Muscle Overexertion During Repetitive Lifting

Dr. William S. Marras*
Dr. Sue A. Ferguson
Dr. Deborah L. Burr
Julia Parakkat
Anne-Marie Chany
Gang Yang

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*Biodynamics Laboratory
The Ohio State University
210 Baker Systems Engineering
1971 Neil Avenue
Columbus, OH 43210
email: marras.1@osu.edu
Phone: 614-292-6670
Fax: 614-292-7852

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1. Introduction

Back injuries are common in industry and extremely costly. Back pain has been described as one of the most common and significant musculoskeletal problems in the United States leading to substantial amounts of morbidity, disability and economic loss (Hollbrook et al, 1984; Praemer et al, 1992). Back disorders were responsible for half a billion lost workdays in 1988 with 22 million cases reported that year (Guo, 1993). Among people under 45 years of age, LBD is the leading cause of activity limitation and effects up to 47% of workers with physically demanding jobs (Andersson et al, 1976). Pope (1993) has reported that the prevalence of LBD has increased by 2700% since 1980. The costs associated with LBD are enormous. Early estimates of lost wages alone, amount to four billion dollars annually (Frymoyer et al, 1983). Webster and Snook (1989) estimated that in 1986 the average direct costs of LBD were $6,800 per case. Recent estimates of societal costs range from 25 to 95 billion dollars per year (Cats-Baril & Frymoyer, 1991).

The risk of LBD is associated with industrial work (Andersson, 1991). Thirty percent of occupational injuries in the United States are caused by overexertion, lifting, throwing, holding, carrying, pushing and/or pulling objects that weigh 50 pounds or less (NSC, 1989). About one-fifth of all workplace injuries and illnesses are back injuries, accounting for up to 40% of compensation costs. Estimates of occupational LBD prevalence vary from 1% to 15% annually, depending upon occupation (Kelsey & White, 1980). Over a career, LBDs can seriously affect 56% of workers (Rowe, 1981).

Low back disorders are associated with occupational lifting. The epidemiologic literature (Andersson, 1991; Pope, 1989) has noted that the type of work involved in an occupation is closely associated with the risk of suffering a LBD. In particular, manual materials handing (MMH) activities, specifically lifting, dominate occupationally-related LBD risk. Retrospective studies (Bigos et al, 1986; Spengler et al, 1986) of industrial injuries have identified MMH as the most common cause of LBD. It is estimated that lifting and MMH account for 50% to 75% of all back injuries (Bigos et al, 1986; Snook, 1989; Spengler et al, 1986). It has been assumed that back pain is discogenic and has a mechanical origin (Nachemson, 1975). Videman et al (1990) also confirmed the notion that LBD risk was associated with physically heavy work, such as MMH, by examining the functional spinal units of 86 cadavers whose work and LBD history were known. They found increased degeneration in the spines of those specimens who had performed physically heavy work. Hence, this suggests that occupationally-related LBDs are often associated with spine loading. Even though studies have also identified psychosocial (Bigos et al, 1991) linkages to back pain, recent prospective studies have shown that both biomechanical factors and psychosocial factors can independently predict LBD (Krause et al, 1998). However, most researchers feel that biomechanical risk factors must be present before psychosocial factors are able to play a role. Thus, biomechanical loading is believed to be the primary injury pathway for occupationally related LBDs. The current study limited its focus to biomechanical risk factors.

2. Background

How much lifting is too much lifting? The relationship between frequency of lifting and subsequent injury to the lower back has not been investigated adequately to provide guidance as to "how much is too much." From a regulation standpoint, several recent instances regarding enforcement and regulation indicate that there is reason for concern over the issue of lifting frequency and lifting duration. Comments to the Occupational Safety and Health Administration (OSHA) Advanced Notice of Proposed Rulemaking (OSHA, 1992) specifically address the scientific evidence associating repetition and low back pain. For example, The Health Care Association of Michigan stated "clear medical evidence is lacking to support OSHA's conclusion that repetitive motion in the workplace is the cause of employee back pain and other musculoskeletal disorders". Likewise, the American Health Care Association of Nursing Homes also believes there is no relationship between repetition and back pain. Finally, recent legal proceedings specifically challenge not only the tools, which are used to assess risk of low back injuries, but also the scientific basis for these tools. The Occupational Safety and Health Review Commission, in their decision in Secretary of Labor vs. Pepperidge Farm, indicated that one large company involved in material handling challenged the scientific basis of lifting and low back pain. They referred to "the inability of science to determine the level of exposure, either in frequency or amount of weight, at which lifting becomes hazardous" (OSHRC, 1997). Thus, many of the consumers of potential regulatory actions have already seriously questioned the role of repetition in occupationally-related LBD.

Low back disorders are cumulative trauma disorders (CTDs) and closely associated with repetition. Repetition has been identified as a major risk factor for occupationally-related musculoskeletal disorders (Silverstein et al, 1986). Even though LBDs are recorded as injuries or discrete events on OSHA 200 logs, most of the research community has recognized the cumulative or progressive nature of LBDs. Changes in the integrity of the intervertebral disc as well as changes in the ability of the vertebral endplates to nourish the disc are thought to be related to repetitive wear on the vertebral structures. Animal studies have shown static and repetitive dynamic loading to the intervertebral disc may cause degenerative changes, such as disorganization of annulus fibrosus, cell death, and matrix gene expression (Lotz et al, 1998; Walsh & Lotz, 2004). In addition, the cumulative effect of repetitive muscle activation has also been well documented in the physiological literature. Electromyography (EMG) studies indicate that repetitive lifting may fatigue the back muscle and the muscular load on the low back increases with higher frequency of lifting (Dolan & Adams, 1998; Bonato et al, 2003; Nielsen et al, 1998)

Given the cumulative trauma nature of occupationally-related LBDs it is logical that repetitive occupational lifting should be considered a risk factor. Much of the literature supports this notion. Industrial surveillance studies (Marras & Kim, 1993; Marras et al, 1995) have reported that lift rates of above 120 lifts per hour increases the probability of LBD risk. This value agrees with the definition of CTD reported by Anderson (Anderson, 1988). Epidemiologic studies (Kelsey et al, 1984; Magora, 1975) have reported that repetitive lifting was indeed a risk factor for LBD. Epidemiologic studies have also reported a dose-response relationship with increased lift frequencies associated with higher rates of low back pain (LBP) (Chaffin & Park, 1973; Kelsey et al, 1984; Svensson & Andersson, 1983). Berquist-Ullman and Larsson (1977) have also observed that LBD is more common in assembly line work than in other types of work. Yet, NIOSH's review of musculoskeletal disorders and workplace factors (NIOSH, 1997) does not even investigate the association between LBD and repetition. Although the National Research Council's review of work-related low back and upper extremity disorders (NRC, 2001) showed inconsistent evidence for repetitive movement to be a risk factor for LBD, only three studies were included for review. This suggests that an under-appreciated and under-explored risk factor for occupationally-related LBD is indeed frequency of lifting.

Repetitive lifting is expected to become more common as the nature of work changes. The nature of work is rapidly changing in the United States. Fewer products are being produced within the U.S. and more products are being produced across U.S. borders. However, distribution of the products always occurs within the U.S. Thus, an explosion in the number of distribution centers and warehouses is occurring in the U.S. these numbers will become even greater as e-commerce makes its way into the marketplace. Hence, lift frequency will become even more of a factor as more workers are moving products manually. Current work standards are based upon the concept of a fair days work which is subjective in nature at best. Unfortunately, current work standards do not consider the effects of lift frequency upon trunk loading or the impact it may have on musculoskeletal risk. Hence, current work practice standards provide no protection from musculoskeletal disorders.

Previous lifting frequency studies exploring the relationship between lift frequency and LBD risk have been based upon three approaches: 1) whole body physiology, 2) whole body psychophysical assessments, and 3) biomechanical assessments. In general, physiological studies have found increases in lift frequency corresponded to increases in heart rate, oxygen consumption, and energy expenditure (Ciriello & Snook, 1983; Ciriello et al, 1990; Garg, 1989; Genaidy & Al-Rayes, 1993; Hamilton & Chase, 1969; Jorgensen & Poulsen, 1974; Karwowski & Yates, 1986; Legg & Pateman, 1984; Miller et al, 1977; Mital, 1984; Mital, 1987a; Petrofsky & Lind, 1978; Snook, 1971; Welbergen et al, 1991, Wu & Hsu, 1993). Psychophysical studies found increases in lift frequency resulted in decreases in the maximum acceptable weight of lift (MAWL) (Ayoub et al, 1980; Bigost al, 1991; Ciriello, 1983; Ciriello, 1990; Garg, 1989; Garg & Saxene, 1979; Karwowski & Yates, 1986; Mital, 1984; Mital, 1986; Mital, 1987a; Mital, 1987b; Mital & Manivasagan, 1983; Snook, 1971; Snook, 1978; Snook & Ciriello, 1991; Snook & Irvine, 1967; Snook et al, 1970; Solomonow et al, 1990; Sonada, 1962; Wu & Hsu, 1993). These decreases in MAWLs were accompanied by increases in the perception of fatigue and level of exertion (Garg, 1989; Genaidy & Al-Rayes, 1993; Karwowski & Yates, 1986; Legg & Pateman, 1984). However, an issue associated with both of these types of studies is that **physiological and psychophysical studies rely upon the assumption that whole body measurements are directly related to a pain mechanism in the lower back** (Leamon, 1994). MAWLs are based on perceptions of exertion and fatigue throughout the body and not necessarily in the lower back. Similarly, oxygen consumption and energy expenditure is measured for the whole body and not for the lower back muscles. Thus, much of the research investigating the effect of changing lift frequency may not accurately represent risk of injury to the lower back. Workers may increase energy expenditure or oxygen consumption well after the point where there is risk to the low back. Davis and colleagues (2000) compared psychophysical acceptance points to biomechanically defined risk and found that people are not necessarily responding to high risk situations during a psychophysical judgement. Particularly troubling is their finding that the majority of subjects often accepted work conditions that clearly placed them at biomechanical risk for LBDs. This is not surprising since LBDs occur cumulatively and are caused by loads that might not stimulate nociceptive pain receptors.

The biomechanical evaluation of lift frequency has been limited to two studies. Garg (1989) reported that compressive forces at L5/S1 actually decreased with increases in lift frequency. However, in this study, compressive force was confounded with weight since less mass was lifted at higher lifting frequencies. Hence, the findings may be a result of changes in lift frequency and/or weight. Additionally, the model used was not sensitive to torso motion that would change with lift frequency. De Looze et al. (1996) investigated the effect of lifting frequency for a bricklaying task. These authors evaluated several different lift frequencies but the higher frequencies were associated with lighter bricks. Thus, they found that the effect of increasing brick weight was generally negated by the increase in lift frequency. However, they used a two-dimensional analysis that was not sensitive to motion increases that occur when lift speed increases. Thus, no biomechanical assessment has adequately investigated lift frequency.

It is well documented that changes in lifting repetition influence trunk kinematics as the frequency of lift changes and as the duration of the lifting period increases (Marras & Granata, 1997; Sparto et al, 1997a; Sparto et al, 1997b). Assessments that explore the implications of lift frequency must be able to interpret the biomechanical consequences of these kinematic changes. Most biomechanical analysis techniques previously used for ergonomic purposes are incapable of such analyses. Previous analysis techniques were static, did not consider the effects of trunk motion on spine loading, and assumed that no coactivation occurs in the trunk musculature during lifting (Andersson et al, 1974; Andersson & Marras, 1996; Andersson et al, 1977; Ayoub et al, 1979; Chaffin, 1969; Chaffin & Baker, 1970; Chaffin & Muzaffer, 1991; Schultz & Andersson, 1981; Schultz et al, 1982a; Schultz et al, 1982b). These models assume that the lifted load is counterbalanced with one equivalent back muscle. These models then sum the forces imposed by the load and those imposed by the equivalent muscle to estimate spinal compression. However, dynamic three-dimensional trunk movement requires a complex coactive recruitment of numerous trunk muscles. Realistically, dynamic lifting tasks greatly increase the magnitude and variability of spinal loads (Freivalds et al, 1984; Goel et al, 1991; Lindbeck & Arborelius, 1991; Marras & Sommerich, 1991b; McGill & Norman, 1985). Thus, a task may be associated with average spinal loads below tolerance limits, but repeated performance will generate a significant number of exertions with spinal loads greater than acceptable tolerance. Furthermore, shear and torsional loads become more prevalent when the speed of trunk motion increases (Marras & Sommerich, 1991b). Shear forces make the spinal motion segment far more vulnerable to injury than compressive loading (Broberg, 1983; Shirazi-Adl, 1989; Shirazi-Adl et al, 1986). There is also in-vitro evidence that the viscoelastic properties of the ligamentous spine may act to increase spinal stress with increased speed of spine motion (Adams & Hutton, 1985; Adams & Hutton, 1986; Brinckmann et al, 1988; Broberg, 1983). Thus, traditional ergonomic analysis techniques of lifting are incapable of evaluating these very effects that one would expect with changes in lifting frequency. **Only biomechanical analysis techniques that are capable of evaluating the systematic changes in muscle coactivity due to trunk motion and muscle fatigue are sufficient for the analysis of repetitive lifting.**

Over the past 20 years, the Biodynamics Laboratory at the Ohio State University has developed a three-dimensional dynamic biomechanical model that can determine how the vertebral joint at L5/S1 is loaded during a dynamic motion (Marras & Sommerich, 1991a; Marras & Sommerich, 1991b). The model yields subject- and task-specific spine loading information. Our model assumes that we can pass one imaginary transverse plane through the thorax and another imaginary transverse plane through the pelvis. According to the laws of physics, only muscles that pass through both of these planes are capable of imposing loads on the lumbar spine. EMG is used to monitor every major muscle group that passes through both of these two planes. The lumbar motion monitor tracks the positions of the two planes relative to one another and permits adjustment of muscle activity for muscle length and velocity. This information is used to assess the muscle force associated with each muscle. These forces are represented as vectors acting between these two imaginary planes. Summation of muscle forces in each cardinal plane is used to compute spinal forces. Comparison of model predicted external moment with measured external moment is used as a validation measure. The model has been validated for forward bending (Granata & Marras, 1995), lateral bending (Marras & Granata, 1997) and twisting (Marras & Granata, 1995) exertions.

Given that a significant void exists in our knowledge base regarding how changes in lifting frequency and duration affect spinal loading and the subsequent risk of LBD, we hypothesized that lift frequency can affect biomechanical risk of LBD in two ways. First, changes in frequency will result in changes in trunk motion and changes in muscle recruitment patterns resulting in alterations in the nature and magnitude of spinal loading. Second, different lift frequencies will result in different muscle fatigue patterns over time, again affecting muscle recruitment and the subsequent spinal loading. Thus, the biomechanical implications of lifting at a given frequency early during a shift may be significantly different from those experienced near the end of a shift. Depending on how much the spinal loading exceeds spine loading tolerance limits, the risk of LBD may also change during a workday.

The purposes of the study were: 1) determine how spinal loading changes as the frequency of lifting changes; 2) determine how spinal loading changes at given frequencies of lift throughout the workday. The EMG-assisted biomechanical model described above was used to determine the compression, anterior-posterior (AP) shear and lateral shear force changes at L5/S1 over time for different frequencies of lifting for both novice and experienced manual materials handlers. Collectively, these loading data were used to assess the risk of spine structure damage as a function of lifting frequency and lifting duration for commonly lifted weights.

3. Methods

Approach

This study was a biomechanical investigation of the spine loading incurred in novice and experience manual material handlers as they performed repetitive, asymmetric lifts at various load levels and frequency levels throughout a period of eight hours. An EMG-assisted biomechanical model was used to evaluate the three-dimensional spinal load (compression, A/P shear, and lateral shear).

Participants

In this study, a total of 24 subjects were tested. Two groups of participants, twelve novice and twelve experienced manual materials handlers, were recruited. The novice subjects (9 males, 3 females) were volunteers recruited from the student population and the local community. The experienced subjects (12 males) were volunteers recruited from local warehouses and other MMH jobs. Experienced subjects were required to have been employed full-time for at least one year at an MMH job. All subjects were screened to ensure that they did not suffer from LBP and were capable of performing the experimental tasks by P. Gupta, M.D. The characteristics of the subject population are given in Table 3.1.

Table 3.1: Anthropometric data of subjects - mean and standard deviation (SD).

Subject (n)	Mean Age (SD) in years	Mean Height (SD) in centimeters	Mean Weight (SD) in kilograms
Overall (24)	23 (3)	176.61 (6)	78 (16)
Novice (12)	24 (3)	176.62 (8)	75 (15)
Experienced (12)	23 (4)	177.60 (4)	81 (16)

Experimental Design

The experiment was a 6x3 repeated measures design with one between subjects factor (load, at three levels) and one within subjects factor (lift frequency, at six levels). This design resulted in 18 different experimental conditions. The design employed a total of 24 subjects. Because it would not be possible for all 24 subjects to attend the 18 test sessions, the desired full randomized block factorial experimental design could not be achieved. Rather, the 24 subjects were divided into three groups of 8. Each group was exposed to one of the three load levels (either 1.1 kg, 4.9 kg, or 11.7 kg) and all six frequency levels. By doing so, all subjects were tested six times on six separate days for one load level. Pilot study data provided support for this choice of design by showing that the average effect size among the three load levels is two to three times that of the six levels of frequency [Marras, 1998]. For a block diagram representation of the experimental design, refer to Figure 3.1.

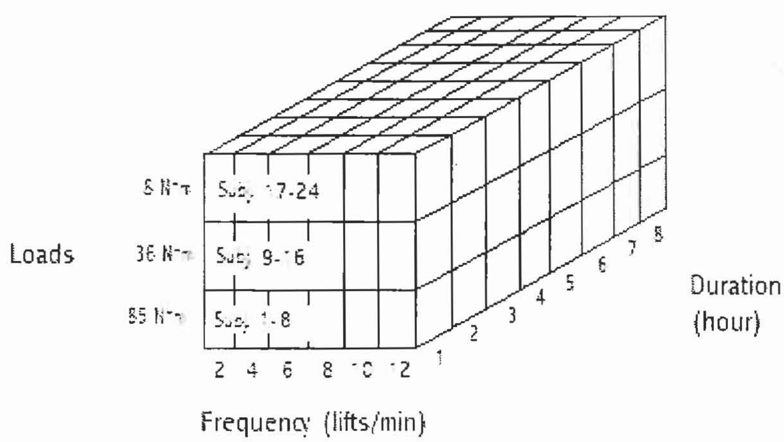

Figure 3.1: Block diagram of the experimental design.

Independent Variables

The independent variables and their levels were chosen to be representative of those observed in industry. The workplace factors consisted of three load-moment levels and six lift frequency levels. The worker factor was experience level. The levels of these variables and their relationship to that observed in industry are:

1. Three load-moments, 8 Nm, 36 Nm, and 85 Nm, were chosen to represent the 25^{th}, 50^{th}, and 75^{th} percentiles respectively of load-moments observed in industry [Marras et al., 1993]. Subjects were randomly assigned to one of the three load-moment levels.
2. Six lift frequencies (2, 4, 6, 8, 10, 12 lifts/min (lpm)) were chosen to a) represent the central 90^{th} percentile range of lift frequencies observed in industry [Marras et al., 1993] and b) include the range of expected changes in spinal loading based on a pilot study [Marras, 1998]. The order of presentation of the frequency levels was randomized.
3. Two experience levels, novice (no MMH experience) and experienced (at least 1 year of full-time MMH experience), were chosen to represent the range of novice and experienced manual materials handlers and so that the results could be applicable to a wide range of MMH workers.

The duration of the asymmetric lifting period for the six load-frequency levels lasted up to eight hours. The end of an experimental session was determined by completion of the eight hour duration or the subject's endurance time, whichever occurred first.

In addition to the asymmetric lifts, as a means of comparison between subjects across experimental task conditions, the standard sagittal lift of a 15-lb box was performed by all subjects. Standard sagittal lifts were recorded immediately prior to and following each break and also every 40 minutes where breaks were not present. Thus, a total of 12 sagittal lifts were recorded per 8-hour day. The lift was such that motion remained in the sagittal plane. The lift started at the same height as the experimental setup and ended with the subjects in an upright position.

Also, a standard exertion lift was performed by one subject of each simultaneously-tested pair. These lifts occurred immediately following the sagittal lifts. The standard exertion consisted of a lift in which the subject was asked to lift the 15-lb. box from the same start height as the experimental setup up to shoulder height with the arms extended away from the body. The subject was to maintain the lift in that position while the experimenter collected data for several seconds. Data was collected once the subject had reached the shoulder level position and stabilized the motion. This data was used to monitor the median frequency of each of the ten monitored trunk muscles in order to assess muscle fatigue over time.

Dependent Variables

The dependent variables included:

1. Perceived discomfort, a subjective measure, collected from a NIOSH developed Borg scale work-related discomfort survey. The survey was administered every hour over the eight hour data collection period and at the beginning and end of the break periods. The survey asked for perceived discomfort on a scale of 0 to 7. No discomfort was equivalent to a rating of 0 and highest discomfort was rated at 7.

For the purposes of this study, back discomfort was of primary interest. The survey used for this experiment separated the back region into the upper and the lower back. For statistical analysis, these two categories were combined (summation) for collective analysis. This measure was used to correlate subjectively reported work stress and the biomechanical responses.

2. The three-dimensional spinal loading predicted by the EMG-assisted biomechanical model (described below) during the experimental task lifts and the standard sagittal lifts. Compression, Anterior-Posterior (AP) Shear, and Lateral Shear in Newtons were all predicted. Spinal loading data was collected every ten minutes throughout the eight-hour session. To allow for comparisons between subjects, spinal loading was normalized to the subject's weight to account for body size (N/N).
3. Median frequency levels of the trunk muscles during the standard exertion lift. The frequency levels were analyzed after normalizing the value to the first value collected in the day to give a percent drop in median frequency as an indicator of muscle fatigue.

The personality type of all subjects was assessed using the Myers-Briggs Personality Type Indicator (MBTI) (Myers, 1998). Subjects were classified according to four different scales: 1) extraversion(E)/introversion (I), sensing (S)/intuition (I), feeling (F)/thinking (T), judging (J) /perceiving (P). Each of the personality traits is associated with certain preferences that may influence a person's response to a given work situation.

The three-dimensional spinal loading of each personality group was analyzed in an attempt to correlate the magnitude of biomechanical responses with personality type.

Apparatus and EMG-Assisted Biomechanical Model

Electromyographic data was collected using bipolar surface electrodes over the right and left pairs of the latissimus dorsi (RLAT & LLAT), erector spinae (RES & LES), rectus abdominus (RRA & LRA), external obliques (REO & LEO) and the internal obliques (RIO & LIO). The inter-electrode distance for the electrode pairs was 3 cm. The bipolar electrodes were placed over the muscle sampling locations [as cited in Mirka & Marras, 1993]. The myoelectric data was low pass filtered at 500 Hz, high pass filtered at 30 Hz, notch filtered at 60 Hz, rectified, averaged using a 20 ms sliding window filter and then normalized relative to the maximum voluntary contraction exertion values.

Trunk kinematics were measured by a Lumbar Motion Monitor (LMM). The LMM is a triaxial electrogoniometer designed to measure the instantaneous three-dimensional motion of the lumbar region [Marras et al., 1992]. The LMM measures the instantaneous trunk angle of the thorax relative to the pelvis so that position, velocity, and acceleration can be obtained (Figure 3.2).

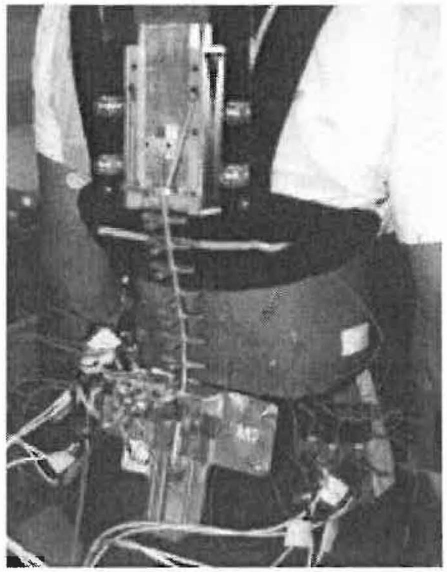

Figure 3.2: Lumbar Motion Monitor (LMM) harnessed to the subject's back [Marras, 1992].

To measure external spinal loads, the method developed by Fathallah, et. al. was employed [Fathallah et al., 1997]. A combination of a forceplate (Bertec 4060A; Bertec, Worthington, Ohio, USA) and two electrogoniometers was used to determine continuous three dimensional forces and moments about the L5/S1 intervertebral joint. The force plate measured the net reaction forces and moments at the feet. The electrogoniometers tracked the location of the L5/S1 intervertebral joint relative to the center of the forceplate (Figure 3.3). Thus, the forces and moments at the L5/S1 position could be calculated relative to the forceplate and the pelvic kinematics including tilt and rotation positions, velocities, and accelerations could be recorded.

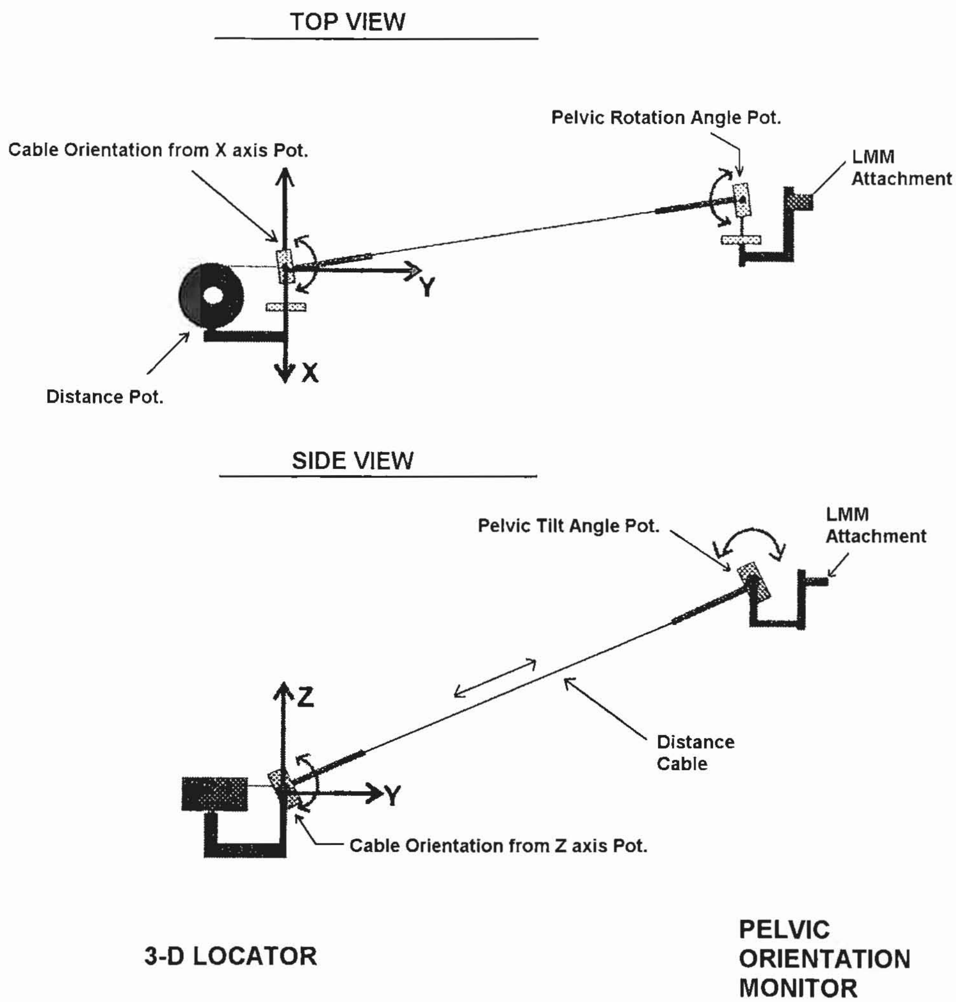

Figure 3.3: Representation of the L5/S1 potentiometer (pot.) locator set-up [Fathallah, 1997].

The electromyographic signals were sampled at 100Hz in one system and 1000Hz in another. The signals from all other experimental apparatus were sampled at 100Hz. All signals were simultaneously collected using customized data acquisition software, Laboratory Information Management System (LIMS). The signals were collected and saved on a computer using an analog to digital conversion board (National Instruments PCI-6033E). LIMS allowed the data to be collected continuously for eight hours and analyzed simultaneously to obtain model results.

The EMG-assisted biomechanical model developed in the Biodynamics Laboratory at The Ohio State University over the past 20 years was used to estimate spinal loads. Electromyographic data combined with measurements from the LMM, the force plate, and the L5/S1 locator were input into the model. Muscle forces calculated in the model were continuously summed to assess spinal loading. This model has been validated for robustness in sagittal bending [Granata & Marras, 1993], lateral bending [Marras & Granata, 1997], axial twisting [Marras & Granata, 1995], lowering exertion [Davis et al., 1998], and repeated measures [Marras et al., 1999]. The model also takes into account gender-based anatomical differences in the muscle size [Marras et al. 2001, Jorgensen et al. 2001].

Experimental Task and Procedures

All 24 subjects underwent the same procedures detailed below. Upon arrival to the laboratory, the subjects were informed about the tasks and procedures involved in the study. Prior to participation, subjects were required to read and sign a form approved by the University's Human Subjects Committee indicating their consent to participate in the study.

Anthropometric measurements, including height, weight, trunk breadth, and trunk depth were recorded. Surface electrodes were placed on the aforementioned ten trunk muscles using standard electrode placement procedures [Marras, 1990]. Once the electrode placement was completed, the subjects were placed in a pelvic support structure that allowed the subject to perform maximum exertions in six directions [Mirka & Marras, 1993]. While in this structure, the subject's maximum voluntary EMG data for the ten trunk muscles were collected while the subject performed static flexion, extension, right lateral bend, left lateral bend, right twist, and left twist exertions in the upright posture. To minimize fatigue and to obtain maximum voluntary EMG data, the subjects were allowed a two-minute rest period between exertions. The maximum voluntary EMG data was used to normalize the EMG data collected from the experimental trials.

The subject was then fitted with a LMM and was instructed to stand on the force plate. The electrogoniometers that tracked the L5/S1 position and the pelvic kinematics were affixed to the subject's LMM. Neutral readings were then taken of the subject in a straight upright posture. Once the subject was instrumented, the experimental trials began. The trials consisted of a repetitive asymmetric lifting task paced at a set frequency for the entire eight hours of lifting. The frequency was set to one of the six aforementioned levels and the sequence of frequency exposure over the six experimental sessions was randomized.

The experimental task was a lifting task that involved whole body free-dynamic lifting from a low vertical height to a higher vertical height. Marras et al. [1993] conducted a surveillance study of MMH industries and found that the most common manual materials handling situation is a palletizing/depalletizing operation. Based upon the database created from this extensive surveillance study, the experimental task represented a common palletizing/depalletizing operation by setting the following workplace factors at a fixed level:

- Lift origin vertical height – 88 cm (25^{th} percentile of database)
- Lift destination vertical height – 121 cm (75^{th} percentile of database)
- Load moment arm distance – 74 cm (50^{th} percentile of database)

- Lift asymmetry – 90 degrees (50th percentile of database).

As noted above, the moment arm distance was set to a fixed value of 74 cm. To study moment changes, rather than changing the distance, the load was varied. Three load weights were used (1.1 kg, 4.9 kg, 11.7 kg). Each subject lifted one of the three weights.

The experimental task was setup such that two subjects were tested simultaneously. One subject lifted the load from the roller conveyer origin and placed it on the roller conveyer destination where it was delivered to the other subject (refer to Figure 3.4). The other subject performed the same operation with an identical load. Subjects were encouraged to lift in a manner that was representative of their typical lifting style. The only lifting style restriction was that the subjects were instructed to position their feet flat on the force plate as they lifted. This was necessary to validate the spine loading model. Subjects were observed throughout the experimental conditions and during static holding and maximum exertions. The static holding and maximum exertions were recorded for calibration purposes.

Subjects performed the experimental task repeatedly at the session's specified frequency, paced by a computer-generated tone. Subjects lifted for eight hours or when the experimental conditions became subjectively unacceptable by the subject. Subjects were given two scheduled 15 minute breaks and one 30 minute lunch in observance of typical industrial rest break schedules.

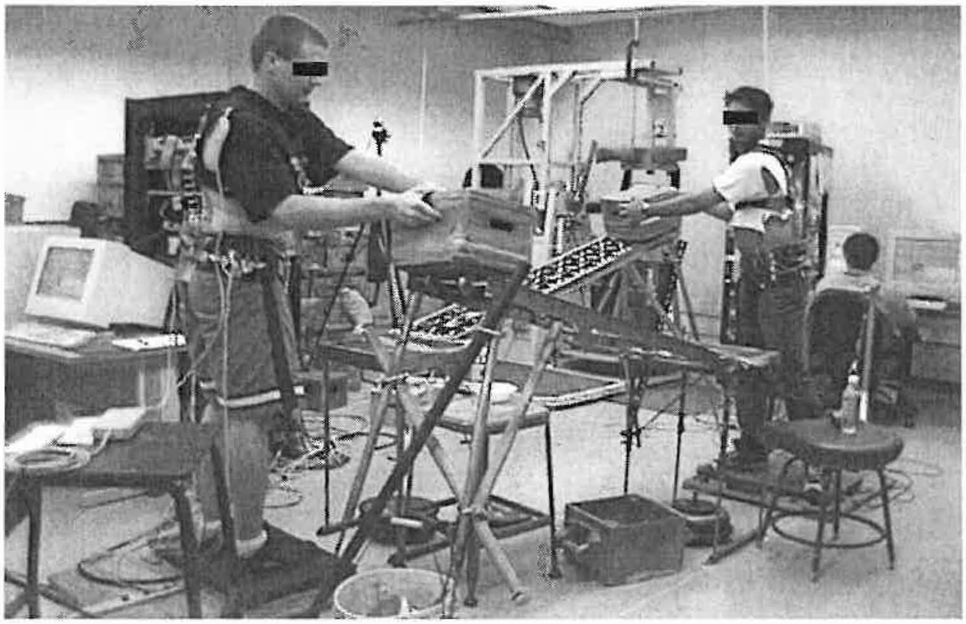

Figure 3.4: Experimental task set up.

Statistical Analysis

Significant differences were statistically analyzed with a repeated measures analysis of covariance structure. Because this was a repeated measures investigation in which repeated measures of the criterion variables were taken from each subject and because the subjects were randomly selected, subjects were viewed as a random effects factor. The levels of the frequency and time block variables were determined prior to experimentation and all subjects observed all levels; as such, frequency and time block were fixed effects. Because this experiment incorporated both random and fixed effects factors, the analysis was done using a mixed model. In particular, the mixed procedures analysis in the SAS software was utilized to identify significant main effects and two-, three-, four-, and five-way interactions of task variables on the dependent measures [SAS, 2001]. To satisfy requirements of linearity by the model, dependent measures were log transformed when necessary. The mixed model was reduced when necessary for more accurate calculations. As a general rule, only three-, four-, and five-way interactions of p>0.15 were reduced out of the model. Post-hoc analyses were used to identify significant contrasts for the main effect and interaction levels. All factors were considered significant at an alpha level of 0.05. The structure of the mixed model included subject, moment level (w), experience level (exp), lift frequency (f), and time (b) during the day as class variables. The influence of these class variables and their interactions on the dependent variables was statistically examined.

Incomplete Data

It was permitted that subjects could terminate the experimental session if the conditions were not tolerable. This occurred five separate times to three subjects and thus, the data set is not complete (Table 3.2).

Table 3.2: Incomplete experimental conditions.

Experience	Gender	Lift Frequency	Moment	Time in Workday
Novice	Male	6 lpm	85 Nm	Last 2 hours
Novice	Male	10 lpm	85 Nm	Last 2 hours
Novice	Female	6 lpm	85 Nm	Last 2 hours
Novice	Female	8 lpm	85 Nm	Last 2 hours
Experienced	Male	12 lpm	36 Nm	Last 2 hours

4. Results – Perceived Discomfort due to Experimental Variables

The perceived discomfort data was analyzed using the Mixed ANOVA statistical model. The discomfort of the back was measured on a scale of 0 to 7, where 0 was no discomfort and 7 was high discomfort. These values were grouped into three categories (0=no discomfort, 1=some discomfort rated at 1 or 2 from the discomfort scale, 2=much discomfort rated at 3+ from the discomfort scale). The perceived discomfort was significantly affected by numerous experimental main effects and interactions as listed in Table 4.1.

Table 4.1: Mixed model for effects of experimental task variables on perceived discomfort.

Mixed ANOVA Model p-values for Perceived Discomfort	
Effect	**p-value**
w	<0.0001
exp	<0.0001
exp*w	<0.0001
f	0.3907
f*w	0.0546
exp*f	0.0229
exp*f*w	0.1743
b	<0.0001
w*b	<0.0001
exp*b	<0.0001
exp*w*b	<0.0001
f*b	0.0035
f*w*b	0.3411
exp*f*b	0.4752
exp*f*w*b	0.1358

Shaded values are significant effects at alpha = 0.05

Main Effect of Moment

The effect of moment level on perceived discomfort was found to be highly significant at $p<0.0001$. The least squares means (lsmeans) and the corresponding standard deviations (SD) were found for the three levels of moment and are shown in Figure 4.1. A post-hoc analysis was done to determine which pairwise differences were significant among the three moment levels and to estimate the difference. The 8 Nm and 36 Nm moment levels were not significantly different from each other but were both significantly lower than the 85 Nm moment level ($p<0.0001$ & $p<0.0001$, respectively). The 85 Nm moment level yielded 68% higher perceived discomfort than the 8 Nm and 78% higher discomfort than the 36 Nm level.

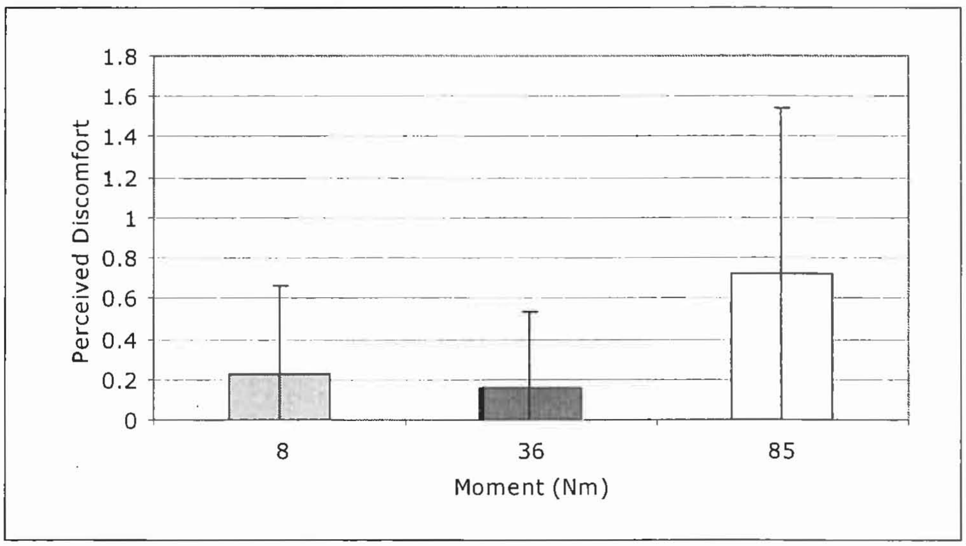

Figure 4.1: Main effect of moment on perceived discomfort.

Main Effect of Experience

The main effect of experience on perceived discomfort was found to be highly significant at $p<0.0001$. The lsmeans and SD for the experience levels are shown in Figure 4.2. Overall, perceived discomfort was 86% higher for novice subjects.

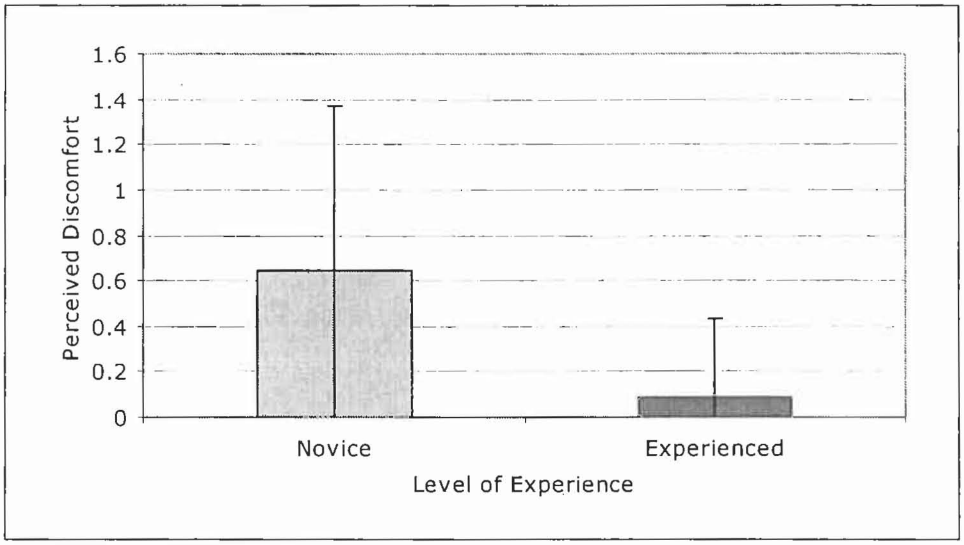

Figure 4.2: Main effect of experience on perceived discomfort.

Main Effect of Time

The main effect of time on perceived discomfort was significant at $p<0.0001$. The lsmeans and SD for the 4 levels of time are shown in Figure 4.3. Post-hoc analyses found that all four time levels were significantly different from each other with each level yielding significantly higher perceived discomfort ratings than the last. Table 4.2 shows the results of the post-hoc tests of significant contrasts.

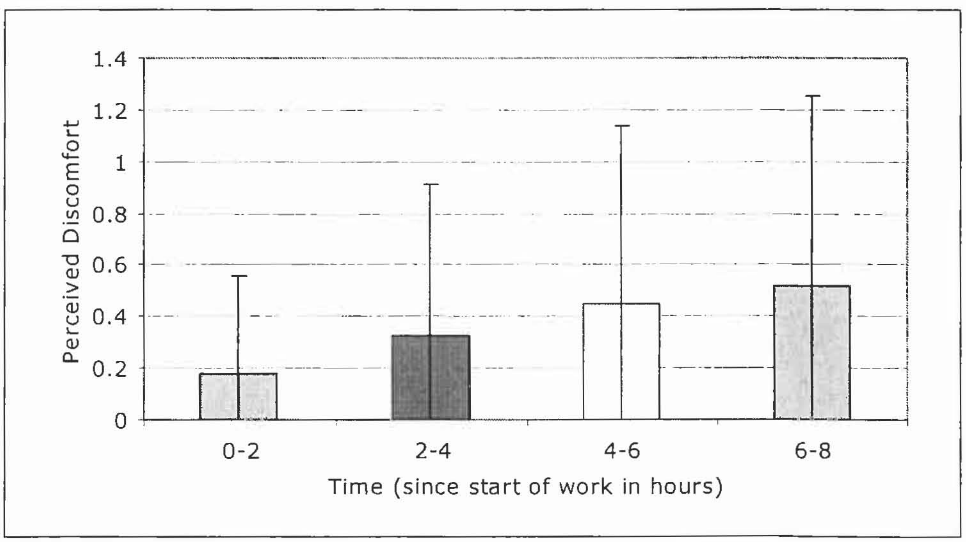

Figure 4.3: Main effect of time of day on perceived discomfort.

Table 4.2: Significant contrasts of main effect of time on perceived discomfort.

Contrast	p-value
Hours 0-2 vs. Hours 2-4	<0.0001
Hours 0-2 vs. Hours 4-6	<0.0001
Hours 0-2 vs. Hours 6-8	<0.0001
Hours 2-4 vs. Hours 4-6	<0.0001
Hours 2-4 vs. Hours 6-8	<0.0001
Hours 4-6 vs. Hours 6-8	0.0148

Interactive Effect of Moment and Experience

The moment by experience interactive effect on perceived discomfort was found to be significant at $p<0.0001$. Figure 4.4 shows the lsmeans and the SD for this interactive effect. Post-hoc analyses showed that in the comparison of experience levels, both the 8 Nm and the 85 Nm moment levels yielded significantly higher perceived discomfort ratings ($p=0.0018$ and $p<0.0001$, respectively) for the novice subjects than the experienced subjects. Within the novice subjects, although the 8 Nm level and the 36 Nm level were not significantly different from each other, they were both significantly lower than the 85 Nm level ($p<0.0001$ and $p<0.0001$, respectively). All three moment levels yielded statistically similar perceived discomfort results for the experienced subjects.

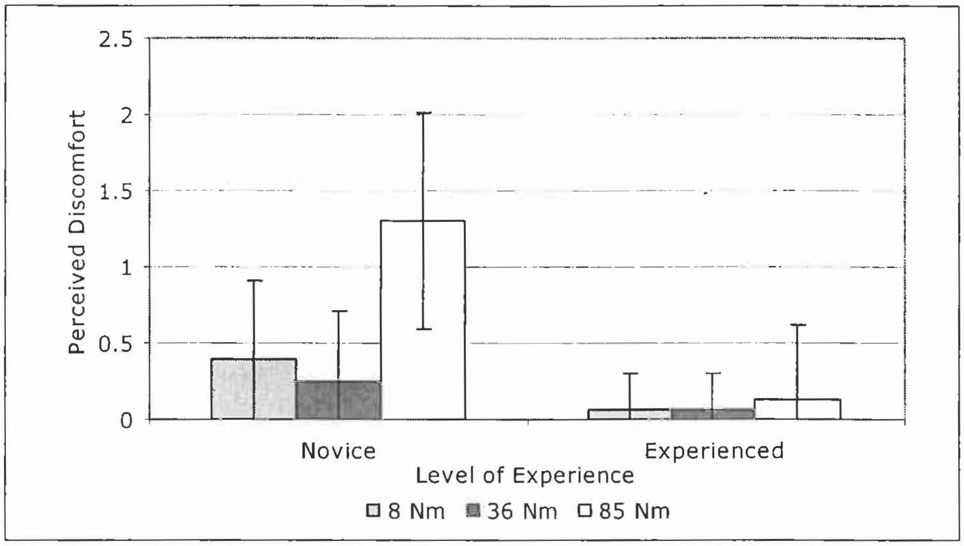

Figure 4.4: Interactive effect of moment and experience on perceived discomfort.

Interactive Effect of Moment and Time

The moment by time interactive effect on perceived discomfort was found to be significant at $p<0.0001$. The lsmeans trends and the SD are shown in Figure 4.5. Post-hoc analyses show that within the time levels, 8 Nm and 36 Nm have significantly lower perceived discomfort ratings than the 85 Nm level (with one exception within the first time level, in which 8 Nm was not statistically different from the 85 Nm). Additionally, for the 8 Nm and 36 Nm moment levels the first two hours have significantly lower discomfort than the last four hours. Interestingly, every time level comparison is significantly different for the 85 Nm level following the same trend as the main effect of time. Table 4.3 shows the results of the post-hoc tests of significant contrasts.

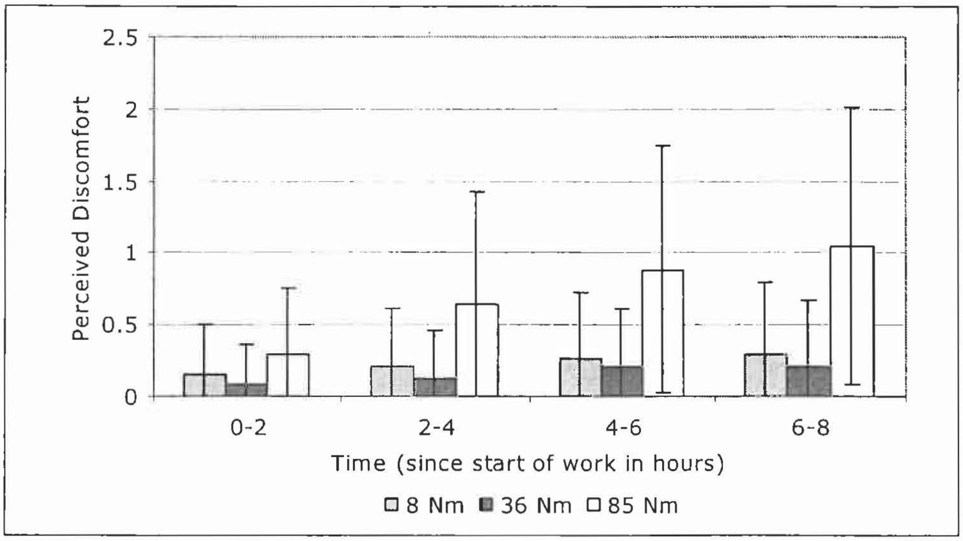

Figure 4.5: Interactive effect of moment and time on perceived discomfort.

Table 4.3: Significant contrasts of the moment by time interactive effect on perceived discomfort.

Contrast	p-value
Hours 0-2 36 Nm vs. 85 Nm	0.0133
Hours 2-4 8 Nm vs. 85 Nm	<0.0001
Hours 2-4 36 Nm vs. 85 Nm	<0.0001
Hours 4-6 8 Nm vs. 85 Nm	<0.0001
Hours 4-6 36 Nm vs. 85 Nm	<0.0001
Hours 6-8 8 Nm vs. 85 Nm	<0.0001
Hours 6-8 36 Nm vs. 85 Nm	<0.0001
8 Nm Hours 0-2 vs. Hours 4-6	0.0039
8 Nm Hours 0-2 vs. Hours 6-8	0.0353
36 Nm Hours 0-2 vs. Hours 4-6	0.0186
36 Nm Hours 0-2 vs. Hours 6-8	0.0129
85 Nm Hours 0-2 vs. Hours 2-4	<0.0001
85 Nm Hours 0-2 vs. Hours 4-6	<0.0001
85 Nm Hours 0-2 vs. Hours 6-8	<0.0001
85 Nm Hours 2-4 vs. Hours 4-6	<0.0001
85 Nm Hours 2-4 vs. Hours 6-8	<0.0001
85 Nm Hours 4-6 vs. Hours 6-8	0.0006

Interactive Effect of Experience and Time

The interactive effect of experience and time on perceived discomfort was significant ($p<0.0001$). The lsmeans and SD are shown in Figure 4.6. In accordance with the main effect of experience trends, it is obvious from Figure 4.6 that experienced subjects have significantly lower perceived discomfort regardless of the time of the work day. Additionally, within the novice subjects, all levels of time are significantly different from each other. However, for the experienced subjects, all four levels of time yielded statistically similar perceived discomfort ratings. Table 4.4 gives a list of the significant contrasts of this interaction.

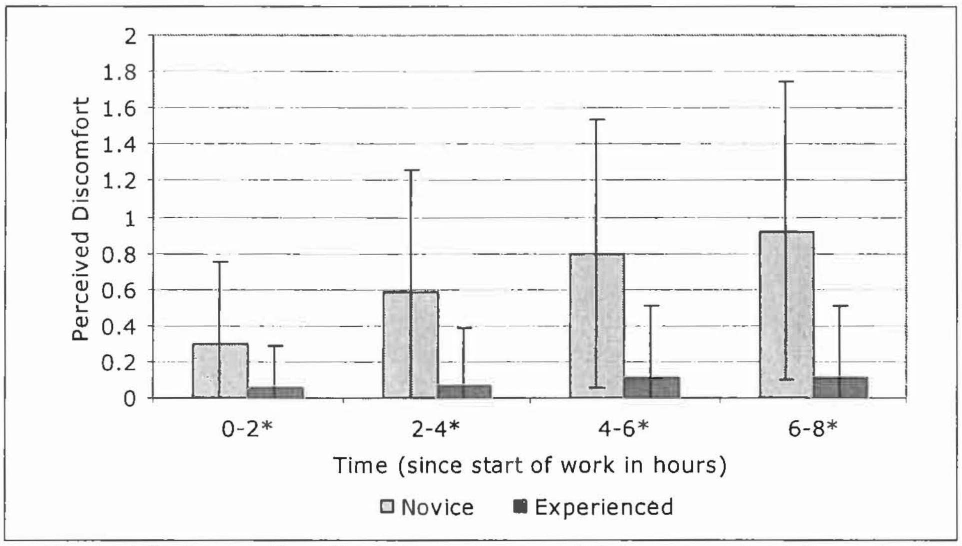

Figure 4.6: Interactive effect of experience and time on perceived discomfort (* indicates significant difference between novice and experienced subjects).

Table 4.4: Significant contrasts of the experience by time interactive effect on perceived discomfort.

Contrast	p-value
Hours 0-2 Novice vs. Experienced	0.0006
Hours 2-4 Novice vs. Experienced	<0.0001
Hours 4-6 Novice vs. Experienced	<0.0001
Hours 6-8 Novice vs. Experienced	<0.0001
Novice Hours 0-2 vs. Hours 2-4	<0.0001
Novice Hours 0-2 vs. Hours 4-6	<0.0001
Novice Hours 0-2 vs. Hours 6-8	<0.0001
Novice Hours 2-4 vs. Hours 4-6	<0.0001
Novice Hours 2-4 vs. Hours 6-8	<0.0001
Novice Hours 4-6 vs. Hours 6-8	0.0007

3-Way Interactive Effect of Moment, Experience and Time

Along with the main effect of time, and the interactive effects of moment and time and experience and time, the 3-way interactive effect of moment, experience and time was found to be significant on perceived discomfort ($p<0.0001$). Figures 4.7 and 4.8 show the lsmeans and SD of the moment and time effect for novice and experienced subjects, respectively. By a comparison of the two figures, it is clear that regardless of time of day, novice subjects have higher perceived discomfort than experienced subjects, which confirms the findings from the experience by time interactive effect. The relevant significant contrasts of this three-way interaction are given in Table 4.5.

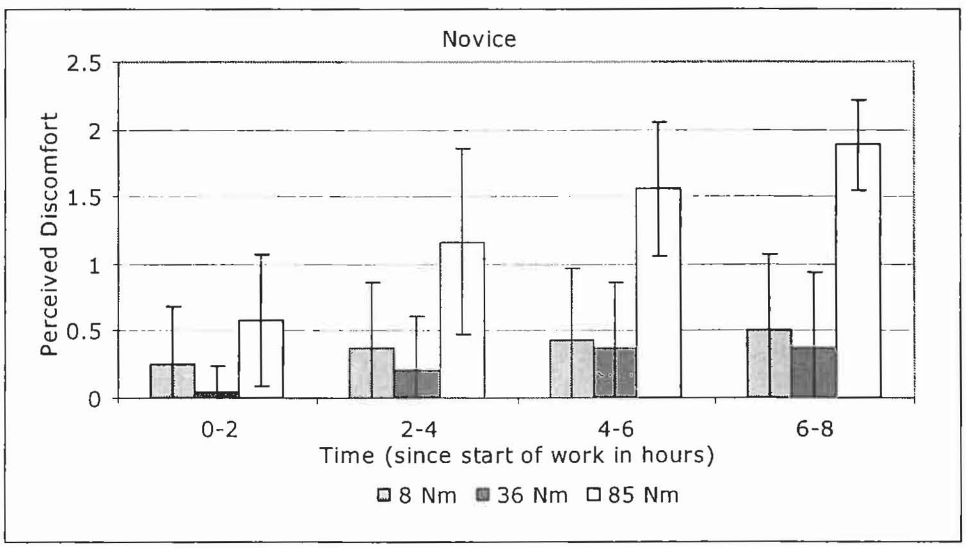

Figure 4.7: Interactive effect of moment and time on novice subjects' perceived discomfort.

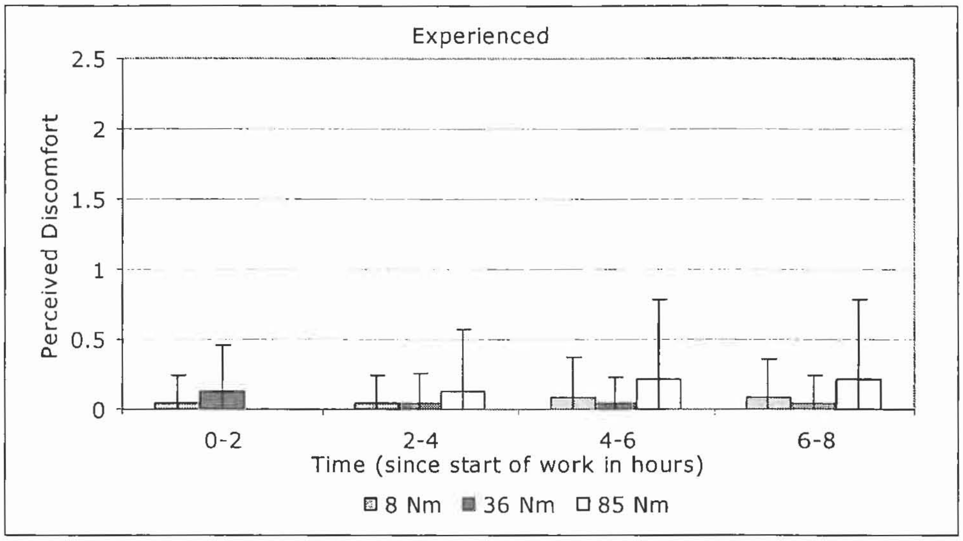

Figure 4.8: Interactive effect of moment and time on experienced subjects' perceived discomfort.

Table 4.5: Significant contrasts of the 3-way interactive effect on perceived discomfort.

Contrast	p-value
Hours 0-2 85 Nm Novice vs. Experienced	<0.0001
Hours 2-4 8 Nm Novice vs. Experienced	0.0052
Hours 2-4 85 Nm Novice vs. Experienced	<0.0001
Hours 4-6 8 Nm Novice vs. Experienced	0.0032
Hours 4-6 36 Nm Novice vs. Experienced	0.0052
Hours 4-6 85 Nm Novice vs. Experienced	<0.0001
Hours 6-8 8 Nm Novice vs. Experienced	0.0005
Hours 6-8 36 Nm Novice vs. Experienced	0.0055
Hours 6-8 85 Nm Novice vs. Experienced	<0.0001

Interactive Effect of Experience and Frequency

The interactive effect of experience and frequency on perceived discomfort was significant at p=0.0229 (Figure 4.9). Novice subjects had similar levels of perceived discomfort for the four highest lift frequencies (6, 8, 10, 12 lpm). Two lpm had statistically lower perceived discomfort ratings than 8 lpm (p=0.0453) within the novice subjects. Additionally, 4 lpm had statistically lower discomfort ratings than 6 (p=0.0251), 8 (p=0.0014), 10 (p=0.0078) and 12 (p=0.0024) lpm. Experienced subjects had much lower perceived discomfort ratings than novice subjects regardless of lift frequency. In fact, for 2 and 8 lpm, the average score was zero. Additionally, the perceived discomfort difference between experience levels for all lift frequencies had a p-value <0.0001 except at 4 lpm with p=0.0477. The perceived discomfort was not statistically different between any lift frequency within the experienced subjects.

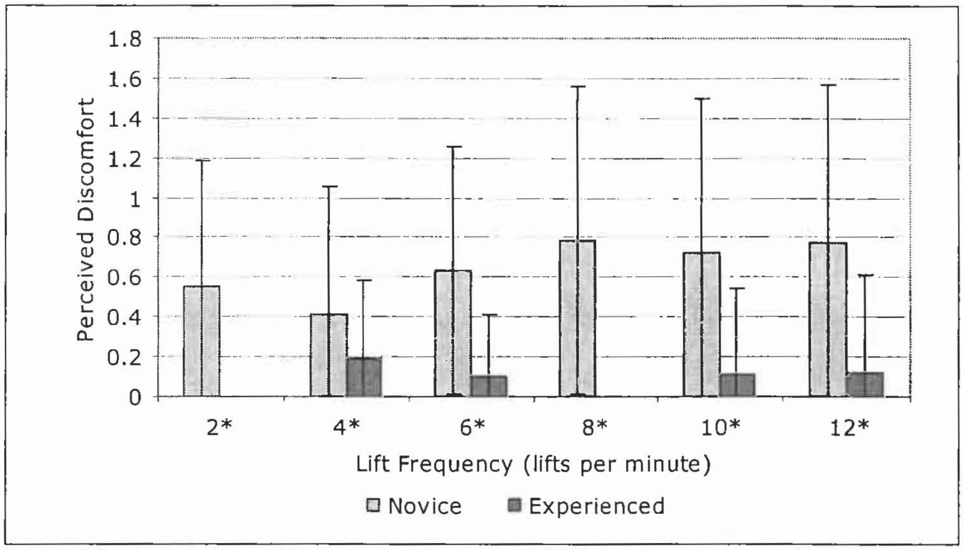

Figure 4.9: Interactive effect of experience and lift frequency on perceived discomfort (* indicates significant difference between novice and experienced subjects).

Interactive Effect of Frequency and Time

The interactive effect of lift frequency and the time of the workday was significant (p=0.0035). The trends are interesting to note from Figure 4.10. For 2 lpm, there is a linear trend of increasing perceived discomfort as the day progresses. Frequencies 4 and 6 lpm have an increase in discomfort after the fourth hour. For 8, 10, and 12 lpm, the discomfort increased significantly immediately following the first two hours. The significant contrasts for this interaction are listed in Table 4.6.

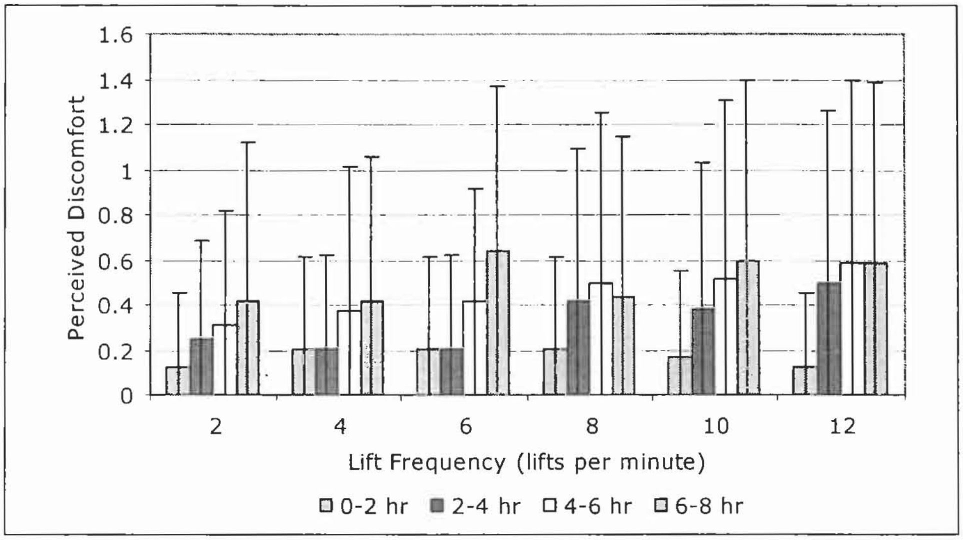

Figure 4.10: Interactive effect of lift frequency and time on perceived discomfort.

Table 4.6: Significant contrasts for the frequency by time effect on perceived discomfort.

Contrast	p-value
2 lpm Hours 0-2 vs. Hours 4-6	0.0284
2 lpm Hours 0-2 vs. Hours 6-8	0.0019
2 lpm Hours 2-4 vs. Hours 6-8	0.0489
4 lpm Hours 0-2 vs. Hours 4-6	0.0489
4 lpm Hours 0-2 vs. Hours 6-8	0.0262
4 lpm Hours 2-4 vs. Hours 4-6	0.0129
4 lpm Hours 2-4 vs. Hours 6-8	0.0139
6 lpm Hours 0-2 vs. Hours 4-6	0.0139
6 lpm Hours 0-2 vs. Hours 6-8	<0.0001
6 lpm Hours 2-4 vs. Hours 4-6	0.0019
6 lpm Hours 2-4 vs. Hours 6-8	<0.0001
6 lpm Hours 4-6 vs. Hours 6-8	0.0013
8 lpm Hours 0-2 vs. Hours 2-4	0.0019
8 lpm Hours 0-2 vs. Hours 4-6	0.0006
8 lpm Hours 0-2 vs. Hours 6-8	0.0143
10 lpm Hours 0-2 vs. Hours 2-4	0.0016
10 lpm Hours 0-2 vs. Hours 4-6	<0.0001
10 lpm Hours 0-2 vs. Hours 6-8	<0.0001
10 lpm Hours 2-4 vs. Hours 4-6	0.0408
10 lpm Hours 2-4 vs. Hours 6-8	0.0125
12 lpm Hours 0-2 vs. Hours 2-4	<0.0001
12 lpm Hours 0-2 vs. Hours 4-6	<0.0001
12 lpm Hours 0-2 vs. Hours 6-8	<0.0001

5. Results – Spinal Loading Throughout the Lifting Conditions

The Mixed ANOVA model results indicated that the three-dimensions of spinal loading were affected by different factors as shown in Table 5.1. Compression was significantly affected by the level of moment, level of experience, level of time, interaction of moment and experience, and interaction of moment and frequency. AP shear was significantly affected by the interaction of moment and time. Lateral shear was affected by the level of frequency, interaction of experience and frequency, and the interaction of experience and frequency with moment.

Table 5.1: Mixed model for effects of experimental task variables on spinal loading.

Mixed ANOVA Model p-values for Spinal Loading			
Effect	**Compression**	**AP Shear**	**Lateral Shear**
w	0.0002	0.4802	0.4331
exp	0.0043	0.4962	0.0663
exp*w	0.0432	0.2108	0.0971
f	0.8448	0.2426	<0.0001
f*w	0.0024	0.9258	0.1798
exp*f	0.2621	0.9260	<0.0001
exp*f*w	---	0.2009	0.0015
b	0.0042	0.7190	0.9517
b*w	0.4255	0.0263	0.6527
exp*b	0.3759	0.8624	0.1701
exp*w*b	---	0.0935	0.9241
f*b	0.4034	0.9145	0.8478
f*w*b	---	0.1954	0.9579
exp*f*b	0.1570	0.5607	0.8838
exp*f*w*b	---	0.1402	0.0750

Shaded values are significant effects at alpha = 0.05
--- term removed for reduced Mixed model

Compression

Main Effect of Moment

The effect of moment on compressive loading was found to be significant at p=0.0002. The least squares means (lsmeans) and corresponding standard deviations (SD) were found for the three levels of moment and are shown in Figure 5.1. A post-hoc analysis was done to determine which pairwise differences were significant among the three moment levels and to estimate the difference. All moment levels were found to be significantly different from each other. When 8 Nm was contrasted with 36 Nm and 85 Nm, the lower moment level yielded decreased normalized compression values than the higher levels ($p=0.0087$ and $p<0.0001$, respectively). 36 Nm had significantly lower compression values than 85 Nm ($p=0.0294$). As expected, compressive loads increased with increasing moment levels. The 85 Nm level had 12% greater compression than the 36 Nm level and 24% greater compression than the 8 Nm level. Likewise, the 36 Nm level had 14% greater compression than the 8 Nm level.

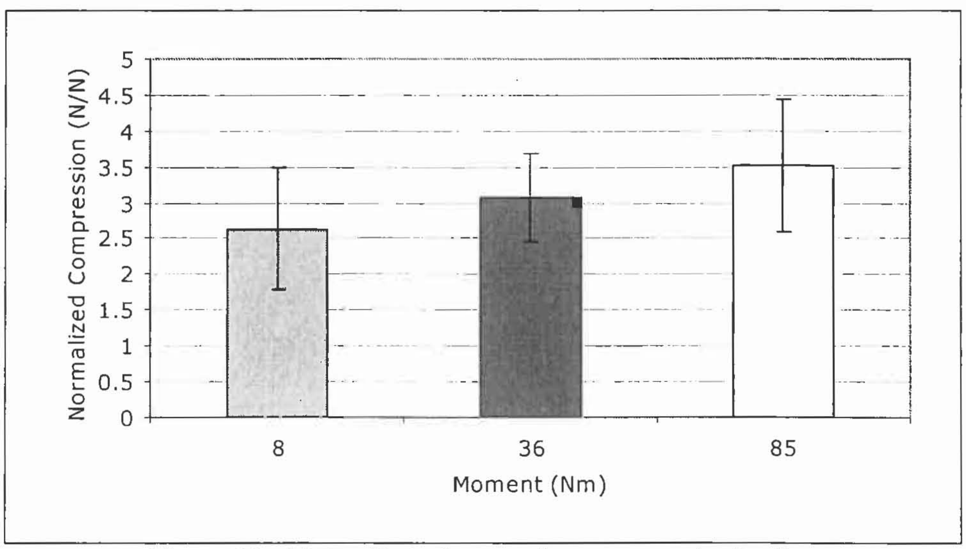

Figure 5.1: Main effect of moment on compressive loading (N/N represents normalized to body weight).

Main Effect of Experience

The main effect of experience on compression was found to be significant at p=0.0043. The lsmeans and SD for novice and experienced levels are shown in Figure 5.2. Compression was 13% less in the experienced group compared to the novice group.

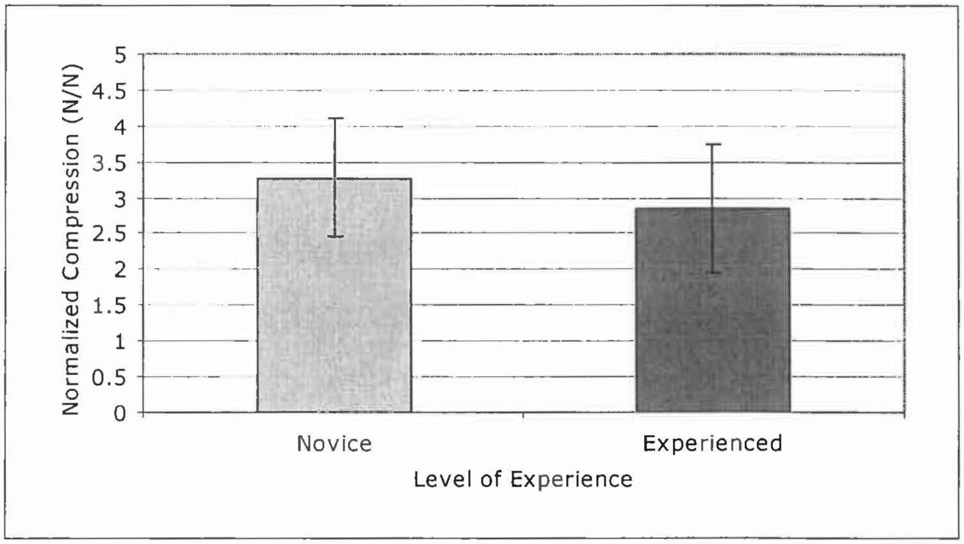

Figure 5.2: Main effect of experience on compressive loading (N/N represents normalized to body weight).

Main Effect of Time

The main effect of time on compression was found to be significant at p=0.0042. Compression increased significantly after the first two hours of exposure and remained relatively constant throughout the rest of the day. The lsmeans and SD for the 4 levels of time are shown in Figure 5.3. Post-hoc analyses confirmed that hours 0-2 were significantly different from the remainder of the workday. When hours 0-2 were contrasted with hours 2-4 (p=0.0060), hours 4-6 (p=0.0345), and hours 6-8 (p=0.0015), it was found that subjects had significantly lower compression during the first two hours.

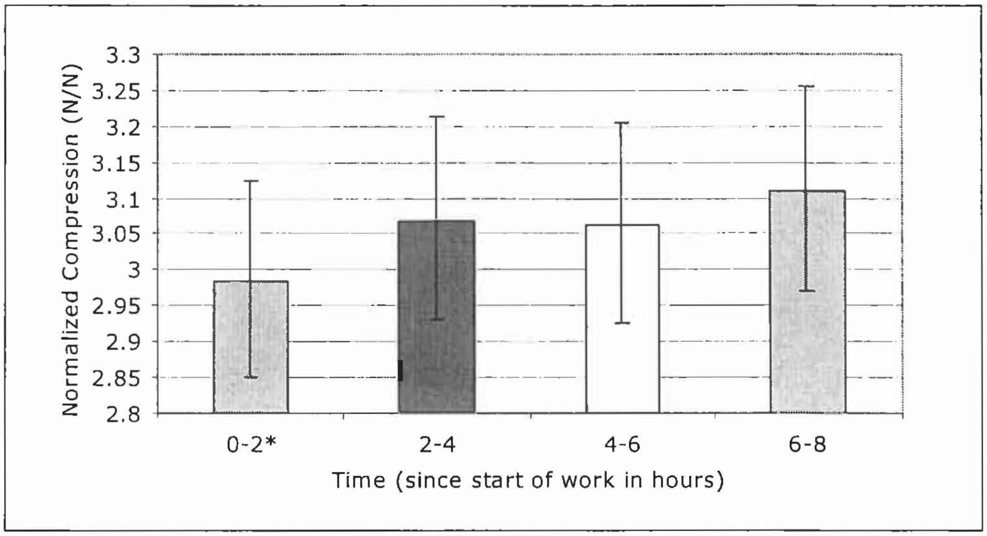

Figure 5.3: Main effect of time of day on compressive loading (* indicates significantly different from other time blocks) (N/N represents normalized to body weight).

Interactive Effect of Moment and Experience

The moment*experience interactive effect on compression was found to be significant at $p<0.0432$. Differences in the compressive load between novice and experienced lifters were greatest for low moment levels and decreased with increasing load. In fact, the difference in compressive loads between experience levels is only statistically significant for 8 Nm ($p=0.0008$). Several significant comparisons were found when comparing weight levels within the experienced workers (Table 5.2). Figure 5.4 shows the normalized compression lsmeans and SD for the levels of the moment and experience interaction.

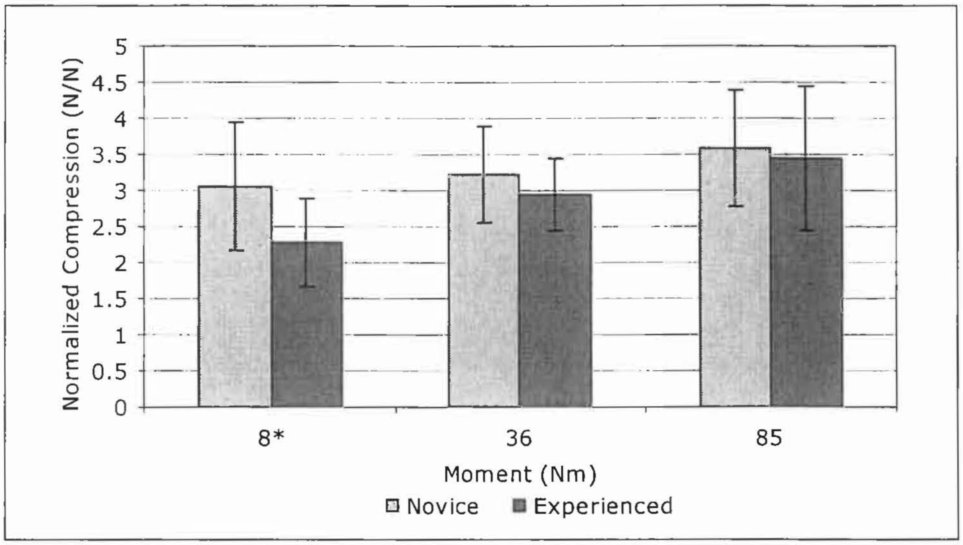

Figure 5.4: Interactive effect of moment and experience on compressive loading (* indicates significant difference between novice and experienced subjects) (N/N represents normalized to body weight).

Table 5.2: Significant contrasts of the moment by experience effect on compression.

	Contrast	p-value
Experienced	8 Nm vs. 36 Nm	0.0032
Experienced	8 Nm vs. 85 Nm	<0.0001
Experienced	36 Nm vs. 85 Nm	0.0376
8Nm	Novice vs. Experienced	0.0008

Interactive Effect of Moment and Frequency

The moment*frequency interactive effect on compression was found to be significant at p=0.0024. The lsmeans and SD for this interactive effect are shown in Figure 5.5. Although it is quite evident from Figure 5.5 that increasing moments caused the compression on the spine to increase, the same trend is not true for increasing lift frequencies. For 8 Nm, 8 lifts per minute (lpm) yielded the highest compression. Regardless of lift frequency, compressive loads remained at approximately three times that of body weight for 36 Nm. For 85 Nm, 10 lpm caused the highest compressive loads and this lift frequency was significantly different from 12 lpm. Table 5.3 provides a summary of the significant contrasts for this interactive effect.