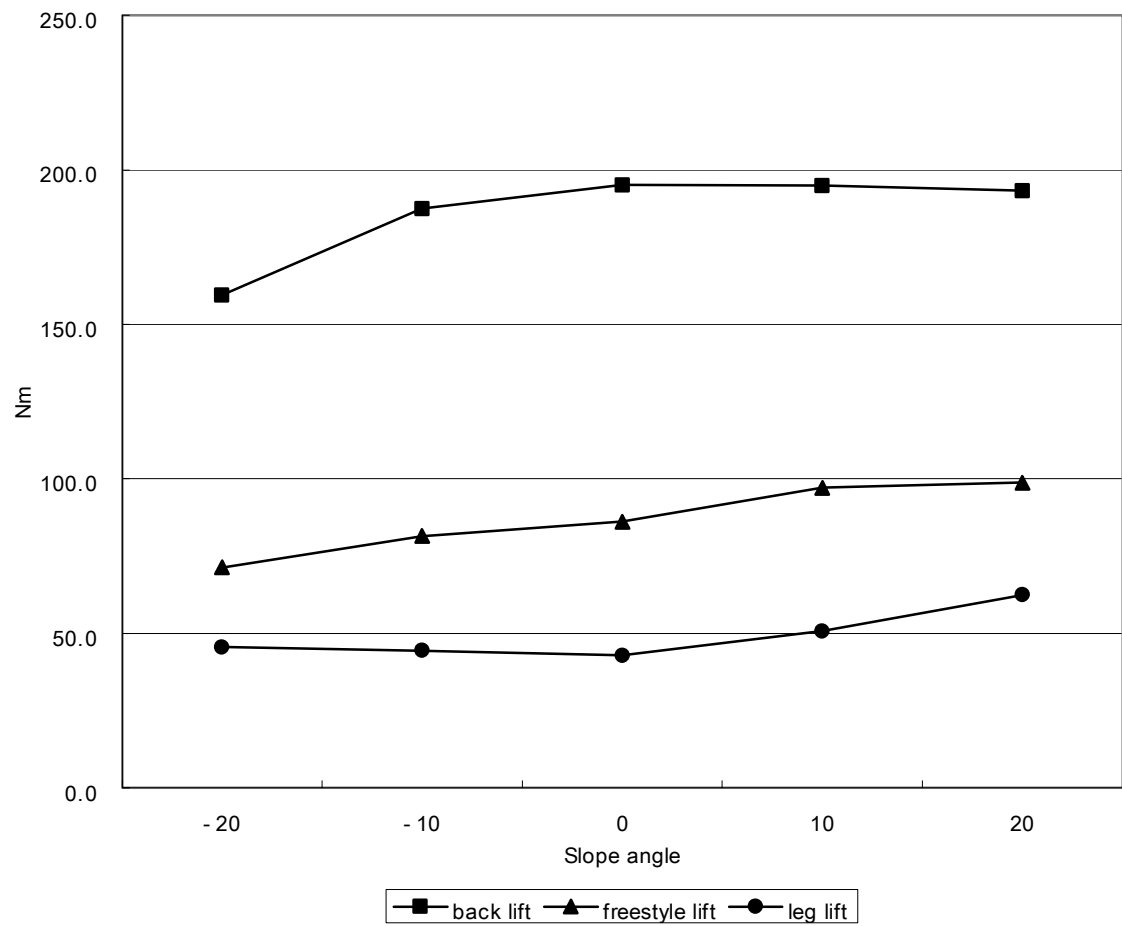


Figure 3.18 Mean peak knee moments

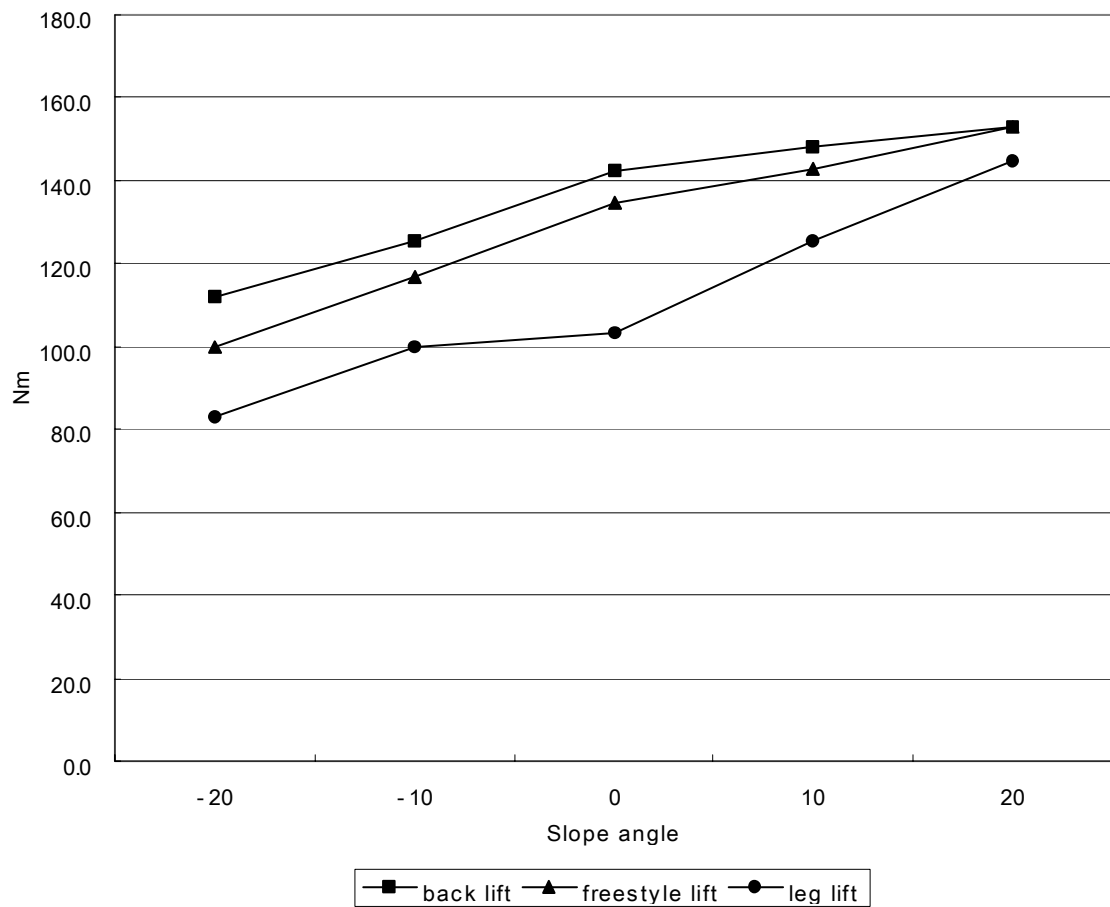


Figure 3.19 Mean peak ankle moments

3.3.2. Slope angle effect on peak joint moments

Table 3.2 ~ 3.4 show the ANOVA results of the null hypotheses state that the mean peak joint moments across five slope angles were identical controlling for lifting technique. The p-values are below 0.05 except for the hip moment in the back lift. The results of the Tukey's multiple comparison tests for peak joint moments are listed in Table 3.5. Means with the same letter in grouping column are not significantly different ($\alpha = 0.05$).

Table 3.2 ANOVA results testing the effect of slope angle on peak hip moment while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	1933.986	483.497	0.39	0.8126
Free lift	4	26291.412	6572.853	4.76	0.0026
Leg lift	4	41784.409	10446.102	5.35	0.0012

Table 3.3 ANOVA results testing the effect of slope angle on peak knee moment while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	59409.462	14852.365	16.50	<.0001
Free lift	4	33633.852	8408.463	3.11	0.0235
Leg lift	4	16460.804	4115.201	6.29	0.0004

Table 3.4 ANOVA results testing the effect of slope angle on peak ankle moment while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	76565.550	19141.387	21.85	<.0001
Free lift	4	115570.446	28892.612	29.15	<.0001
Leg lift	4	152500.501	38125.125	17.29	<.0001

Table 3.5 Tukey's grouping of mean peak joint moments for slope angle effect

Lifting technique	Peak hip moment (Nm)			Peak knee moment (Nm)			Peak ankle moment (Nm)		
	Tukey grouping	Mean	Slope angle	Tukey grouping	Mean	Slope angle	Tukey grouping	Mean	Slope angle
Back	P > 0.05 in ANOVA	302.62	0	A	195.12	0	A	152.88	20
		299.98	20	A	194.87	10	B	148.31	10
		298.78	10	A	193.20	20	C	142.54	0
		297.29	-10	B	185.69	-10	D	125.29	-10
		295.41	-20	C	159.53	-20	E	111.84	-20
Free-style	A	295.13	20	A	98.85	20	A	153.03	20
	B	284.94	10	A	97.11	10	B	141.63	10
	C	276.77	-10	B	86.21	0	C	134.44	0
	C	276.29	0	B	81.49	-10	D	116.68	-10
	D	268.70	-20	C	71.38	-20	E	99.68	-20
Leg	A	270.35	20	A	62.47	20	A	144.91	20
	B	254.99	10	B	50.76	10	B	125.70	10
	C	248.04	-10	C	45.62	-20	C	103.31	0
	C	245.25	-20	C	44.47	-10	C	99.73	-10
	D	236.48	0	C	42.91	0	D	82.82	-20

3.3.3. Lifting technique effect on peak joint moments

The lifting technique effect on peak joint moment, controlling for slope angle was statistically significant ($p < 0.05$) except the ankle moment at 20° slope (Table 3.6 ~ 3.8). The results of the Tukey's multiple comparison tests are listed in Table 3.9.

Table 3.6 ANOVA results testing the effect of lifting technique on peak hip moment while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	81905.405	50952.703	8.29	0.0018
-10	2	79558.642	39779.321	8.60	0.0015
0	2	144140.683	72070.341	19.31	<.0001
10	2	65155.972	32577.986	11.16	0.0004
20	2	32845.579	16422.789	10.18	0.0006

Table 3.7 ANOVA results testing the effect of lifting technique on peak knee moment while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	463855.968	231927.984	75.46	<.0001
-10	2	697084.750	348542.375	53.92	<.0001
0	2	799554.868	399777.434	57.29	<.0001
10	2	703544.973	351772.487	48.23	<.0001
20	2	591829.621	295914.810	67.19	<.0001

Table 3.8 ANOVA results testing the effect of lifting technique on peak ankle moment while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	27612.019	13806.009	8.22	0.0019
-10	2	21977.449	10988.724	4.72	0.0187
0	2	55759.439	27879.720	9.22	0.0011
10	2	17547.518	8773.759	4.89	0.0165
20	2	2803.587	1401.793	1.71	0.2021

Table 3.9 Tukey's grouping of mean peak joint moments for lifting technique effect

	Peak hip moment (Nm)			Peak knee moment (Nm)			Peak ankle moment (Nm)		
Slope angle	Tukey grouping	Mean	Lifting technique	Tukey grouping	Mean	Lifting technique	Tukey grouping	Mean	Lifting technique
-20	A	295.4	back	A	159.5	back	A	111.8	back
	B	268.7	free	B	71.4	free	B	99.7	free
	C	245.2	leg	C	45.6	leg	C	92.8	leg
-10	A	297.3	back	A	187.4	back	A	125.3	back
	B	276.8	free	B	81.5	free	B	116.7	free
	C	248.0	leg	C	44.5	leg	C	99.7	leg
0	A	302.6	back	A	195.1	back	A	142.5	back
	B	276.3	free	B	86.2	free	B	134.4	free
	C	236.5	leg	C	42.9	leg	C	103.3	leg
10	A	298.8	back	A	194.9	back	A	148.3	back
	B	284.9	free	B	97.1	free	B	142.8	free
	C	255.0	leg	C	50.8	leg	C	125.7	leg
20	A	300.0	back	A	193.2	back	P > 0.05 in ANOVA	153.0	back
	A	295.1	free	B	98.8	free		152.9	free
	B	270.3	leg	C	62.5	leg		144.9	leg

3.4. Peak segment angle

3.4.1. Interaction effect on peak segment angle

Significant interaction effects ($p < 0.05$) are observed in all segment angle variables

(Table 3.10). Thus, the same way of data set partitioning was performed as of the analysis of

peak joint moments (refer to section 3.3) and the Tukey's test was performed to examine the significant main effects of slope angle (Table 3.14) and lifting technique (Table 3.18) on peak segment angle.

Table 3.10 ANOVA results testing the effect of slope angle, technique, and interaction on peak segment angle

Dep. variable	Source	Error Term	DF	Type III SS	Mean Square	F Value	Pr > F
Trunk	angle	angle* subject	4	23750.79	5937.70	31.60	<.0001
	technique	technique* subject	2	386325.93	193162.97	81.28	<.0001
	angle* technique	angle* technique* subject	8	6079.36	759.92	4.90	<.0001
Thigh	angle	angle* subject	4	16228.91	4057.23	27.57	<.0001
	technique	technique* subject	2	339625.46	169812.73	110.20	<.0001
	angle* technique	angle* technique* subject	8	4697.54	587.19	3.95	0.0004
Shank	angle	angle* subject	4	691.61	172.90	1.85	0.1342
	technique	technique* subject	2	110820.08	55410.04	111.22	<.0001
	angle* technique	angle* technique* subject	8	2779.39	347.42	5.07	<.0001

Trunk : peak trunk (T9) angle

Thigh : peak thigh angle

Shank : peak shank angle

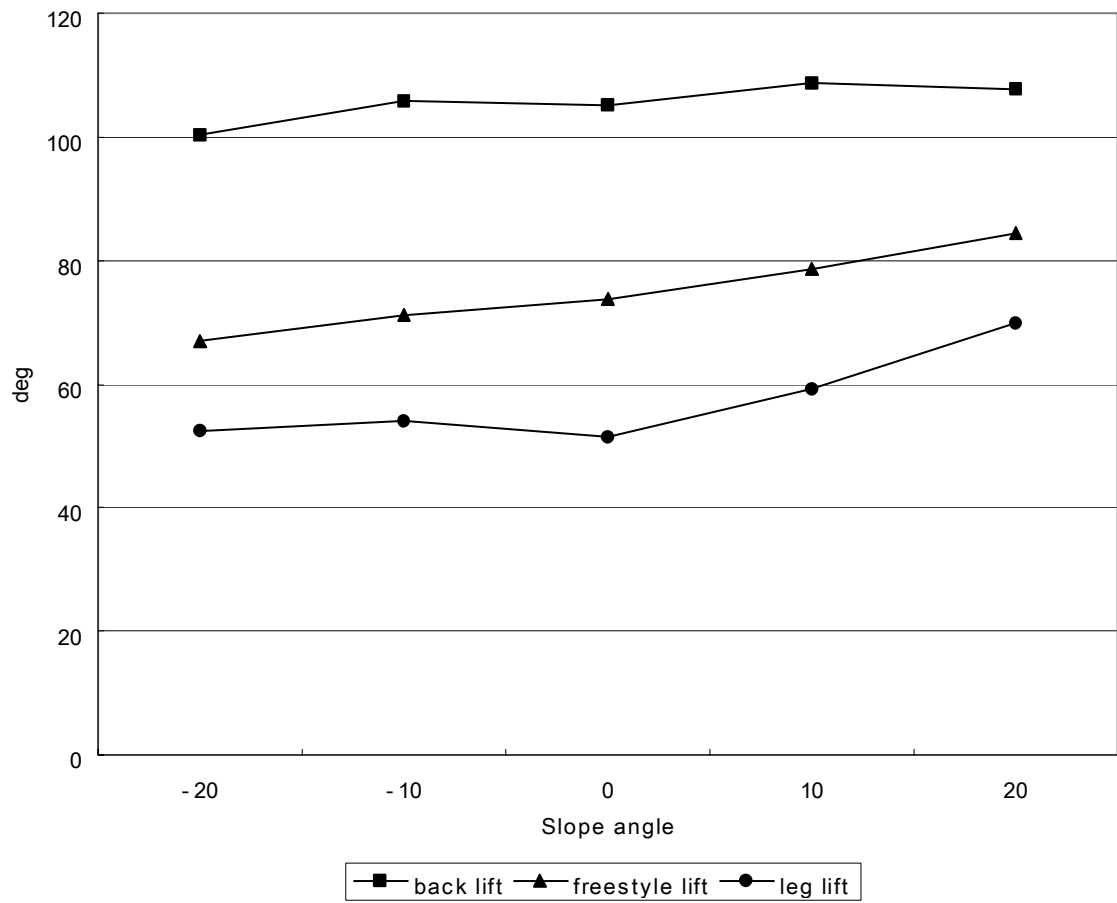


Figure 3.20 Mean peak trunk (T9) angles

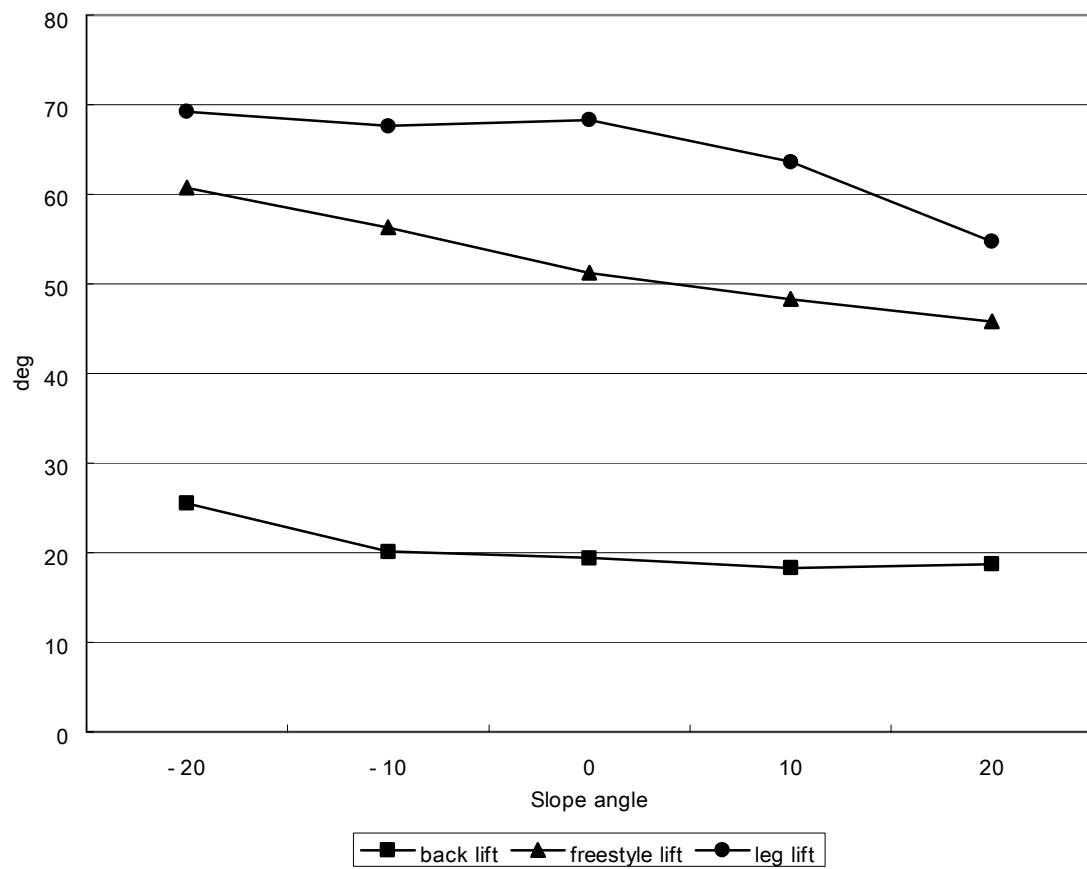


Figure 3.21 Mean peak thigh angles

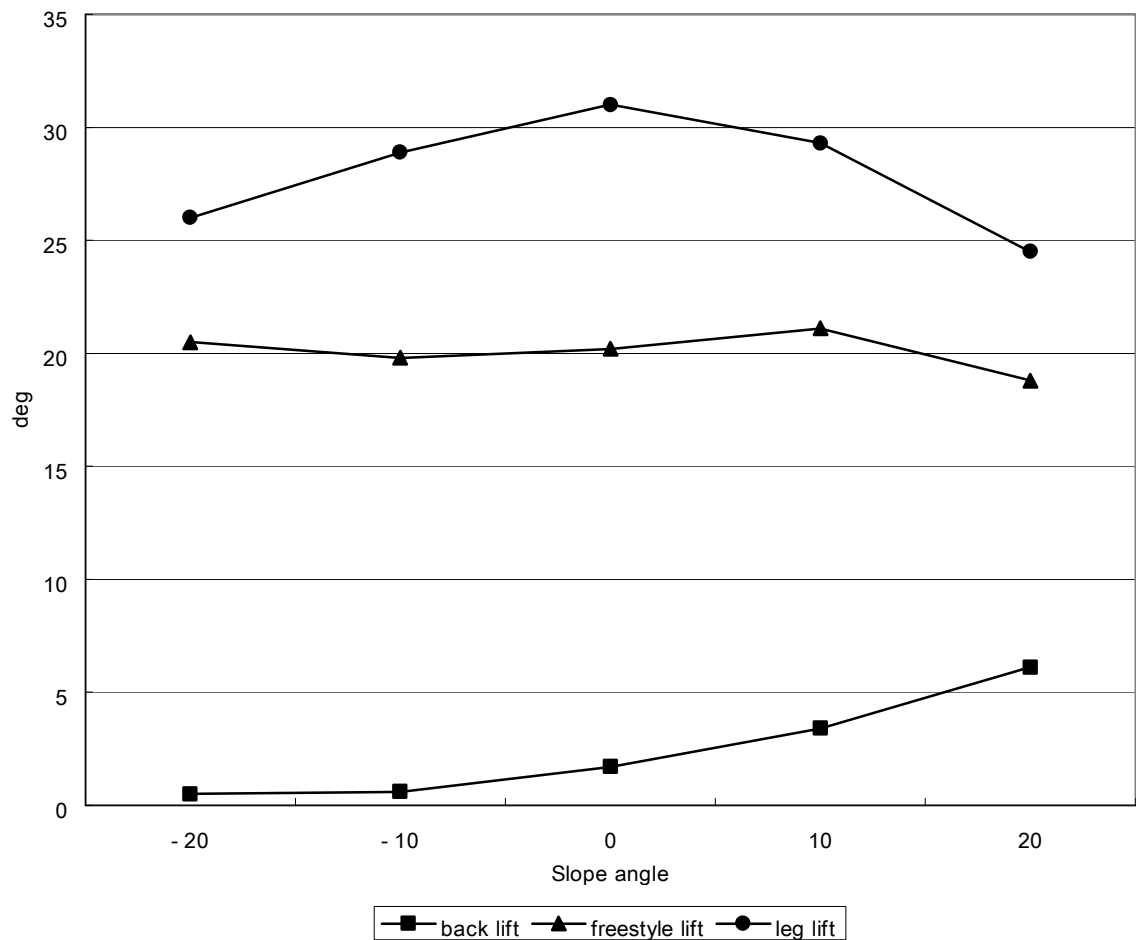


Figure 3.22 Mean peak shank angles

3.4.2. Slope angle effect on peak segment angles

Table 3.11 ~ 3.13 display the results of ANOVA that test the slope angle effect on peak segment angle, controlling for lifting technique. The p-values were much less than 0.05 except the shank angle in the freestyle technique.

Table 3.11 ANOVA results testing the effect of slope angle on peak trunk angle while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	2805.690	701.422	14.60	<.0001
Free lift	4	11659.396	2914.849	8.29	<.0001
Leg lift	4	15365.061	3841.265	39.04	<.0001

Table 3.12 ANOVA results testing the effect of slope angle on peak thigh angle while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	2176.810	544.202	12.25	<.0001
Free lift	4	9485.301	2371.325	7.69	<.0001
Leg lift	4	9264.342	2316.085	25.37	<.0001

Table 3.13 ANOVA results testing the effect of slope angle on peak shank angle while controlling for lifting technique.

Lifting technique	DF	Type III SS	Mean Square	F Value	Pr > F
Back lift	4	1441.312	360.328	43.45	<.0001
Free lift	4	185.149	46.287	0.27	0.8967
Leg lift	4	1844.545	461.136	9.24	<.0001

Table 3.14 Tukey's grouping of mean peak segment angles for slope angle effect

Lifting technique	Peak trunk angle			Peak thigh angle			Peak shank angle		
	Tukey grouping	Mean	Slope angle	Tukey grouping	Mean	Slope angle	Tukey grouping	Mean	Slope angle
Back	A	108.66	10	A	25.45	-20	A	6.097	20
	A	107.81	20	B	20.10	-10	B	3.438	10
	B	105.92	-10	C B	19.45	0	C	1.693	0
	B	105.20	0	C D	18.74	20	D	0.588	-10
	C	100.24	-20	D	18.35	10	D	0.487	-20
Free-style	A	84.30	20	A	60.72	-20	P > 0.05 in ANOVA	21.07	10
	B	78.62	10	B	56.28	-10		20.50	-20
	C	73.72	0	C	51.13	0		20.20	0
	C	71.10	-10	D	48.31	10		19.81	-10
	D	67.06	-20	D	45.82	20		18.81	20
Leg	A	70.02	20	A	69.24	-20	A	31.05	0
	B	59.24	10	B A	68.27	0	B	29.34	10
	C	53.95	-10	B	67.58	-10	B	28.94	-10
	D C	52.50	-20	C	63.59	10	C	26.03	-20
	D	51.26	0	D	54.72	20	D	24.46	20

3.4.3. Lifting technique effect on peak segment angles

All peak segment angle variables were strongly affected by lifting technique on all slope angles (Table 3.15 ~ 3.17). The p-values of all cases are less than 0.0001.

Table 3.15 ANOVA results testing the effect of lifting technique on peak trunk angle while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	77840.011	38920.005	64.08	<.0001
-10	2	91179.894	45589.947	68.19	<.0001
0	2	95452.115	47726.058	81.19	<.0001
10	2	80611.866	40305.933	51.95	<.0001
20	2	47321.402	23660.701	66.26	<.0001

Table 3.16 ANOVA results testing the effect of lifting technique on peak thigh angle while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	70073.391	35036.695	108.38	<.0001
-10	2	79965.230	39982.615	96.37	<.0001
0	2	79775.561	39887.780	81.73	<.0001
10	2	68862.596	34431.298	67.13	<.0001
20	2	45646.229	22823.115	57.67	<.0001

Table 3.17 ANOVA results testing the effect of lifting technique on peak shank angle while controlling for slope angle.

Slope angle	DF	Type III SS	Mean Square	F Value	Pr > F
-20	2	23480.182	11740.091	113.10	<.0001
-10	2	27223.809	13611.904	69.06	<.0001
0	2	28648.533	14324.267	86.26	<.0001
10	2	22748.459	11374.229	77.35	<.0001
20	2	11498.495	5749.247	36.26	<.0001

Table 3.18 Tukey's grouping of mean peak segment angles for lifting technique effect

	Peak trunk angle			Peak thigh angle			Peak shank angle		
Slope angle	Tukey grouping	Mean	Lifting technique	Tukey grouping	Mean	Lifting technique	Tukey grouping	Mean	Lifting technique
-20	A	100.2	back	A	-25.5	back	A	26.0	leg
	B	67.1	free	B	-60.7	free	B	20.5	free
	C	52.5	leg	C	-69.2	leg	C	0.5	back
-10	A	105.9	back	A	-20.1	back	A	28.9	leg
	B	71.1	free	B	-56.3	free	B	19.8	free
	C	53.9	leg	C	-67.6	leg	C	0.6	back
0	A	105.2	back	A	-19.4	back	A	31.0	leg
	B	73.8	free	B	-51.1	free	B	20.2	free
	C	51.3	leg	C	-68.3	leg	C	1.7	back
10	A	108.7	back	A	-18.3	back	A	29.3	leg
	B	78.6	free	B	-48.3	free	B	21.1	free
	C	59.2	leg	C	-63.6	leg	C	3.4	back
20	A	107.8	back	A	-18.7	back	A	24.5	leg
	B	84.3	free	B	-45.8	free	A	18.8	free
	C	70.0	leg	C	-54.7	leg	B	6.1	back

3.5. Components analyses of the peak joint moments within technique

The computed peak moments at the hip, knee and ankle joints were analyzed in order to investigate how each biomechanical component contributed to the variation in the peak moments as a function of slope angle. Each peak net moment was separated into eight components. Tables 3.19, 3.20, and 3.21 are the lists of components of net hip, knee, and ankle moments.

3.5.1. Component analysis of peak hip moment across slope angles

The 'sd_vrs' and 'tr_vs' were observed as main components ($> 20\%$ of peak net moment) and two horizontal dynamic components ('sd_hrd' and 'tr_hd') were negligible for all techniques. The 'hip_aa' component accounted for over 10% of peak hip moment only in the back lift, and the 'sd_m' component contributed more in the leg lift than in other techniques.

During the back lifts (Figure 3.23), the two main components had little variation across slope angles and the 'hip_aa' showed inverted 'V' shape trend as slope angle changed from -20° to 20° . In the freestyle lift, the two main components had a strong linear increasing trend as slope angle increased, and the 'hip_aa' mildly contributed to the increasing trend of peak hip moment (Figure 3.24). During the leg lift, the two main components increased sharply as slope angle increased from 0° to 20° , and the 'sd_m' had a linear decreasing trend as slope angle changed from -20° to 20° (Figure 3.25).

Table 3.19 Hip moment components

Unit : Nm

Name	Descriptions	Terms of Equation (2)
sd_m	moment at shoulder joint	Ms
sd_vrs	vertical static reaction force at shoulder joint $\times$ horizontal distance from shoulder to hip joint	$R_{s,z} \times D_{tr,h} \times \sin(T9)$
sd_vrd	vertical dynamic reaction force at shoulder joint $\times$ horizontal distance from shoulder to hip joint	
sd_hrd	horizontal dynamic reaction force at shoulder joint $\times$ vertical distance from shoulder to hip joint	$R_{s,y} \times D_{s,h} \times \cos(T9)$
tr_vs	trunk vertical static gravitational force $\times$ horizontal distance from COG of trunk-neck-head to hip joint	$F_{tr,z} \times D_{tr,h} \times \sin(T9)$
tr_vd	trunk vertical dynamic inertial force $\times$ horizontal distance from COG of trunk-neck-head to hip joint	
tr_hd	trunk horizontal dynamic inertial force $\times$ vertical distance from COG of trunk-neck-head to hip joint	$F_{tr,y} \times D_{tr,h} \times \cos(T9)$
hip_aa	moment-of-inertia of trunk-neck-head about hip joint $\times$ angular acceleration of trunk	$(I_{tr} + m_{tr} \times (D_{tr,h})^2) \times \alpha_{tr}$

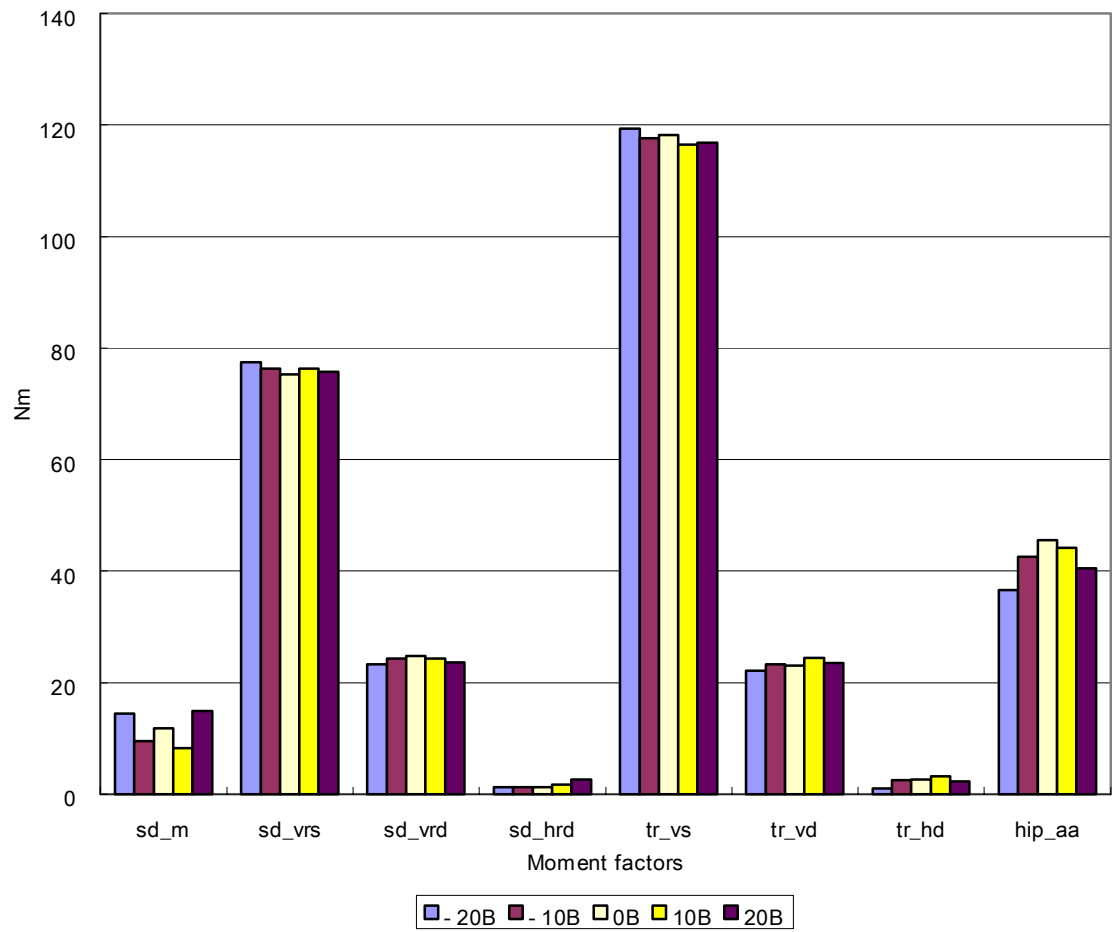


Figure 3.23 Component analysis of peak hip moment in the back lift

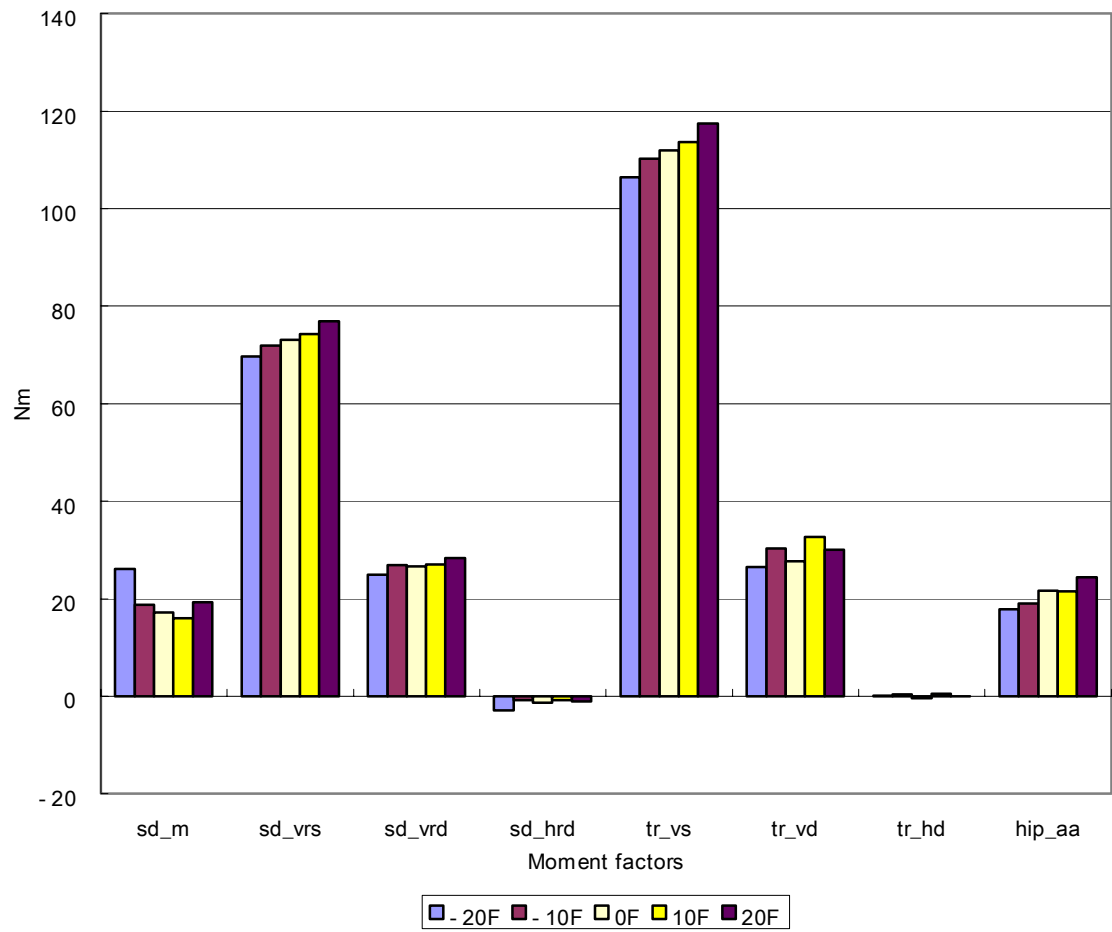


Figure 3.24 Component analysis of peak hip moment in the freestyle lift

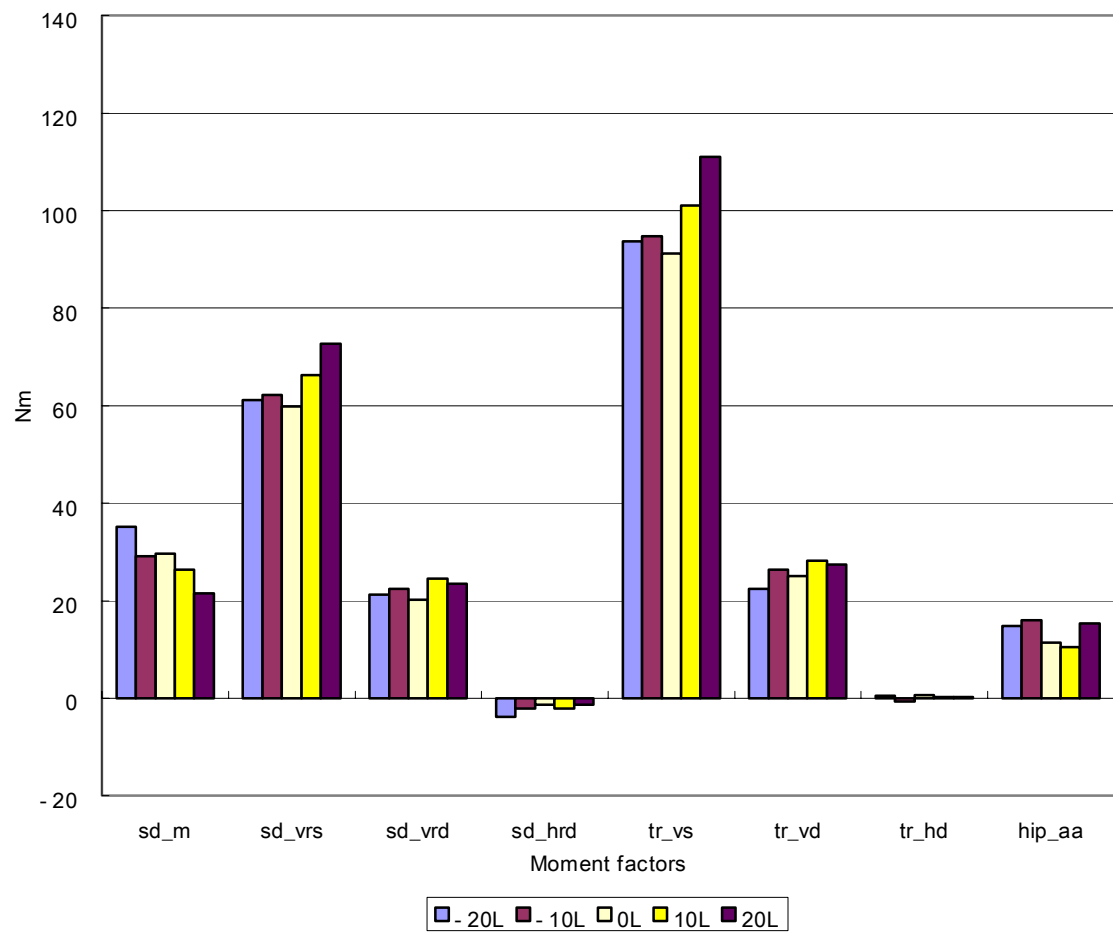


Figure 3.25 Component analysis of peak hip moment in the leg lift

3.5.2. Component analysis of peak knee moment across slope angles

For all lifting techniques, the 'hip_m' and 'hp_vrs' components were decided as main components (absolute value > 20 % of peak net knee moment).

In the back lift, the 'hip_m' component varies little compared to other techniques (Figure 3.26). During the freestyle lift, the 'hip_m' component shows large difference between -20° and 20° slope, and this makes significant difference between the peak knee moments at -20° and 20° slope (Figure 3.27). The two main components of the leg lift show mirror effect. The 'hip_m' component shows 'V' shape and the 'hp_vrs' component shows inverted 'V' shape. Both components have the largest amount at 20° slope (Figure 3.28).

Table 3.20 Knee moment components

Unit : Nm

Name	Descriptions	Terms of Equation (3)
hip_m	moment at hip joint	Mh
hp_vrs	vertical static reaction force at hip joint $\times$ horizontal distance from hip to knee joint	$R_{h,z} \times D_{h,k} \times \sin(\text{Th})$
hp_vrd	vertical dynamic reaction force at hip joint $\times$ horizontal distance from hip to knee joint	
hp_hrd	horizontal dynamic reaction force at hip joint $\times$ vertical distance from hip to knee joint	$R_{h,y} \times D_{h,k} \times \cos(\text{Th})$
th_vs	thigh vertical static gravitational force $\times$ horizontal distance from COG of thigh to knee joint	$F_{th,z} \times D_{th,h} \times \sin(\text{Th})$
th_vd	thigh vertical dynamic inertial force $\times$ horizontal distance from COG of thigh to knee joint	
th_hd	thigh horizontal dynamic inertial force $\times$ vertical distance from COG of thigh to knee joint	$F_{th,y} \times D_{th,h} \times \cos(\text{Th})$
knee_aa	moment-of-inertia of thigh about knee joint $\times$ angular acceleration of thigh	$(I_{th} + m_{th} \times (D_{th,k})^2) \times \alpha_{th}$

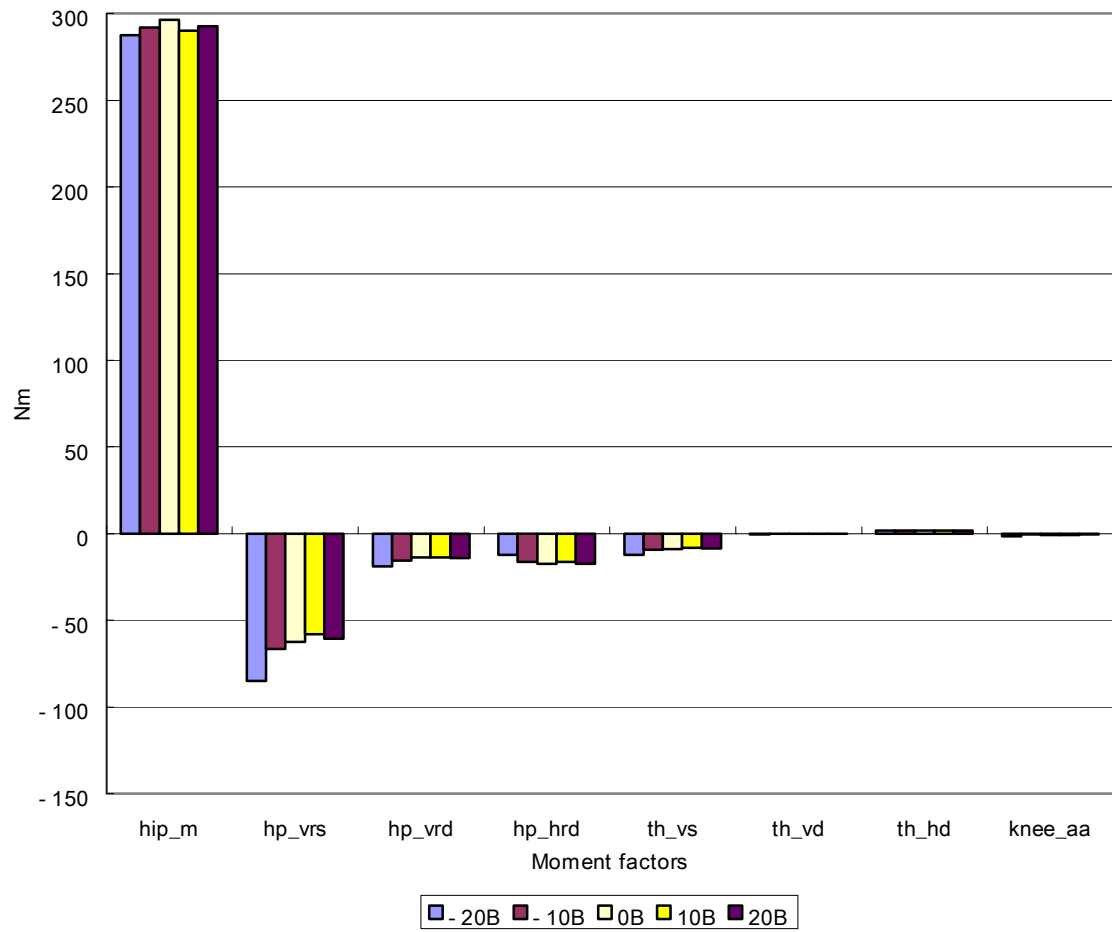


Figure 3.26 Component analysis of peak knee moment in the back lift

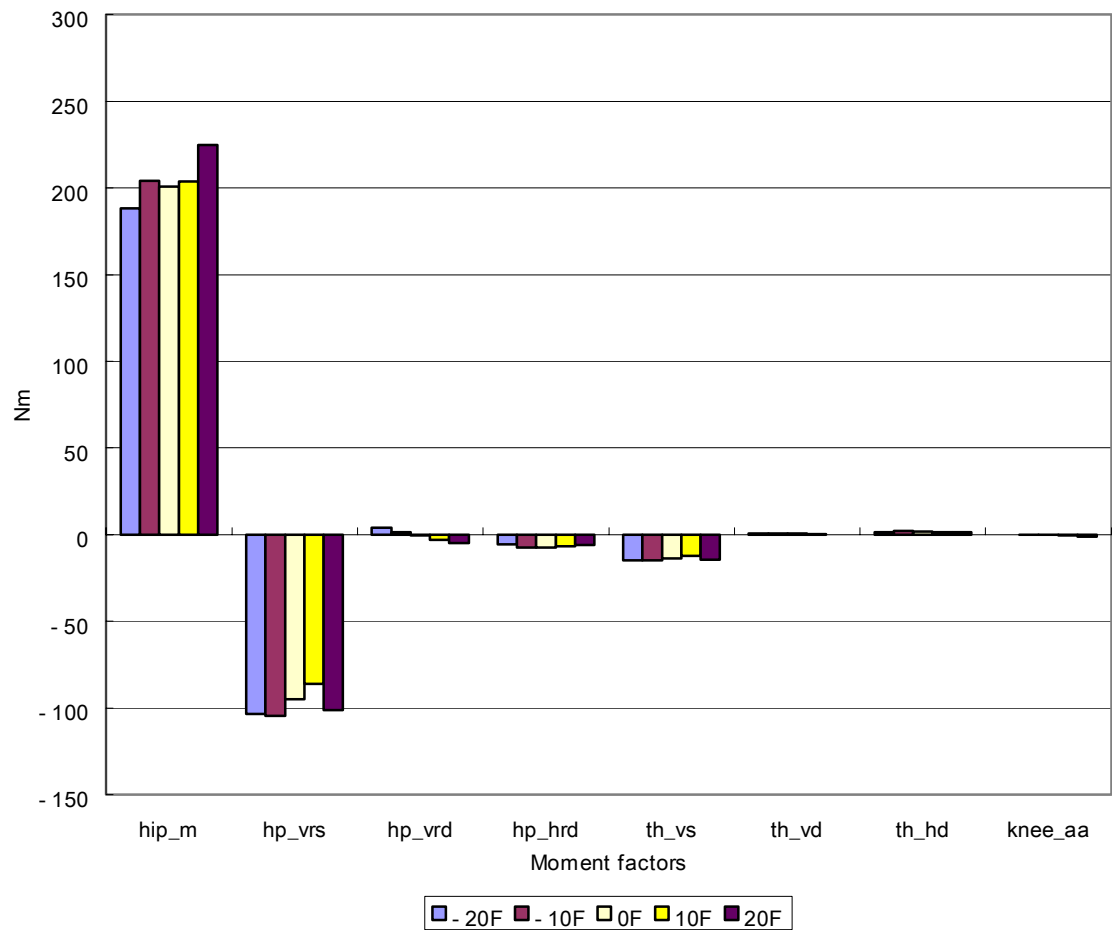


Figure 3.27 Component analysis of peak knee moment in the freestyle lift

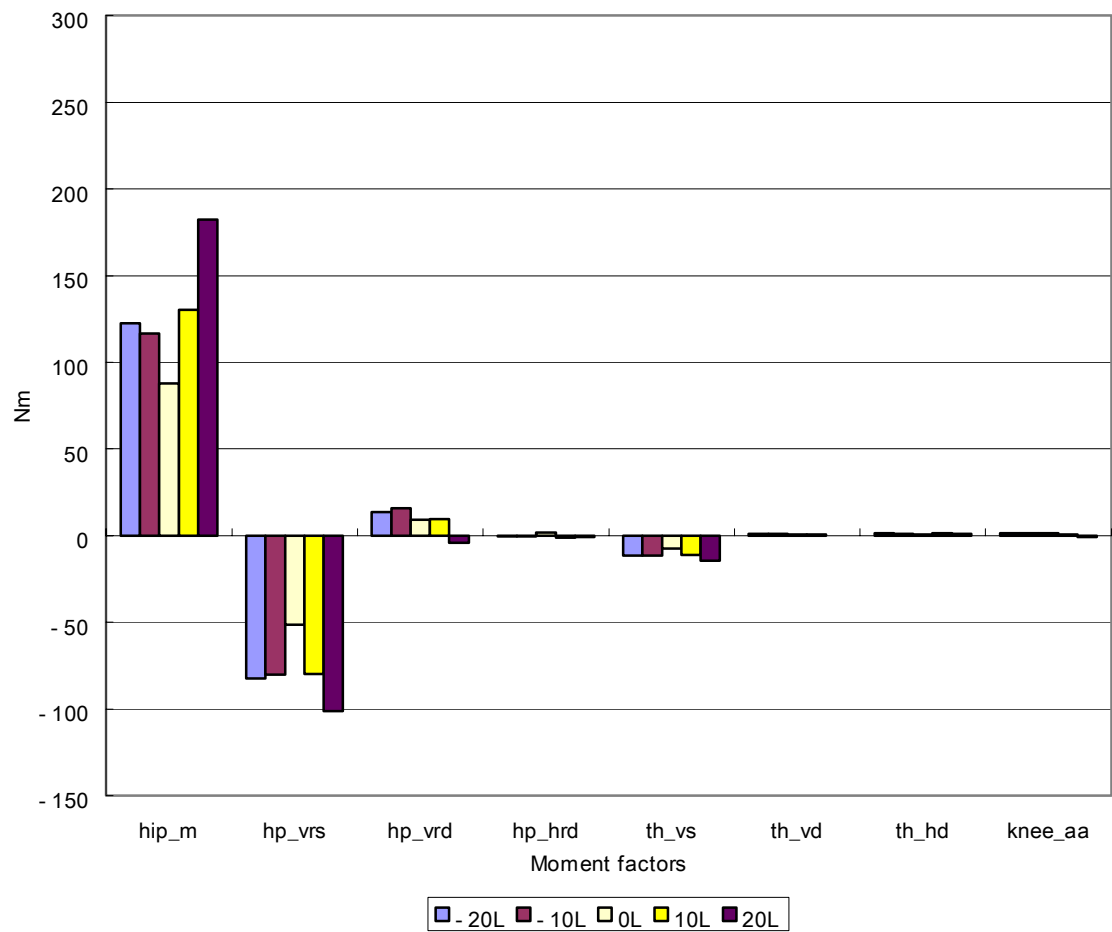


Figure 3.28 Component analysis of peak knee moment in the leg lift

3.5.3. Component analysis of peak ankle moment across slope angles

During the back lift, the amount of 'knee_m' component is over 20 % of peak net ankle moment and much larger than the amount of the 'kn_vrs' component. In the freestyle lift, both the 'knee_m' and 'kn_vrs' are positive main components. Different from 'kn_vrs' component which shows little variation, the 'knee_m' component increases very rapidly as slope angle increases from -20° to 20° , thus indicates the 'knee_m' component mainly contributes the change of peak ankle moment across slope angles (Figure 3.30). In the leg lift, the 'kn_vrs' is positive main component and shows inverted 'V' shape in change of slope angles. The 'knee_m' component changes from negative to positive rapidly as slope angle increases from 0° to 20° and this makes the increasing trend of peak net ankle moment in the leg lift (Figure 3.31).

Table 3.21 Ankle moment components

Unit : Nm

Name	Descriptions	Terms of Equation (4)
knee_m	moment at knee joint	Mk
kn_vrs	vertical reaction static force at knee joint $\times$ horizontal distance from knee to ankle joint	$R_{k,z} \times D_{k.ak} \times \sin(\text{Sh})$
kn_vrd	vertical reaction dynamic force at knee joint $\times$ horizontal distance from knee to ankle joint	
kn_hrd	horizontal reaction dynamic force at knee joint $\times$ vertical distance from knee to ankle joint	$R_{k,y} \times D_{k.ak} \times \cos(\text{Sh})$
sh_vs	shank vertical static gravitational force $\times$ horizontal distance from COG of shank to ankle joint	$F_{sh,z} \times D_{sh,h} \times \sin(\text{Sh})$
sh_vd	shank vertical dynamic inertial force $\times$ horizontal distance from COG of shank to ankle joint	
sh_hd	shank horizontal dynamic inertial force $\times$ vertical distance from COG of shank to ankle joint	$F_{sh,y} \times D_{sh,h} \times \cos(\text{Sh})$
ankle_aa	moment-of-inertia of shank about ankle joint $\times$ angular acceleration of shank	$(I_{sh} + m_{sh} \times (D_{sh.ak})^2) \times \alpha_{ah}$

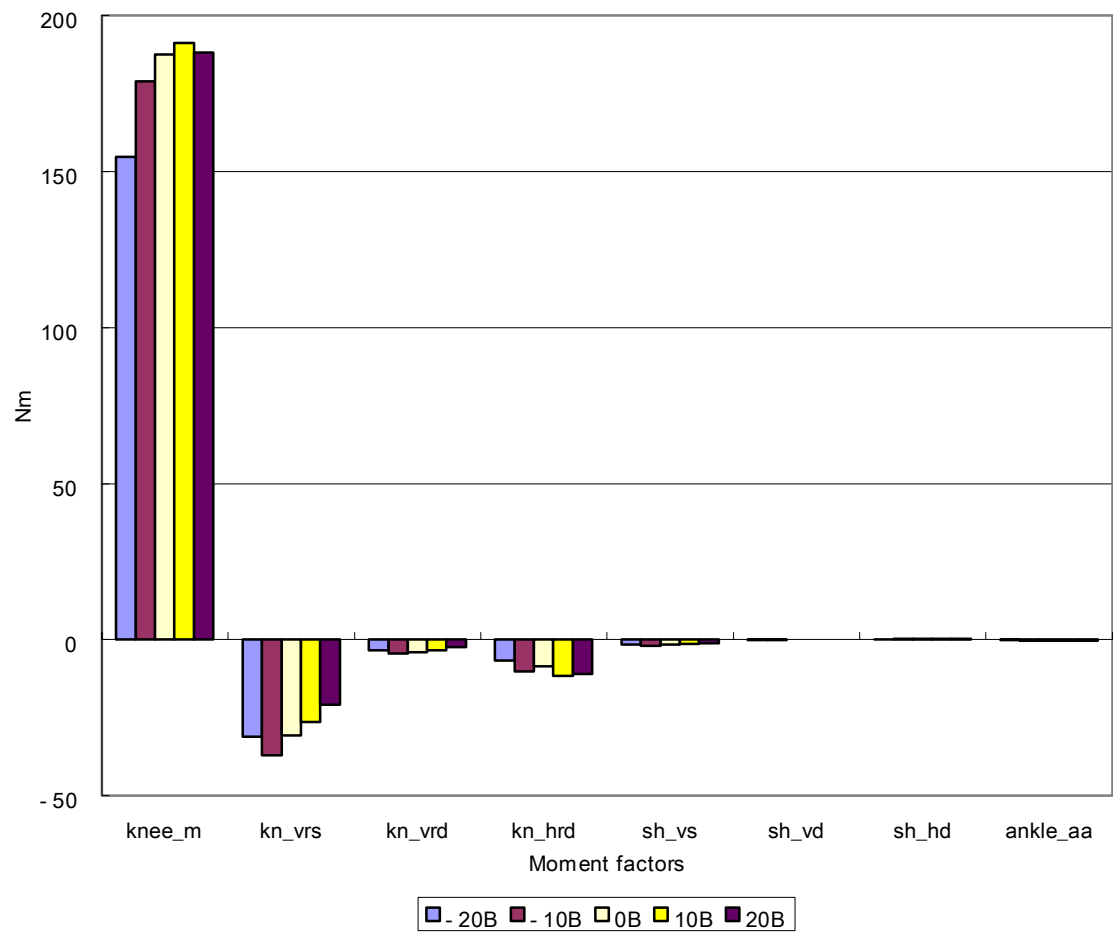


Figure 3.29 Component analysis of peak ankle moment in the back lift

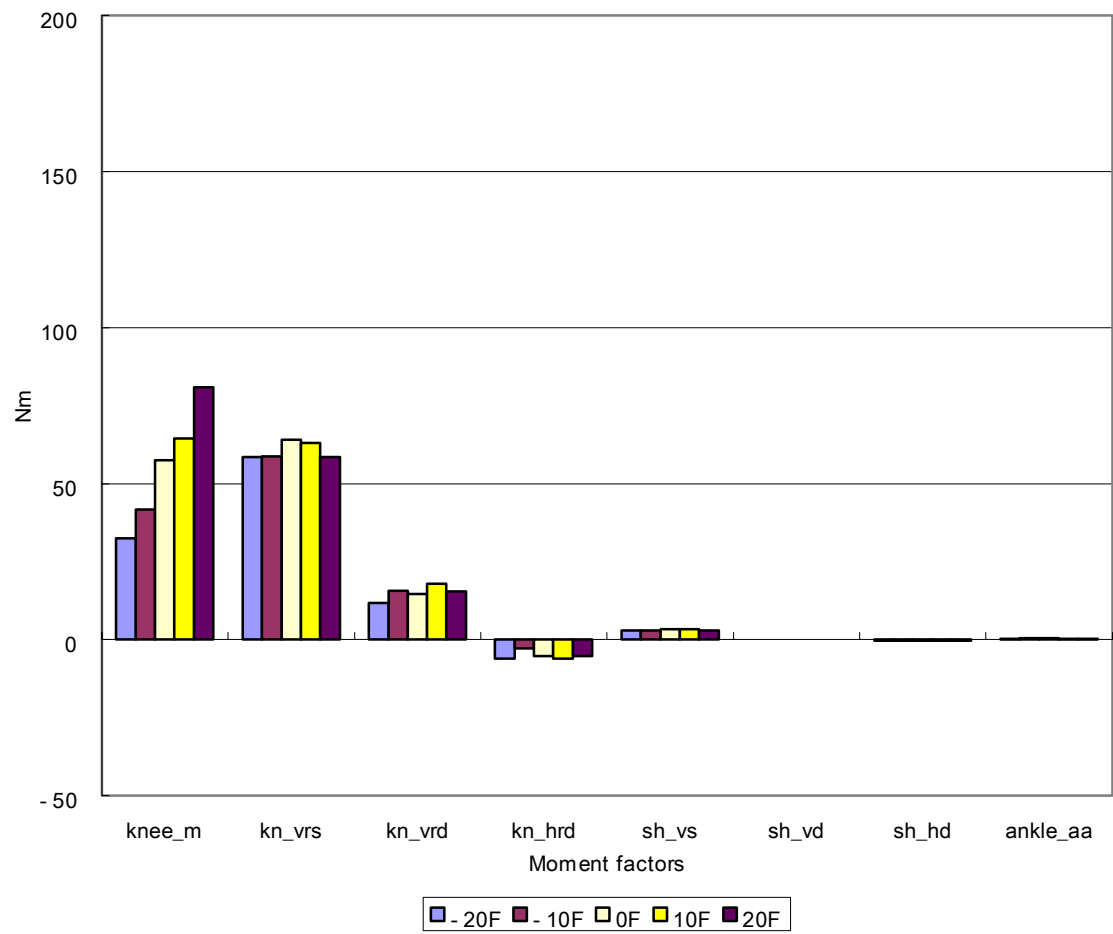


Figure 3.30 Component analysis of peak ankle moment in the freestyle lift

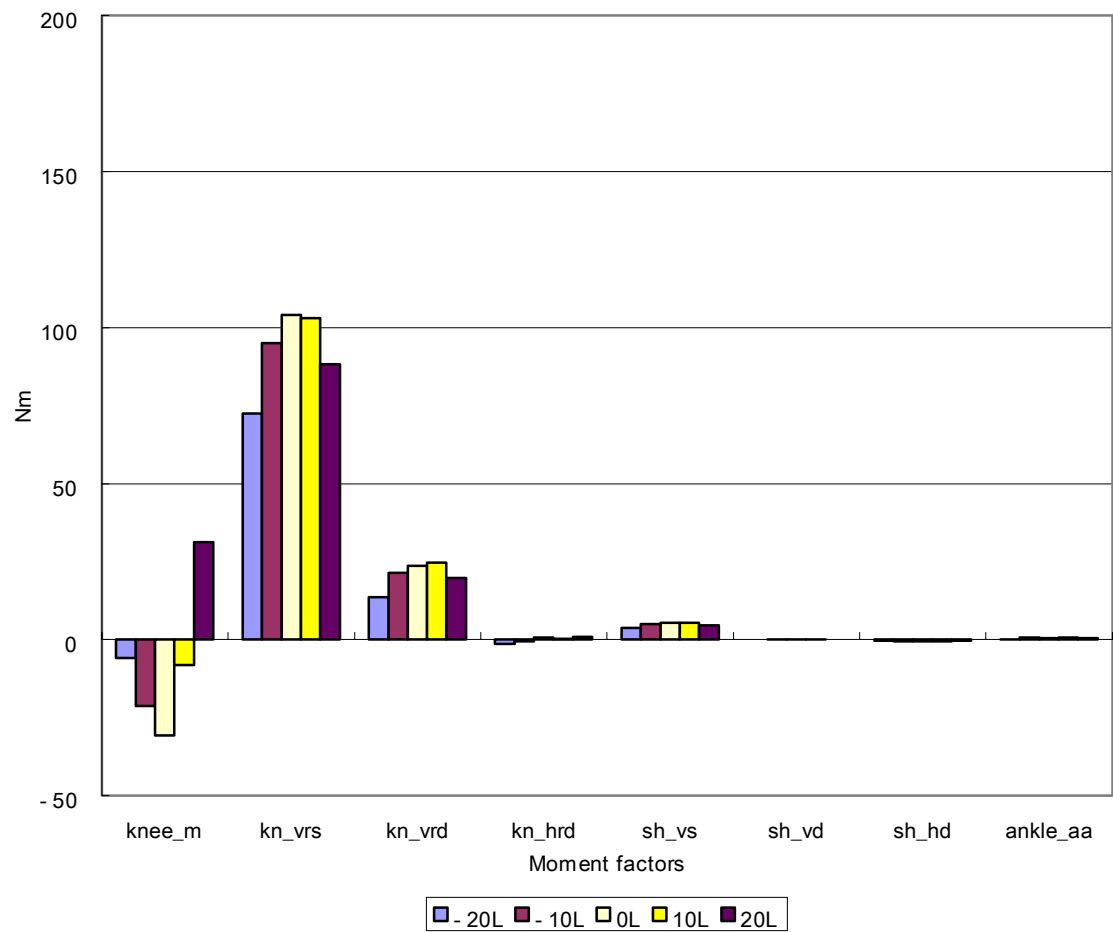


Figure 3.31 Component analysis of peak ankle moment in the leg lift

3.6. Components analyses of the peak joint moments between lifting techniques

The components of net joint moments were analyzed to examine the component contributions to the variation of peak joint moments between lifting techniques. Because similar results were observed in all slope angles, only the results of 0° slope are displayed.

3.6.1. Component analysis of peak hip moment across lifting techniques

In Figure 3.17, the back lift produced the largest peak hip moment at all slope angles. The differences between the back lift and others are observed again in component analyses. Figure 3.32 shows the components of the peak hip moments of three lifting techniques at 0° slope. The amount of 'sd_vrs', 'tr_vs', and 'hip_aa' components in the back lift are larger than in other techniques. The 'sd_m' component is larger in the leg lift than in other techniques. Thus, the two static components ('sd_vrs' and 'tr_vs') and 'hip_aa' component are the major contribution components for the larger peak hip moments in the back lift.

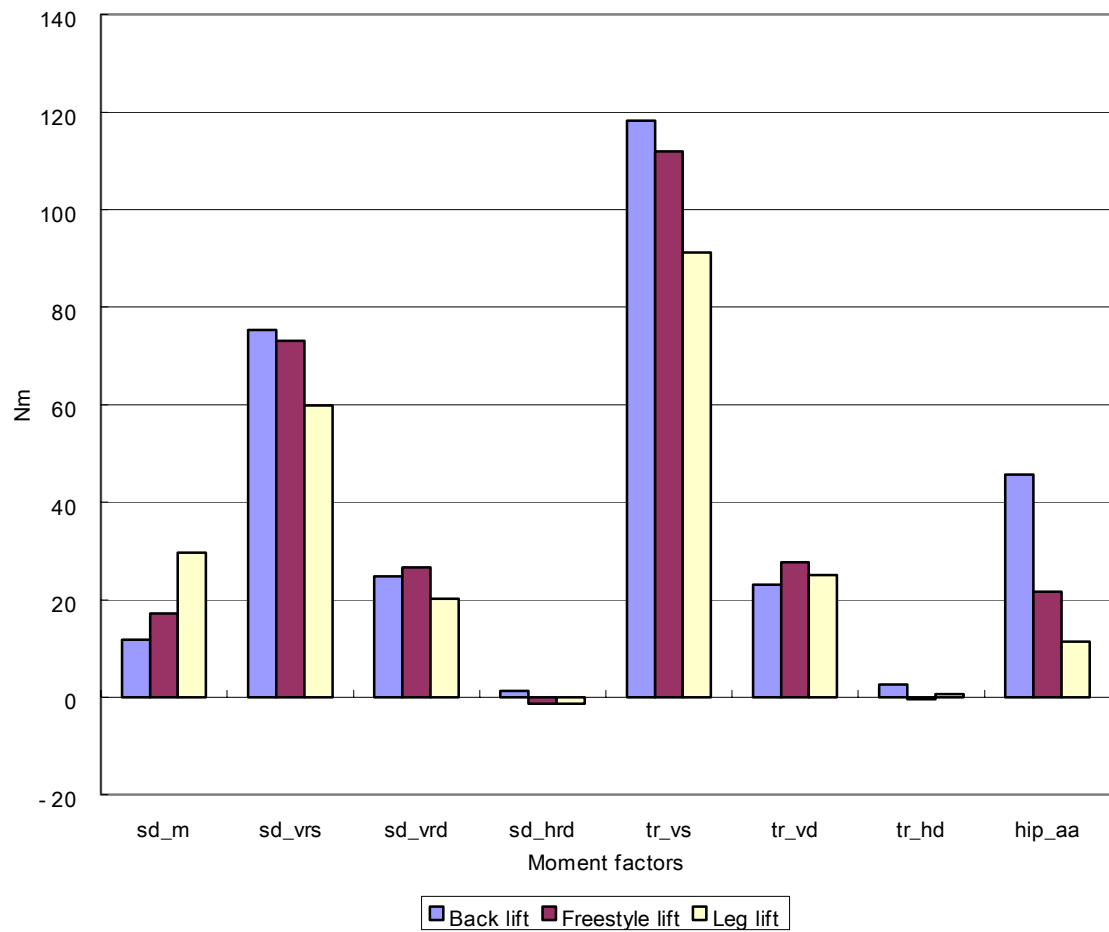


Figure 3.32 Component analysis of peak hip moment at 0° slope

3.6.2. Component analysis peak knee moment across lifting techniques

The 'hip_m' is always positive and much larger in the back lift than in leg lifts, indicating that this component mainly contributed to the difference of peak knee moments between techniques.

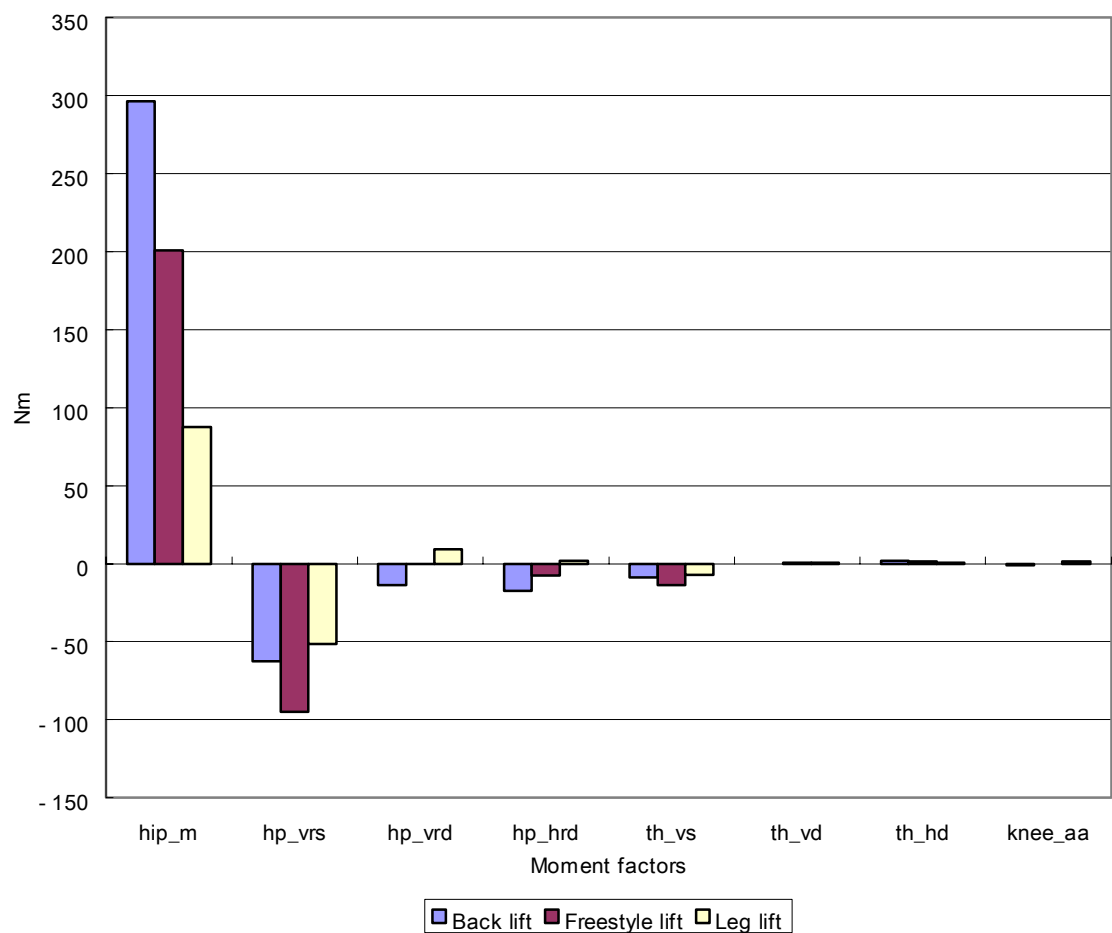


Figure 3.33 Component analysis of peak knee moment at 0° slope

3.6.3. Component analysis of peak ankle moment across lifting techniques

In the component analysis of peak ankle moment, the two main components ('knee_m' and 'kn_vrs') show large differences between lifting techniques. The 'knee_m' component was much larger in the back lift than other techniques and turned to be negative in the leg lift. To the contrary, the 'kn_vrs' was negative in the back lift and changed to positive in the freestyle and leg lift. Thus, both components contribute to the differences of peak ankle moment between lifting techniques.

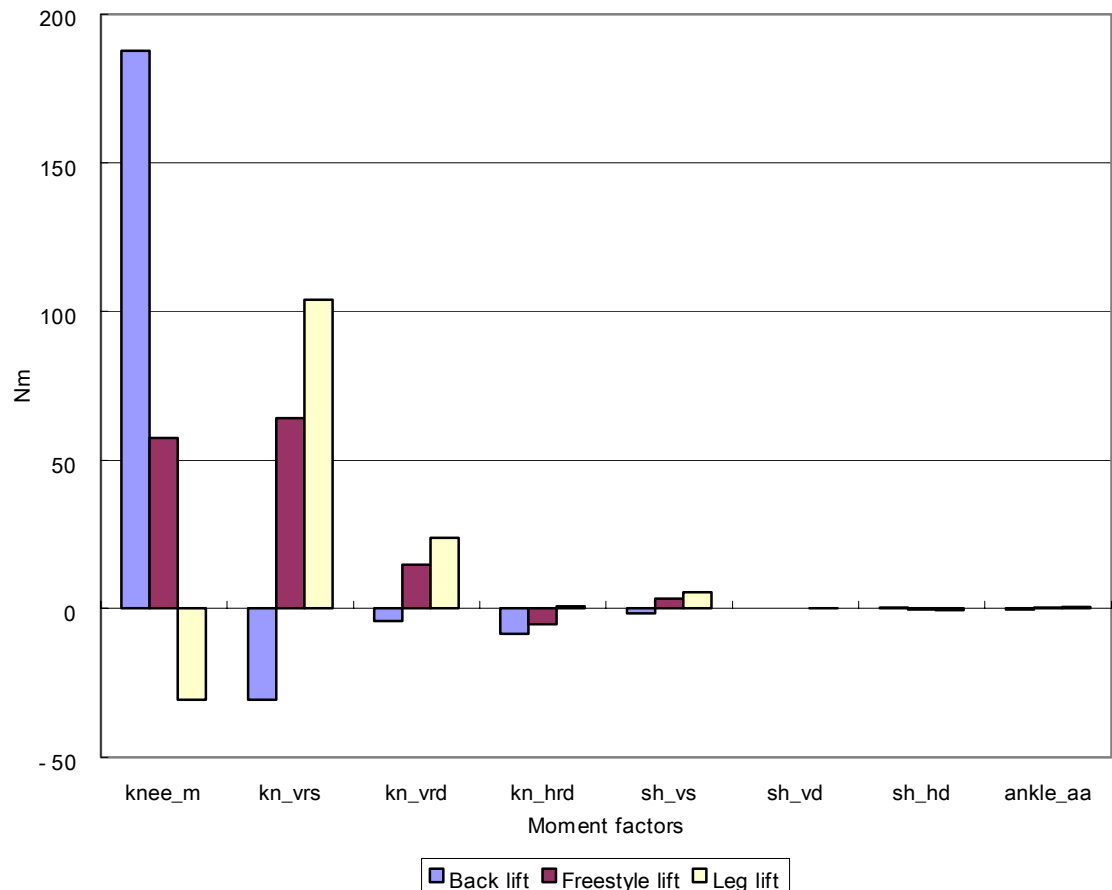


Figure 3.34 Component analysis of peak ankle moments at 0° slope

4. DISCUSSION

A back injury that occurs during manual lifting task has been a serious problem in industry. The likelihood of its occurrence depends on the magnitude of the moment acting on the back or compressive force acting on the L5/S1. In this study the amount of peak hip moment was significantly larger on increased slopes than flat and declined slopes, which indicated the risk for LBP from lifting on inclined slope could be higher than the risk on flat or declined slopes. Also the leg lift showed significant positive effects on the back so it could be considered as a better lifting technique to reduce the potential risk for LBP.

4.1. Variation between and within subjects

The dependent variables were more variable between subjects than within subject as other studies have observed (e.g. Kjellberg et al., 1998). Sources of between subjects variation were variation in the subjects' lifting motion and variability in the subjects' anthropometry because the biomechanical model includes subjects' body mass and segment lengths. The fatigue and learning effects on dependent variables were negligible. Figures 3.15 and 3.16 show little between-repetition variation in the peak hip moment and peak trunk angle, respectively. Therefore, the statistical analysis method which blocks on subject is a reasonable approach for this study.

4.2. The slope angle effects on the peak joint moments and peak segment angles

The peak hip moment was significantly affected by slope angle in the freestyle lift and the leg lift, while during the back lift the peak hip moments were not significantly different across slope angles. The peak hip moment increased 6.8 % and 14.3 % as slope angle increased from 0°

to 20° during the freestyle lift and the leg lift respectively. The component analysis and peak trunk angle plots could explain the little variation of peak hip moment.

In the component analysis plot of the back lift (Figure 3.23) all moment components, except the 'hip_aa' (moment-of-inertia of trunk-neck-head about hip joint $\times$ trunk angular acceleration), vary little across slope angles, indicating that subjects' trunk and arm angles did not change much during lifting. The changes of 'hip_aa' across slope angles indicate that subjects extended their backs with different angular acceleration. Interestingly, the 'hip_aa' is the highest at 0° slope and linearly decreases as the slope angle changes to -20° or 20°. This suggests that subjects may have felt more unsure / unstable on sloped ground as observed in Zhao et al. (1987) so they may have lifted the box with more caution than on flat ground. Mirka et al. (1998) investigated the interaction effect between load and hand coupling while subjects lifted the seven levels of load (4.5 kg ~ 31.5 kg). Above 13.5 kg of weight, they observed that the peak dynamic L5/S1 moments with 'poor' coupling were lower than the moments with 'fair' and 'good' couplings, suggesting the interaction between perception and human performance might cause the higher peak moments under more stable conditions. Similar results were observed in Freivalds et al. (1984). In their study, both vertical ground reaction forces and the L5/S1 compressive forces showed faster rise times and larger peaks for the box with handles than without handles. During the freestyle lifts, the lowest mean peak hip moment occurred at -20° and significant linear increase was observed as slope angle increased.

The component analysis plot of freestyle lift (Figure 3.24) shows strong linear increase of 'sd_vrs' (vertical static reaction force on shoulder joint $\times$ horizontal distance from shoulder to hip joint) and 'tr_vs' (trunk vertical static inertial force $\times$ horizontal distance from COG of trunk-neck-head to hip joint) as slope angle changes from -20° to 20°. This means that, at the instance

of peak moment occurred, the horizontal distances between hip joint and COG of trunk-neck-head, and between hip joint and shoulder joint increase as slope angle changes from -20° to 20° . The linear increase of mean peak trunk angle in Figure 3.20 confirms this belief because the horizontal distances are the function of trunk angle and they increase as trunk angle increases until trunk angle reaches 90° .

In the leg lift, the mean peak hip moment was the lowest at 0° slope and linearly increased as slope angle increased from 0° to 20° . This was due to the sharp increase of two static components; 'sd_vrs' and 'tr_vs' (Figure 3.25). Although the 'sd_m' (moment at shoulder joint) decreased with an increase of slope angle, the increase of two static main components overcame the 'sd_m' component and made the significant increase of peak hip moment. Similar to the freestyle lift, the change of the horizontal distances between the hip joint and the points of forces made the variation of peak hip moment, as the peak trunk angle plot confirmed this. These postural changes on sloped ground might be due to the shift of center of body mass. On the inclined slopes, subjects tended to bend their back more during lifting so as not to lose balance. To keep their COG of body anterior to the ankle during lifting, the COG of trunk was shifted to anterior side by bending down further. On the declined slopes, to the contrary, subjects tended to keep their COG of body more posterior to prevent falling forward. Thus, the increased peak trunk angle with increased slope angle can be explained as a natural balance response of the human body. The less postural change during the back lift might be due to the more stationary COG of body than during the leg lift, as Zhao et al. (1987) observed in their study. They traced the COG of the body during the back and leg lift on inclined slopes and the larger variation in the position of the COG of body was observed during the leg lift.

In all three lifting techniques, the peak knee moments were significantly affected ($p <$

0.05) by slope angle. During the back lifts, the lowest mean peak knee moment occurred at -20° slope and increased 23 % as slope angle increased to 0° . However the peak thigh angle changed in the opposite direction; it decreased as slope angle increased from -20° to 0° . This relationship is observed also in the freestyle and leg lifts. In the biomechanical model of the present study, the knee moment consists of hip moment, the moment from reaction forces at hip joint, and the moment from inertial forces of thighs. Among them, the two static components ('hp_vrs' and 'th_vs') are negatively associated with the thigh angle in nature because the longer moment arms, which increase as the thigh flexes, produce larger negative moments on the knee joint. The net joint moments of this study are the net reactive moments resulting from the muscle contraction forces. Thus, the net knee moment is negative if the moment created by the knee extensors is larger than the moment created by the knee flexors. In this study, all subjects showed negative net knee moments in the leg lift right before they picked up the box and most of them turned to positive after they picked up the box. Figure 4.1 shows an example of the profiles of the peak joint moments and shows that the negative knee moment increases rapidly right after 'lift off'. On flat ground, only two of thirteen subjects had negative mean peak knee moments during their five leg lifts and the average of all subjects (75 lifts) was positive. In the component analyses, the moment at hip joint ('hip_m') and vertical static reaction force on hip joint ('hp_vrs') were observed as main contributors to the variation of the peak knee moment in changes as a function of slope angle.

The peak ankle moments in all lifting techniques were strongly affected by slope angle. In all techniques, the peak ankle moment increased significantly as slope angle changed from -20° to 20° . The peak ankle moment at 20° slope was 75 % larger than the peak moment at -20° slope in the leg lift, and 54 % larger in the freestyle lift. In component analysis of the back lifts,

the ‘knee_m’ (moment at knee joint) is the largest component and seems to make the increase of peak ankle moment. During the freestyle lifts, the ‘knee_m’ component shows strong linear increase in increase of slope angle while ‘kn_vrs’ (vertical static reaction force at knee joint $\times$ horizontal distance from knee to ankle joint) component varies little.



Figure 4.1 Moment profiles during the leg lift

4.3. Lifting technique

The second goal of this study was to examine the effects of three lifting techniques on

dependent variables during sagittally symmetric lifting. The back lift caused the largest peak hip, knee, and ankle moments at slopes of -20° , -10° , 0° , and 10° , and the leg lift produced the lowest peak joint moments at all slopes. The average peak hip moment of all back lifts (298.8 Nm) was 6.6 % and 19.0 % larger than the average of freestyle (280.4 Nm) and leg lifts (251.0 Nm), respectively.

The positive effects of the leg lift have not been observed consistently in previous studies. Van Dieën et al. (1999) reviewed 27 studies comparing leg and back lift with respect to the mechanical load on the back, and they found that only one study which had conditions similar to the present study came up with the positive effect of leg lift. They concluded that the leg lift did not bring about positive effects if the horizontal distance between the load and foot was the same as with the back lift. However, the present study shows a significant positive effect of leg lift on the hip moment. At 0° slope, the mean peak hip moment in the back lift was 9.5 % and 30.0 % larger than the mean peak moment in the freestyle and the leg lift respectively. In component analysis, three components ('sd_vrs', 'tr_vs', and 'hip_aa') are much larger and one component ('sd_m') is smaller in the back lift compared to the values in the leg lift. The differences in the two static components ('sd_vrs' and 'tr_vs') resulted from the larger trunk flexion angle during the back lift. The obviously larger 'hip_aa' during the back lift shows a different result from that of Kjellberg et al. (1998). In their experiments, no differences were found in the magnitudes of the peak trunk angular acceleration between the back and leg lifts even though they expected higher peak trunk angular acceleration during the back lifts because the higher angular acceleration of the trunk would be required to raise the trunk from the more bent position during back lift. The last component that shows significant difference between lifting techniques is 'sd_m', showing the larger moment during the leg lift. The 'sd_m' is the

moment at shoulder joint and this is mainly affected by the arm angle. Thus it is believed that, during the leg lift, subjects extended their arms further from shoulder to reach the box than during the back lift.

The larger hip moment during the back lift caused three times larger peak knee moment than the leg lift. This result agrees with the results of Toussaint et al. (1992). In their study the 13.5 kg barbell was lifted in the back and leg lifts and the net knee moment was significantly reduced by shifting the lifting technique from the back lift to the leg lift.

Similarly, the larger peak ankle moment during the back lift is due to the difference of the knee moment when the peak ankle moment occurs.

4.4. Limitations

The biomechanical model of this study assumed a human body as five rigid segments so the arm was treated as one rigid segment neglecting elbow joint. However, even though subjects were asked to perform lifts without serious forearm flexion, some subjects mildly flexed their forearm especially in the leg lift. Although the amount of flexion was negligible, the jerking at the elbow joint, which was not detected in the model, might affect the moment on the other joints.

The trunk, also, was considered as one rigid segment with shoulder joint and hip joint at both ends. If the trunk was bent like a bow during lifting, the horizontal moment arms about hip joint might be smaller than the model assessed. Specifically, the trunk might be bent more during the back lift than during the leg lift. So, there was possibility that the differences of the peak hip moments during the back lift and leg lift might be reduced if the trunk bending was considered.

The effects of slopes angle and lifting technique were tested only with one load (10 kg). Even though Zhao et al. (1987) did not observe a significant effect of box weight on slipping

force during lifting on an inclined slope, the peak joint moments or peak segment angles may be affected by load magnitude during lifting on sloped ground. With respect to the lifting posture, the effect of the amount of load was observed in previous studies. Schipplein et al. (1990) examined the influence of load magnitude on the freestyle lift technique with varying the load from 50 N to 250 N. With heavier weights, there was a tendency to extend the knees earlier during the lift than with lighter weights, suggesting that the subjects would lift more with the back and less with the legs with heavier weight.

4.5. **Recommendations**

The recommendations from this study are,

- Lifting on sloped ground should be avoided. Specifically, lifting on the inclined slope requires more muscle forces in the freestyle and leg lift than lifting on the declined slope.
- Leg lift technique is recommended when the load is about 10 kg, lifting is sagittally symmetric, and a task does not produce a fatigue on human body.
- For the analysis of manual lifting tasks, the linear and angular accelerations of body segments need to be included in the biomechanical model.

4.6. **Future work**

In this study, the peak moment of each joint was computed as a function of segment angles and accelerations. Using the same model, it is also possible to find the best lifting technique that produces the least joint reactive moments or reactive forces in a specific condition. The peak reactive force on joint can be computed using the reactive moments and equilibrium equations (Freivalds et al., 1984). Future work will try to find the optimum lifting techniques

under given working environments using this biomechanical model.

During each trial of this study, subjects lifted the box six to nine times depending on their own lifting speed and all dependent variables showed little variation between repetitions. However, if subjects were asked to perform more lifts so they felt fatigued during task, it might affect the dependent variables of this study. Van Dieën et al. (1998) observed a decrease of trunk extension velocity with the number of repetitions when subjects felt fatigued during repetitive lifting. The changes in lifting techniques in fatigue were also observed by Fogleman and Smith (1995). They investigated the changes in lifting techniques that occurred due to the effects of fatigue and results indicated that there was a change from a leg lift to a back lift. Thus, in future studies, the kinetic and kinematic effects of fatigue on repetitive lifting on sloped grounds need to be investigated.

Most studies on manual lifting tasks have been focused on the lifting on flat and stable grounds. However, in the real work environment, workers often need to lift a weight on unstable or irregular surfaces as well as stable flat ground. As the present study showed the increased load on hip joint during lifting on inclined grounds, irregular or unstable surfaces may bring about more risks than flat and stable surfaces on human body. Therefore, further studies will focus on the risks of manual lifting tasks on the irregular or unstable surfaces.

5. CONCLUSIONS

The main goal of the present study was to investigate the effect of ground slope angle and lifting technique on joint moments and lifting posture during sagittally symmetric lifting tasks. The peak net moment at hip, knee, and ankle joints were computed by two-dimensional dynamic biomechanical model and peak flexion angles of trunk, thigh, and shank were observed, and results were analyzed by two-way ANOVA with blocking 'subject' effect.

The results are,

- The computed peak joint moments were significantly affected by slope angle and lifting technique. The inclined slope angles (10° and 20°) caused up to 6.8 % and 14.3 % larger peak hip moments than flat ground during freestyle and leg lifts, respectively. The lowest peak hip moment (236.48 Nm) was observed during leg lift on flat ground and the largest peak hip moment (302.62 Nm) occurred during back lifts. The component contribution analysis showed that the two static components (vertical reaction static force on shoulder joint and trunk mass) were main contributors to the responses of peak hip moment in changes of slope angle. These two static components were computed by trunk flexion angle which varied to keep balance of body on sloped grounds.
- In the freestyle and the leg lift, the peak trunk angle increased 14.4 % and 36.6 % respectively, and the peak thigh angle decreased 10.3 % and 19.8 % respectively as slope angle increased from 0° to 20° .
- The leg lift technique produced significantly less peak joint moments than the back and freestyle techniques regardless of slope angles. The mean peak hip moment was 16.0 % and 10.5 % less during the leg lift (251.0 Nm) than the back (298.8 Nm) and freestyle lift (280.4

Nm) respectively. Specifically, the trunk angular acceleration acted as a major contributor of significant difference between peak hip moment during back lift and leg lift. The peak flexion angles of trunk, thigh, and shank, as expected, separated leg lift from the back lift.

6. REFERENCES

Andersson, G. B. J. (1998) Epidemiology of low back pain. Acta Orthop Scand Suppl, 298: 528-831

Bejjani, J., Gross, C. M., and Pugh, J. W. (1984) Model for static lifting: Relationship of loads on the spine and the knee. Journal of biomechanics, 17(4): 281-286

Burdorf, A., Naaktgeboren, B., and de Groot, H. C. W. M. (1993) Occupational risk factors for low back pain among sedentary workers. JOM, 35(12): 1213-1220

Bush-Joseph, C., Schipplein, O., Andersson, G. B. J., and Andriacchi, T. P. (1988) Influence of dynamic factors on the lumbar spine moment in lifting. Ergonomics, 31(2): 211-216

Bureau of Labor Statistics. (2000) <http://www.bls.gov/iif/home.htm>

Chaffin, D. B. (1969) Computerized biomechanical models - development of and use in studying gross body actions. Journal of biomechanics, 2: 429-441

Chaffin, D. B., Andersson, G. B. J., and Martin, B. J. (1999) Occupational biomechanics. 3rd edition. A Wiley-Interscience publication

De Lateur, J., Giacon, R. M., Questad, K., Ko, M., and Lehmann, J. F. (1991) Footwear and

posture. American journal of physical medicine & rehabilitation, 70(5): 246-254

Fogleman, M., and Smith, J. L. (1995) The use of biomechanical measures in the investigation of changes in lifting strategies over extended periods. International journal of industrial ergonomics, 16(1); 57-71

Franklin, M. E., Chenier, T. C., Brauninger, L., Cook, H., and Harris, S. (1995) Effect of positive heel inclination on posture. JOSPT, 21(2): 94-99

Freivalds, A., Chaffin, D. B., Garg, A., and Lee, K. S. (1984) A dynamic biomechanical evaluation of lifting maximum acceptable loads. Journal of biomechanics, 17(4): 251-262

Frymoyer, J. W., and Cats-Baril, W. L. (1991) An overview of the incidences and costs of low back pain. Orthopedic clinics of North America, 22(2): 263-271

Garg, A., Moore, S. J. (1992) Epidemiology of low-back pain in industry. Occup med: State of the art rev 7(4): 593-608

Hagen, K. B., Hallen, J., Harms-Ringdahl, K. (1993) Physiological and subjective responses to maximal repetitive lifting employing stoop and squat technique. European journal of applied physiology, 67: 291-297

Hashemi, L., Webster, B. S., Clancy, E. A., and Volinn, E. (1997) Length of disability and cost of

workers' compensation low back pain claims. JOEM, 39(10): 937-945

Granata, K. P., and Marras, W. S. (1995) An EMG-Assisted model of trunk loading during free dynamic lifting. Journal of biomechanics, 28(11): 1309-1317

Kilbom, Å., and Persson, J. (1987) Work technique and its consequences for musculoskeletal disorders. Ergonomics, 30(2): 273-279

Kjellberg, K., Lindbeck, L., and Hagberg, M. (1998) Method and performance: two elements of work technique. Ergonomics, 41(6): 798-816

Kraus, J. F., Schaffer, K. B., McArthur, D. L., and Peek-Asa, C. (1997) Epidemiology of acute low back pain injury in employees of a large home improvement retail company. American journal of epidemiology, 146(8): 637-645

Korff, M. V., Dworkin, S. F., Le Resche, L., and Kruger, A. (1988) An epidemiologic comparison of pain complaints. Pain, 32: 173-183

Kumar, S. (1984) The physiological cost of three different methods of lifting in sagittal and lateral planes. Ergonomics, 27(4): 425-433

Lavender, S. A., Li, Y. C., Andersson, G. B. J., and Natarajan, R. N. (1999) The effect of lifting speed on the peak external forward bending, lateral bending, and twisting spine moments.

Ergonomics, 42(1): 111-125

Lanczos, C. (1956) Applied analysis. Prentice hall

Lee, C., Jeong, E., and Freivalds, A. (2001) Biomechanical effects of wearing high-heeled shoes. International journal of industrial ergonomics, 28: 31-326

Leskinen, T. P. J. (1985) Comparison of static and dynamic biomechanical models. Ergonomics, 28: 289-291

Liira, J. P., Shannon, H. S., Chambers, L. W., and Haines, T. A. (1996) Long-term back problems and physical work exposures in the 1990 Ontario health survey. American journal of public health, 86(3): 382-387

Lindbeck, L., and Arborelius, U. P. (1991) Inertial effects from single body segments in dynamic analysis of lifting. Ergonomics, 34(4): 421-433

Magnusson, M. L., Pope, M. H., Wilder, D. G., and Areskoug, B. (1996) Are occupational drivers at an increased risk for developing musculoskeletal disorders? Spine, 21(6): 710-717

Marras, W. S., Lavender, S. A., Leurgans, S. E., Fathallah, F. A., Ferguson, S. A., Allread, W. G., and Rajulu, S. L. (1995) Biomechanical risk factors for occupationally related low back disorders. Ergonomics, 38(2): 377-410

McConville, J. T., Churchill, T. D., Kaleps, I., Clauser, C. E., and Cuzzi, J. (1980) Anthropometric relationships of body and body segment moments of inertia. Air force aerospace medical research laboratory, AFAMRL-TR-80-119

McGill, S. M., and Norman, R. W. (1985) *Dynamically and statically determined low back moments during lifting*. Journal of biomechanics, 18(12): 877-885

McGill, S. M., Norman, R. W., and Sharratt, M. T. (1990) The effect of an abdominal belt on trunk muscle activity and intra-abdominal pressure during squat lifts. Ergonomics, 33(2): 147-160

Mirka, G. A., Baker, A., Harrison, A., and Kelaher, D. (1998) The interaction between load and coupling during dynamic manual material handling tasks. Occupational Ergonomics, 1(1); 3-11

Montgomery, C. (2001) Design and analysis of experiments. 5th edition. Wiley

National Research Council and Institute of Medicine. (2001) Musculoskeletal disorders and the workplace – Low back and upper extremities. National Academy Press

NIOSH. (1997) Musculoskeletal disorders and workplace factors. A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back. U. S. Department of health and human services, Public health service, Centers for

disease control and prevention, National institute for occupational safety and health. Publication No. 97-141

Opila, K. A., Wagner, S. S., Schiowitz, S., and Chen, J. (1988) Postural alignment in barefoot and high-heeled stance. Spine, 13(5): 542-547

Pheasant, S. (1986) BodySpace. Taylor & Francis

Pope, M. H., Frymoyer, J. W., and Andersson, G. B. J. (1984) Occupational low back pain. Praeger

Praemer, A., Furner, S., and Rice, D. P. (1999) Musculoskeletal conditions in the united states. Rosemont, IL: American Academy of Orthopaedic Surgeons

Punnet, L., Fine, L. J., Keyserling, W. M., Herrin, G. D., and Chaffin, D. B. (1991) Back disorders and nonneutral trunk postures of automobile assembly workers. Scand J Work Environ Health, 17(5): 337-346

Schipplein, O. D., Trafimow, J. H., Andersson, G. B. J., and Andriacchi, T. P. (1990) Relationship between moments at the L5/S1 level, hip and knee joint when lifting. Journal of biomechanics, 23(9): 907-912

Spengler, D. M., Bigos, S. J., Martin, N. A., Zeh, J., Fisher, L., and Nachemson, A. (1986) Back

injuries in industry: A retrospective study – I. Overview and cost analysis. Spine, 11(3): 241-245

Svensson, H., and Andersson, G. B. J. (1989) The relationship of low-back pain, work history, work environment, and stress – A retrospective cross-sectional study of 38- to 64-year-old women. Spine, 14(5): 517-522

Toussaint, H. M., Van Baar, C. E. V., Langen, P. P., De Looze, M. P., and Van Dieën, J. H. (1992) Coordination of the leg muscles in back lift and leg lift. Journal of biomechanics, 23(11): 1279-1289

Van Dieën, J. H., Burg, P. V. D., Raaijmakers, T. A. J., and Toussaint, H. M. (1998) Effects of repetitive lifting on kinematics: inadequate anticipatory control or adaptive changes? Journal of motor behavior, 30(1); 20-33

Van Dieën, J. H., Hoozemans, M. J. M., and Toussaint, H. M. (1999) Stoop or squat: a review of biomechanical studies on lifting technique. Clinical biomechanics, 14: 685-696

Videman, T., Nurminen, T., Tola, S., Kuorinka, I., Vanharanta, H., and Troup, J. D. G. (1984) Low-back pain in nurses and some loading factors of work. Spine, 9(4): 400-404

Waters, T. R., Baron, S. L., Piacitelli, L. A., Anderson, V. R., Skov, T., Haring-Sweeney, M., Wall, D. K., and Fine, L. J. (1999) Evaluation of the revised NIOSH lifting equation. A cross-sectional epidemiologic study. Spine, 24(4): 386-394

Webster, S., and Snook, S. H. (1994) The cost of 1989 workers' compensation low back pain claims. Spine, 19(10): 1111-1116

Xu, Y., Bach, E., and Ørhede, E. (1997) Work environment and low back pain: the influence of occupational activities. Occupational and environmental medicine, 54: 741-745

Zhao, Y., Upadhyaya, S. K., and Kaminaka, M. S. (1987) Foot-ground forces on sloping ground when lifting. Ergonomics 30(12): 1671-1687