ABSTRACT

Drum, Jonathan Everett. An Investigation of the Effects of Fatigue and Stance Width on Horizontal Ground Reaction Forces and Trunk Kinematics (Under the Direction of Dr. Gary A. Mirka)

Manual material handling (MMH) is often required in challenging outdoor environments (e.g. agriculture and construction) that may require fatiguing, repetitive lifting while standing on slippery ground surfaces. Slips and falls can result in a variety of injuries as a result of both the impact of the fall and extreme muscular forces used to attempt to counteract a fall. Few studies have explored the effects of a fatiguing lifting task on slip potential. The goal of the study was to assess the effects of fatigue and stance width on ground reaction forces and trunk motion during an asymmetric, repetitive lifting task.

Twelve individuals participated in this study. They were required to lift a load equal to 40% of their maximum lifting capacity at an angle of 45 degrees in the transverse plane. Participants lifted the load (eccentric followed by concentric) for 10 minutes at a rate of 12 lifts per minute. Stance was changed once per minute from shoulder width to twice shoulder width or vice versa. Ground reaction forces were recorded using a force plate for each foot, and trunk motion data were recorded by using a Lumbar Motion Monitor (LMM). Fatigue was verified by both electromyographic (EMG) median frequency shift of the erector spinae muscle group and a verbal questionnaire. MANOVA and ANOVA statistical analysis techniques were used to analyze these data, and the modified Levene's test was used to identify changes in variability of the dependent measures as a result of the main effects.

The results showed a statistically significant ($p < 0.05$) increase in lateral ground reaction forces (from 43 N to 51 N) as Time into the lifting task increased in the narrow

stance. Stance was also found to affect lateral shear forces (resulting in an increase from about 40 N to about 80 N as stance width doubled) and anteroposterior shear forces (decreased from 40 N to 30 N as stance width doubled). Further, Time into the lifting task resulted in parabolic shifts in peak sagittal flexion (ranging from 75 degrees at the beginning and end to 70 degrees in the middle of the trial) and peak sagittal acceleration (ranging from around 600 deg/s^2 at the beginning and end of trials to around 540 deg/s^2 in the middle) in both stances. Coronal peak flexion followed a similar parabolic pattern with respect to Time in the wide stance (10 degrees at the beginning and end and 8.5 degrees in the middle), but showed a decreasing trend in the narrow stance (moving from 9 degrees in the first Time block to 8 degrees by the final Time period). Coronal acceleration was found to increase slightly as a function of Time in the narrow stance (moving from 61 deg/s^2 to 68 deg/s^2).

The results of the study indicate clear, but small magnitude , increases in shear forces due to Time into task, but only in the narrow stance. Even larger increases in shear forces are shown as a result of the change from a narrow to a wider stance. In order for the recorded shear forces to cause a slip, the coefficient of friction would have to be very low. Employers in industries such as agriculture and construction, who occasionally work on wet, icy, or muddy ground, should take caution to help limit employees' fatigue and teach proper lifting techniques with a shoulder-width stance.

Ultimately, this research can be used to further the information base on the effects of fatigue on external ground reaction forces. These results are largely consistent with similar studies, and it is hoped that, with those studies, more accurate and safe lifting techniques and guides may be developed.

An Investigation of the Effects of Fatigue and Stance Width on Horizontal Ground Reaction Forces and Trunk Kinematics

By

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Biography

Jonathan Everett Drum was born on October 22, 1980 in Hickory, North Carolina. He moved with his family to Catawba, North Carolina, where he graduated from Bandys High School in 1999. He enrolled as an undergraduate at North Carolina State University in the autumn of 1999, and, after much deliberation and curriculum changing, he graduated with a Bachelor's Degree in Mechanical Engineering in 2003. Jonathan began his graduate studies in the Industrial Engineering Department at NCSU in the autumn of 2003. His concentration of study was ergonomics with a minor in interdisciplinary studies. Since the defense of this thesis, Jonathan has accepted a position working for the United States Army Center for Health Promotion and Preventative Medicine as an ergonomist. He currently lives in Abingdon, Maryland.

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1.0 Introduction

Manual material handling (MMH) has been a part of the human workplace throughout the course of recorded history. From the construction of the pyramids at Giza to the Roman Coliseum, building materials and supplies were transported, handled, and manipulated predominately by hand. Similarly manually intensive were the agricultural bases required to feed masses of builders. From the fields of Greece to the American South, countless farm hands have toiled endlessly harvesting crops and raising livestock, often to the detriment of their own health. Despite the technological innovations that have been developed since the collapse of these societies with regard to transportation, production, and communication, relatively few pivotal events have occurred on either the construction or the farming fronts to fundamentally alter the way the work was performed. Twenty-first century farms still require masses of employees to work the land, harvest crops, and handle animals, and the construction of modern behemoth structures like the Gateway Arch and the English Channel Tunnel required the used of hundreds of manual laborers.

The persistent human dependence on manual labor might lead one to believe that perhaps the conditions of labor have achieved an equilibrium or a plateau, where there is simply no better way to perform such tasks, that any technological innovations would only harm construction, farming, or industrial processes by making them slower or more expensive. In previous societies, it was the case that these industries could not have been improved not only because much of the supporting technology did not exist, but also because those societies were not terribly concerned with the welfare of workers or the cost of any injuries they incurred. That is because those societies relied chiefly on a work force composed of slaves or serfs who were not protected by workers' compensation laws and company insurance policies. In today's society, injury costs are high for many industries, farming and construction among them. Companies with high casualty rates acquire increased medical expenses which must be passed to consumers in order for them to make profits.

1.1 The Dangers of MMH

Humans move things every day; books, computers, bar bells, and even desks or tables are all things that an individual might find him or herself lifting, carrying, or lowering over the course of a day. Despite all our lifting and moving of objects, some of them quite heavy, many people manage to escape unharmed. However, a number of people do find themselves injured when moving objects in an industrial setting. From lift induced back injuries to trips and falls, material handling can have painful and costly side effects. So what then, is it that can cause materials handling to change from the realm of the mundane to the realm of injury?

1.1.1 Lifting

The principal component of material handling is the lift. While there are numerous ways to move objects via machine, a human is often part of the loop in places where a machine is too large or too clumsy to operate. Therefore, to move a product from one place to another, it generally has to be raised from its starting position, lowered from its starting position, or both.

One of the principal problems associated with lifting is low back pain (LBP), located around the lumbar region of the spine, or general back pain, located in the thoracic or cervical regions of the back. Presently, back pain and low back pain are frequently referred to in both industrial and academic literature with varying degrees of clarity and prevalence. Despite any discrepancies in frequency and definition, however, both are generally regarded as serious conditions which can affect productivity and quality of life for those afflicted. As the goal of many design and ergonomics projects is to eliminate LBP from a work environment, the design engineer or ergonomist must have a clear definition of LBP, as well as accurate data as to its prevalence and causes within the workplace.

Low back pain is best defined as pain in the spine or muscles of the low back (in the lumbar or sacral region of the spine), muscle stiffness in the low back region, or muscle tension in the lower back. While many incidences of LBP are a result of an evident pathology, some are still classified as nonspecific LBP if the injury pathway is not clear.

Low back pain is generally regarded to be a significant occupational problem throughout the world in both industrial and agricultural environments. It has been estimated that the lifetime prevalence for a single episode of severe low back pain is between 60 and 90 percent of all individuals (Korff et al. 1988, Andersson 1998, Levin et al. 2001). Further, there is a nearly 14 percent lifetime prevalence rate of an individual having an episode of significant LBP lasting longer than two weeks (Deyo et al. 1987). Back pain has become so large a problem that it is responsible for 25 percent of all lost workdays in the United States in the late 1990s (Levin et al. 2001). Data from 1988 show that there were around 175.8 million restricted workdays related to spinal and back disorders (Andersson 1991, Frymoyer et al. 1991, Deyo et al. 1992). The following year, an estimated $11 billion were paid to LBP victims in the form of workers' compensation (Webster and Snook 1994).

Deyo, Cherkin, Conrad, and Volinn (1991) conducted a review of 86 sources to combine low back pain statistics. According to the authors, LBP affects between 70% and 80% of adults at some point in their lives. A vast majority of those cases (90%) last six weeks or less, which is still a considerable amount of time if it causes a person to be absent from work. The high rate of back pain development resulted in an estimated cost of 12.9 million dollars in 1977 (equivalent to 41.8 million dollars in 2005 when adjusted for inflation). In 1984, approximately 1.7 million individuals reported they missed work due to LBP. The authors reported that researchers from Liberty Mutual Insurance Company found that the company’s total compensation payments totaled approximately 11.1 million dollars in 1986.

1.2 Risk Factors for Injury

Clearly, back pain has caused a substantial amount of physical and fiscal pain in the United States over the past thirty years. One can only imagine what injury statistics must be like in the developing countries of Asia and Africa, where many of the mechanical assist devices present in American industries have yet to be employed. Such staggering injury and cost data are taken very seriously by engineers, ergonomists, and managers alike, but they cannot be remedied without first understanding their root causes. In his guide to LBP for primary care physicians, Devereaux (2004) compiled a list of many of the risk factors leading to back pain as well as methods for treatment. He listed the following risk factors associated with acute and chronic LBP: age, heavy physical work, holding static postures, heavy lifting, twisting, vibration, psychosocial factors, depression, obesity, smoking, severe scoliosis, drug abuse, and history of headache. He also listed false risk factors for LBP which have been thought to be contributors in the past: Anthropometric variables, posture, modest scoliosis, lordosis, gender, and state of physical fitness. He failed to exclude static postures, for which there is insufficient evidence of their contribution to LBP (NIOSH 1997).

Of the sources of back pain Devereaux (2004) named, some are clearly outside the scope of the abilities of the design engineer. Namely, factors such as depression, age, obesity, and other psychosocial factors can only be used as a measure for screening candidates for a job. However, it should be the objective of design engineers to design lifting work environments which account for human limitations with respect to heavy physical work, static work postures, heavy lifting, twisting, and vibrations. A significant amount of work has gone into each of these areas over the past twenty years. The National Institute for Occupational Safety and Health (NIOSH) compiled many of the available studies to create general recommendations with regard to each.

1.2.1 Vibrations

Whole body vibrations (WBV) are cyclical mechanical energy waves that pass through the body of a worker, most often when he or she is operating heavy machinery such as a jack hammer or a vehicle. NIOSH (1997) reviewed 19 studies in order to determine how WBV might affect back injury or back pain. While four of the subjective studies were found to show no evidence to a causal relationship, the remaining 15 studies, both subjective and objective, found odds ratios between 1.2 and 39.5 for the risk of developing a back injury as a result of whole body vibration. NIOSH (1997) also noted that evidence existed to suggest WBV may combine with prolonged sitting, heavy lifting, and awkward postures in order to increase the probability of developing a back injury. It was also noted that the source of vibration may also be an important factor in determining the extent of risk or injury, though most often researchers did not break down their data by source.

1.2.2 Bending and Twisting

Bending and twisting occurs when individuals are required to move the trunk in transverse plane while also flexing the trunk in the sagittal plane, the coronal plane, or both. NIOSH (1997) also included kneeling, squatting, and stooping in its definition. It its review of the available literature, NIOSH (1997) found sufficient evidence that back disorder risk increases with exposure to awkward postures. Of the 12 studies reviewed, three showed odds ratios above three for developing back disorders with exposure to awkward postures. Further, NIOSH (1997) noted that many of the studies suggested that lifting, in conjunction with awkward postures, could lead to even higher risks of injury.

One of the stronger cases against awkward postures, not even extreme postures, as a cause for back pain came from the research of Burdorf et al. in 1991. Burdorf and others (1991) attempted to determine factors in postural load that were at least partially responsible for the development of low back pain in concrete workers. The authors selected 114 individuals in a prefabricated concrete factory as participants for their analysis. For the purposes of the experiment, worker jobs were divided into five categories: steel benders, operators (responsible fro pouring and finishing concrete products), model makers (responsible for building patterns out of wood), maintenance personnel, and a miscellaneous group (managers, fork truck drivers, etc.). The authors also used a control group of 52 persons from an engine manufacturing and repair facility. The control group's job was considered comparable to the job of the maintenance personnel in the concrete facility. With this control group selected, the authors would be able to establish what specifically occurred in the concrete industry that caused back injury. Rather than use a electro-mechanical observation and evaluation system, the authors employed an observation technique (Ovako Working posture Analysis System or OWAS) in which a skilled observer recorded subject posture every twenty seconds (This ensured the inclusion of all postures, but, as it was not random, makes it very difficult to determine the amount of time a subject spent in each posture. The authors claim otherwise.). Using the OWAS codes for recorded postures, each posture was categorized in one of four groups: 1) normal postures, 2) slightly harmful postures, 3) distinctly harmful postures, 4) extremely harmful postures.

In addition to the OWAS analysis technique, the researchers contracted an occupational physician to conduct a survey of the participants to obtain personal, employment, and injury history information. The authors defined back pain as any pain in the back that had lasted for at least "a few" hours at any point during the past year. The authors also included questions about previous employment, but made no mention of questioning worker hobbies to screen for alternate causes of LBP.

The results of the OWAS analysis showed that members of the steel bender and operator groups spent around 50 % of the observed time in a slightly harmful posture. This is compared to 38% for the model makers, 37% for the maintenance group, 14% for the miscellaneous group, and 27% for the control group.

According to the surveys, the authors found that 59% of all the concrete workers reported back pain at least once in the previous year (that number rose as high as 74% in the operators group). A majority of workers with back pain reported having more than two instances during the previous year. With respect to specific episodes of LBP, 50% of episodes lasted one week or less, 20% lasted between 8 and 30 days, and 30% lasted for more than 30 days. Additionally, 37% of workers had taken sick leave as a result of their pain, and 46% of workers with back pain sought medical attention.

Within each workgroup, the authors conducted a logistic regression and concluded that the amount of time spent in a bending and/or twisted posture (OWAS category 2) was positively correlated with reported back pain and medical visitation. The results of the analysis also suggest that whole body vibration experienced by many of the workers was a predictor of LBP, as the two were highly correlated.

1.2.3 Heavy Physical Work

Heavy physical work consists not only of lifting objects, some of them heavy, but carrying and otherwise manipulating objects with sufficient intensity and duration to be tiring. It has also been defined as high energy work or work that imposes large compressive forces on the spine. Through its literature review, NIOSH (1997) found there to be sufficient evidence that heavy labor did have a correlation to back pain and injury. It was found that the studies which included the effects of temporality between exposure and injury showed the most positive correlations between heavy work and back disorders.

1.2.4 Heavy Lifting and Forceful Movements

Heavy lifting is any lift where an individual moves a subjectively heavy object from one height to another. Forceful movements involve moving subjectively heavy objects in other ways, such as moving a heavy object parallel to the ground, whether holding it in the air or pushing it along the ground. NIOSH (1997) again reviewed 18 studies which dealt with heavy lifting. The reviewers discarded five subjective studies, but found that all of the remaining research pointed to an odds ratio (OR) between 1.2 and 11 for developing a back injury associated with heavy lifting. Further, NIOSH (1997) found that groups who lifted heavy objects more frequently experienced even higher rates of injury than those groups exposed to sporadic heavy lifting.

1.3 Lifting in Outdoor Environments

The risk factors for LBP exist in many industries worldwide, from furniture manufacturing to mining. However, in certain industries, such as agriculture or construction, additional risk factors are present. A summary of the unique characteristics of these two industries is presented in the following two sections (Sections 1.3.1 and 1.3.2). The next two sections (Sections 1.3.3 and 1.3.4) focus on the specific risk factors for low back injury in these industries and provide a more detailed overview of the relevant literature.

1.3.1 Nature of Agricultural Work

The majority of farms in the United States are small, family-owned businesses. They can be divided into four categories: crop farms, livestock farms, horticulture farms and aquaculture facilities. On a crop farm, work responsibilities include preparing seed and equipment, tilling soil, planting crops, fertilizing crops, cultivating crops, spraying pesticides, harvesting, packaging and transporting crops. On livestock farms, farmers must feed and care for animals, clean barns, stables, and coops, and oversee breeding and other business activities. Horticultural farmers plant and cultivate ornamental plants, nursery products, and fruits and vegetables grown in greenhouses. Aquaculture farmers feed and raise fish and shellfish in a variety of different marine environments.

Specifically in the case of livestock farms, the work is strenuous and persists year round. Most cattle, unless grazing, must be fed and watered daily. Feeding often involves transporting feed around the farm in a truck, then using a pitchfork to move the feed from the truck to feeding troughs. From personal observation, lifting and moving the feed is fairly heavy work. In dairy operations, cows must be milked two to three times per day. In smaller farm operations, this is a largely manual process involving handling cows and awkward postures of the back and shoulders while connecting milking machines to the udders of the cows. Farmers on both dairy and beef cattle farms are also involved in the upkeep of their herds, including help in birthing and weighing newborn calves. Birthing and weighing calves both involve lifting calves which typically weigh 360 N or more and are fighting the farmer, which creates additional dynamic forces on the body of the farmer.

Specifically in crop farming, a large portion of work takes place in the field. In harvesting ground crops such as potatoes or strawberries, farm hands can spend many hours on their feet with their trunks flexed nearly 90 degrees so that their hands can reach the crops. Also dangerous is the fact that farmers are also involved in lifting and carrying large, heavy buckets or baskets of harvested crops while in the field. Additionally, workers are exposed to extreme temperatures and poor footing conditions brought about by wet soil. These poor postures, heavy lifting, heavy work, and slippery conditions can lead to back disorders as previously mentioned, or to acute injury as the result of a slip and fall. (Source: BLS: www.bls.gov/oco/pdf/ocos176.pdf *Farmers, Ranchers, and Agricultural Managers*)

1.3.2 Nature of Construction Work

The nature of construction work varies widely depending upon what the workers are building, whether it be highway construction, tunnel excavation, hazardous waste removal, or demolition. Responsibilities of highway workers include clearing work zones, installing barricades and cones, and traffic control. At hazardous waste sites, workers are involved in removal of asbestos, radioactive wastes, and heavy metals. These activities often require workers to lift or move heavy objects, such as barricades and cones. When done by hand, these activities clearly fall into the category of heavy lifting and heavy physical work. When done by the use of machine, this work can result in exposure to WBV. In the construction of buildings and homes, workers are often required to lift heavy objects like shingles, which can then be transported up ladders.

This type of work can result in exposure to heavy lifting and awkward postures in addition to the risk of a slip on a ladder which could be wet or icy due to precipitation.

Equipment often used by highway and building construction workers includes pavement breakers, jackhammers, concrete mixers, pavement tampers, electric and hydraulic boring machines, torches, hoists, and surveying equipment. Using these heavy machines exposes workers not only to vibration, but also to heavy lifting and forceful movements needed to wield them. Some jobs require laborers to work outdoors in all conditions, including wet and icy weather. In hot weather, the nature of the work can more easily cross into the realm of heavy physical work, as the additional heat requires the body to work harder. In cold weather, workers may be exposed to icy or wet conditions on ladders or beams, which could cause them to slip and fall. (source: BLS: www.bls.gov/oco/pdf/ocos178.pdf)

1.3.3 Slips, Trips, and Falls

Occasionally in industrial environments contaminants are spilled on the floor of the facility, causing a surface with a low coefficient of friction. However, slippery surfaces are more common in outdoor environment, as rain and snow occur quite frequently. Because jobs such as harvesting or bricklaying often take place in active precipitation, the ground may remain somewhat wet for hours or days after precipitation, creating a lifting and walking surface which may be both uneven and slick.

The root cause for any slip and fall is insufficient friction at the shoe-ground interface to counterbalance inertial forces in the body caused by walking or any other outside disturbance. Some have defined a slip as "a sudden loss of grip, often in the presence of liquid or solid contaminants and resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity" (Gronqvist et al. 2001).

Factors that can create a situation where there is limited friction are slippery coatings on the ground and excessive forces acting on the body. Substances that can make a surface slippery in outdoor environments include sand, oil, and mud to name a few. Excessive forces acting on the body can be generated by an individual himself in trying to correct for a balance loss, or they can also be generated by an outside force striking, pushing, pulling, or otherwise acting on the lifter. Additional factors other than liquids or solids which can cause slipping include insufficient lighting, poor housekeeping, aging, neuromuscular dysfunction, alcohol, drugs, physical fatigue, etc. More specific to the mechanics of falls, Gronqvist (2001) mentioned tripping, stumbling, missed footing, and collapsed surface as mechanical causes of falls in addition to the foot contacting an unexpectedly low friction substance covering the floor (Gronqvist et al. 2001).

There are many instances in literature where slip-and-fall or trip-and-fall events led to the onset and report of back pain in industry. This is likely due not to the impact, but to the overexertion of the trunk musculature when trying to correct body posture and momentum in order to prevent a fall. Some research suggests that individuals can create very large forces in the muscle groups around the spine when trying to avoid falling. Studies by Manning et al. (1984) and Manning and Shannon (1981) found that 67% of all accident related LBP was related to slip and fall accidents. Another study by Murphy and

Courtney (2000) found that 21% of LBP medical costs were distributed to people whose pain was a direct result of a fall.

With regard to the mechanics of slipping, tripping, and falling, nearly all research has been conducted in the areas of pushing or walking, not lifting. In one such study concerning the effects of low coefficient floors, Ciriello, McGorry, and Martin (2001) examined the three dimensional forces between the feet and the floor while participants pushed a cart along floors with varying coefficients of friction. The cart pushed by the participants was loaded with differing amounts of water for each trial so that it had a mass ranging from 262 to 780 kg. The participants were instructed to push on two handles which were attached to four load cells each. These load cells measured horizontal and vertical forces exerted by the subject on the push cart. During each push, the experimenters recorded the initial force needed to overcome static friction (the maximum force recorded during the first 1 second of pushing) as well as the sustained force required to overcome sliding friction (average force while the cart was in motion, beginning one half second after the initial force was recorded).

The experiment described in this article was only part of a 19-day, multipart experiment. During the portion of the experiment testing the effect of coefficient of friction (COF), the participants performed 40 pushes (two, 20-minute segments) on the high COF surface and 20 pushes (one, 20 minute segment) on the low COF surface. Pushes were conducted once per minute for a total distance of 7.6 meters. The participants were given two hours of practice time, and the beginning weights for each trial were selected at random. The participants were allowed to change the weights during the trials to what they believed they could push during an eight hour shift without becoming unduly fatigued. Some participants were given high cart weight ranges and others were given low ranges. The ranges, high and low, were alternated from one subject to the next. The three dimensional force values were averaged for the pushes where the subject retained a constant cart weight. Up to ten of the push trials were averaged.

The authors found that the participants' preferred cart weight was significantly lower (31 %) in the low friction environment than on the high friction surface. As a result, the initial and sustained forces were lower in the low friction environment (41 % and 38 %, respectively). The experimenters also measured the probability of slipping for each subject, based upon a linear regression model. In the high friction environment ($\mu_s = 0.68$), the COF required to prevent a slip was calculated to be 0.321, and the probability of slip was calculated to be 7.4 %. Using the low friction surface ($\mu_s = 0.26$), the COF needed to prevent a slip was calculated to be 0.193, resulting in a slipping probability of 77.5 % in the linear slip model. Interestingly, while the COF of the low friction environment was deemed dangerous when encountered in an industrial environment, no falls were recorded during any portion of the experiment.

While no falls were reported, it should be noted that the participants were allowed to determine a comfortable weight to push; it is unlikely they would choose a weight which would cause them to lose balance and fall. Also, participants had the benefit of using the cart to stabilize themselves when slips were initiated. In a scenario where participants were carrying a load over such a slippery surface, it is possible that the additional inertia caused by the carried object could cause a force of slip from which the subject would be unable to recover.

Beyond individual weight preferences, Cham and Redfern (2002) examined how body kinematics are affected when a person comes in contact with a slippery surface during normal walking. The goal of the authors' study was to determine if individuals change gait mechanics when told that there is a possibility that the walking surface will be slick or slippery. The authors recorded three dimensional body motion using an OPTOTRAK 3020 system. Additionally, they recorded three dimensional force and moment data regarding the interface between the participants' left foot and the floor using a force plate.

During the experiment, the independent variables were ramp angle (0, 5, or 10 degrees of incline), floor type (vinyl tile, smooth painted plywood, and rough painted plywood), and trial type (baseline, unknown, and recovery). During the baseline and recovery trials, the participants knew that the floor was dry. During the unknown trials, the participants were told that a slippery condition might exist. The recovery trials always followed trials that were slippery. All participants wore the same type of shoe which had PVC hard soles. The experimenters recorded and calculated a variety of dependent variables, including shear forces in the anterior-posterior (A-P) direction, normal force, joint angles, required coefficient of friction (RCOF is the ratio of shear force to normal force), etc. The RCOF is one of the most important characteristics of this ground-shoe interface. At any point where the RCOF is greater than the static coefficient of friction between a person's foot and floor, a slip is very likely.

With regard to the anticipation effect on kinetic and kinematic data, the data showed that while similarly shaped curves governed each of the trial types, the magnitude and timing of normal force, A-P force, and RCOF curves were significantly different between types for each of the three angle conditions. Most notably, the authors found RCOFs that were between 16 % and 33 % less in the anticipatory trial type than the baseline ramp conditions. Additionally, the A-P shear forces in the anticipatory condition were between 17 % and 40 % lower than the shear forces in the baseline trials. The peak normal ground reaction forces were also lower in the anticipatory trials, with a reduction from 2 % to 13 %, depending upon ramp angle. The authors then decided to further examine exactly how participants were able to decrease RCOF and, consequently, their risk of slipping. By analyzing the captured motion data, they were able to determine that participants routinely took smaller strides and reduced heel acceleration, which led to a slower rate of foot loading as well as decreased A-P shear force due to the decreased angle of the leg vector.

Ultimately, the literature suggests that when working on a slippery surface, an individual who knows how slick the surface is will tend to be more cautious if given the opportunity. He will take smaller steps, move more slowly, and handle less weight than he would in an environment where he had high-friction footing. However, the literature has all focused on slipping while the body was already in motion as is walking. One is still left to wonder about the human performance response in an agricultural, construction or other outdoor work environment where a worker is required to repetitively lift heavy loads, perhaps with awkward postures, on a surface where the coefficient of friction was sufficiently low as to cause the possibility of a slip. There has been little discussion of how ground reaction forces are affected by internal moments generated by muscles or external moments created by external loading during the act of lifting rather than walking. Further, the question of the effect of fatigue on the nature of the ground reaction forces during a lifting task may shed some light on the risk of a slip and fall event during lifting.

1.3.4 Repetitive Lifting and Fatigue

Throughout the literature, however, there is one risk factor for LBP that not only seems logical, but has been studied extensively, which was neglected by both Devereaux (2004) and NIOSH (1997) in their explanations of the many causes of low back pain and disorders: repetitive lifting. Repetitive lifting does not necessarily imply a heavy load or extreme body positions, but simply the lifting of a load repeatedly for many hours per day for many days or perhaps years, such as the case of many construction or crop farming tasks.

One of the most dangerous scenarios in any environment is lifting a heavy or unstable load in an awkward posture on a low-friction surface. Despite the already high probability of injury for lifting in conditions such as these, the likelihood of injury can be increased by muscular fatigue. Fatigue can occur locally in a specific muscle or muscle group or globally throughout the entire body as a result of high exertion level, high number of repetitions, temperature, and metabolism among others. Fatigue is defined by some as a "reduction in the ability to exert force in response to voluntary effort" (Edwards 1981, Bigland-Ritchie et al. 1995). That loss of voluntary force exertion translates directly into loss of postural control, inability to adequately account for disturbances such as load shifts and slippery surfaces, and the need to recruit alternate muscle groups to perform a given task. It follows that if an individual cannot accurately control his movements, let alone perturbations, it is likely that he could either experience an outside force for which he could not compensate or generate body inertia which he could not stop. Both scenarios would lead to increased horizontal ground reaction forces, and could conceivably lead to either a slip if the coefficient of friction between the feet and the ground were sufficiently low or a tip caused by the center of pressure extending beyond the stable envelope of the foot trapezoid.

Many researchers have studied the effects of fatigue on primary muscle groups. More still have specifically studied the effects of fatigue on the muscles of the erector spinae group in a lifting scenario. One of the first works conducted in this area was conducted by Parnianpour et al. (1988). Being an introductory lab study, the group utilized the constrained environment of the B200 Isostation three-dimensional dynamometer to determine the effects of fatigue on muscles of the trunk. After the participants performed isometric voluntary maximum contractions of the trunk muscles in both directions of all three planes of motion, the resistance in the B200 was set at 70% of maximum for flexion and extension in the sagittal plane, but it was set at a low resistance (7 Nm) for motion in both the transverse and coronal planes. During the fatiguing portion of the experiment, each subject was directed to perform as many flexion and extension cycles as quickly and accurately as possible while moving with maximum effort. The experimenters measured average and maximum torque and velocity, range of motion in three cardinal planes of human trunk motion, and total angular distance traveled in the sagittal plane. For each subject, only data from three lifting cycles were recorded: the first, middle, and last. It is possible that the data would not appear so linear when observed in a continuous manner.

The findings of the research team were interesting with regard to fatigue effects in the different planes. As expected, it was found that maximum and average torque in the sagittal plane was significantly affected by fatigue. It was also found that range of motion in all planes were significantly affected by fatigue. Practically, while the ranges of motion in all planes were affected by a similar amount (4-7 degrees per cycle), the ranges of motion in the coronal and transverse planes increased as the range of motion in the sagittal plane decreased. The magnitude of sagittal range of motion was between 60 and 67 degrees, while the range of motion in the coronal and transverse planes were 5 to 10 degrees and 4 to 8 degrees, respectively. With respect to trunk velocity, it was discovered that both maximum and average velocities in the sagittal and coronal planes were varied significantly with fatigue. Similarly to the range of motion, sagittal velocities decreased with fatigue while coronal velocities increased with fatigue. An identical trend was found in total angular excursion with regard to the sagittal and coronal planes.

Ultimately, the authors point to the lack of lift uniformity and increase in motion as a function of fatigue to be the most significant results. This is because the individual is less able to deal with external perturbations due to the decreased strength and reaction capacity of fatigued muscles. The lack of neuromuscular control also prevents the trunk muscles from stiffening in order to protect the passive tissue. The authors assign the decreased range of motion and velocity in the sagittal plane to decreased muscle contraction rate and subsequent inability to perform the task. They attribute the increased motion and velocity in the coronal plane to decreasing muscular coordination caused by time delays in neuromuscular system due to fatigue.

With regard to the participants' loss of strength of muscles in the sagittal plane and loss of coordination with muscles in motion in the coronal plane, the increasing coronal velocity as a function of fatigue also implies an increasing coronal acceleration over time. This increased lateral acceleration would, by definition, require an increased force or torque to stop coronal trunk motion before the subject became unstable and fell. The only available means for the subject to stop himself during the previous experiment was to exert a lateral force against the floor with his feet in the direction of trunk motion. This force was then transferred through the legs and spine as a stabilizing torque. It is conceivable that lateral acceleration could reach a point where a large enough lateral foot force were required which would exceed the static friction between the floor and the participants' shoes. Practically, due to high friction shoe soles and the substantial weight of most individuals, the coefficient of friction would need to be quite low (similar to wet soil or ice) for such a fatigue-caused slip to occur.

Because the study by Parnianpour et al. (1988) was so constrained in terms of the apparatus used to control and measure the sagittal trunk motion, there were concerns about the generalizability of the results. In an effort to achieve the same types of postural deviations in a more realistic MMH environment, Sparto and colleagues (1997) conducted a similar fatiguing study in which the subject was not confined to a B200 type device, but was instead allowed to lift freely. In this endurance study, the independent variable was fatigue. The experimenters measured body kinematics and kinetics using a Lumbar Motion Monitor, LIDO lift lifting simulator, Hip Monitors, Video Surveillance, and a Forceplate. The protocol of the experiment allowed the participants to lift at any rate they chose for as long as they were able. The experimenters verified fatigue by documenting a decline in maximum lifting force as well as hip and lumbosacral torque production. It was found that the ranges of motion of the hip and knee had been significantly reduced by the end of the experiment, and the amount of trunk flexion was greater at the end then the beginning. The authors also noted that participants experienced a loss of postural control as noted by increasing deviations of the center of mass and center of pressure from the starting point, supporting the Parnianpout et al (1988) results. The authors believed that this could lead to a reduction in the stability margin, which in turn would increase the probability of a slip or trip. Further, they stated that because of the lack of postural stability, any fall event would likely be more detrimental to an individual's health than it would be in an unfatigued state. One critical bit of information not included by the authors, however, were the slip forces (i.e. horizontal ground reaction forces) present throughout the lifting task. While the data they recorded lent much insight into the area of postural control during fatigue, there was no mention of shear force, which leads directly to slipping. Without knowing shear forces, it is not possible how likely a slip and fall injury would be.

1.4 Fatigue as a Cause for Increased Horizontal Ground Reaction Forces

In addition to awkward postures and heavy lifting, fatigue and low coefficients of friction in the shoe-ground interface should also be considered when assessing risk of low back injury in industries such as construction and agriculture. Heavy lifting and awkward postures can lead directly to muscle, ligament, or disc damage, while fatigue decreases postural control and opens the window for perturbations to cause increased horizontal GRFs, which could conceivably lead to a slip. While many studies have examined the various pieces of this composite injury puzzle, in only one study have all of these factors been linked together in an empirical assessment of slip potential.

Shu et al (2005) developed a study that built on the foundational work of Parnianpour et al (1988) in that it evaluated the "off-plane" motions (i.e. lateral motions) during a sagittally symmetric, free-dynamic lifting task. A main goal of this research, however, was to analyze more thoroughly what was occurring at the foot-floor interface, thus combining two common risk factors for back injury, fatigue and slip risk. In the study, participants performed a fatiguing lifting task in which they lifted a 0.3 meter cube weighing 45 % of their MVC strength at 60 degrees from vertical. In a sagittally symmetric posture, participants lifted the load 100 times over an eight-minute trial with stance being changed once per minute. (lifts were performed at a rate of 12 lifts per minute with ten seconds allotted each minute for stance adjustment and communication with the participants). The task was targeted to fatigue the multifidus muscles of the erector spinae group. The independent variables were fatigue and stance width. Fatigue was verified by documenting a significant median frequency decrease in the multifidus muscles. Participants' stance width was changed from 75 % to 150 %, or vice versa, of acromion to acromion (a measure of shoulder breadth) distance each minute.

The dependent variables included trunk kinematic data as well as the horizontal ground reaction forces present between the participants' feet and a force plate. Kinematic data were recorded using a magnetic motion tracking system. Ground reaction force (GRF) data were recorded using a four-cell force platform. During the continuous lifting bout, participants were not allowed to let go of the box and were required to change their foot stance between a wide and narrow stance once per minute. The principal goal of the research was to determine if an individual was indeed more susceptible to increased horizontal GRFs as a function of either fatigue or stance, implying increased potential for a slip and fall event. The secondary goal of the study was to document the changes in kinematics as a function of fatigue.

With respect to the kinematic data, the researchers experienced similar results to those of Parnianpour et al (1988), including increasing lateral motion as a function of fatigue. The GRF data, however, were the piece of knowledge that the experimenters were intent on studying. It was found that anteroposterior shear forces increased throughout the lifting bout. The direct cause of this was ascribed to the increased flexion experienced as the time into the experiment increased. As there was no external resistance in the flexion direction, it makes sense that torso flexion angle could increase as fatigued erector spinae muscles became less able to control trunk position or to stop the falling load. The researchers also found that GRFs in the lateral direction increased as a function of both fatigue and stance width.

The principal limitation to the study was that only one force plate was used. Having only one force plate was a drawback because slip force is something that occurs between each foot and the floor separately. By having both feet on the same platform, lateral forces between one foot and the platform would be negated by the force between the other foot and the platform. Therefore, individual lateral shear forces could not be calculated. Instead, the composite of both the positive and negative lateral forces was calculated, resulting in a combined lateral shear force that must necessarily be lower in magnitude than the individual foot lateral shear forces. Recognizing this limitation, the authors hypothesized that, due to the behavior of fatigue-altered trunk motion and the change in leg angle between stances, the trends in the data would remain the same but that maximum shear forces measured for each foot individually would be larger in magnitude than for both feet together. It makes sense that lateral GRFs would increase with stance width if each foot were measured individually, as with one force plate the two lateral forces negated one another. However, it was unclear whether the magnitude of the effect of fatigue on lateral shear forces would increase. It was considered unlikely that the forces in the anteroposterior direction would remain unchanged with the change from one force plate to the use of two. Another limitation of this work is that all tasks were sagittally symmetric lifting tasks. This may limit, somewhat , the interpretation of the data for more realistic three-dimensional lifting tasks seen in the agriculture and construction work environments.

1.5 Purpose and Goals of Current Study

The purpose of this study was to evaluate the impact of a repetitive, fatiguing, asymmetric lifting task on ground reaction forces and trunk kinematics as a function of time. Also of interest was how the fatigue that was developed would impact the variability in these human performance measures. By determining the relationship between fatigue and stance and ground reaction forces and trunk kinematics, it was hoped that the potential slipping danger in a low coefficient of friction environment could be inferred.

My hypothesis concerning the ground reaction forces was that the behavior of both the peak lateral and anteroposterior shear forces would be similar to those in the Shu et al. study (i.e. they would increase as a function of time). Further, it was expected that stance would impact the peak lateral forces with the wide stance generating higher lateral forces, but no effect of stance width was expected in the anterior-posterior direction. In terms of trunk motion effects, fatigue would increase the peak values of position and acceleration in the sagittal and coronal planes but stance would have no significant effect. Finally, it was hypothesized that variability of these measures would increase all shear forces and trunk motion to become more variable as time into the lifting trial increased.

2.0 Methods

2.1 Participants

Participants in this study consisted of twelve students, eight women and four men, ranging in age from 20 years to 35 years. Subjects were required to be at least 18 years old and have no chronic or current low back pain. Subjects were informed of all lifting requirements before the experiment began and were asked to sign a university-approved informed consent form prior to the initiation of the study. The mean and standard deviation for the subjects' height, weight, acromion to acromion shoulder width, acromion to L5/S1 height, and age can all be seen in Table 2.1, below.

Table 2.1 Average and Standard Deviation of Participants' Anthropometry and Age

	Stature (cm)	Shoulder Width (cm)	L5/S1 to Shoulder (cm)	Weight (N)	Age (years)
Average	174.9	37.8	43.0	698.4	23.8
Standard Deviation	6.7	2.6	3.0	78.7	4.5

2.2 Equipment

This study required a variety of equipment in the form of the lifting task apparatus, the measurement devices, and setup instruments. The organization of the study was such that there was a defined task preparation, or setup, period followed by the actual experiment, called the lifting task. Therefore, because of this design and the relative importance of the two phases of the study, it is most convenient to begin with the explanation of the equipment used for the lifting task, followed by a description of the tools used during the task preparation phase. Further, in order to be clear about the equipment during the lifting task, the description of those tools was divided into two parts: the apparatus used during the lifting task and the instruments used to collect data.

2.2.1 Lifting Task Apparatus

The lifting task apparatus was simple in nature, consisting of two force plates, a wooden frame housing for the force plates, an elevated lifting platform, and a lifting crate. The force plates (Bertec® of Columbus, Ohio) were 60 cm long by 30 cm wide. The frame was made out of 3.81 cm x 3.81 cm square beams, cut to the length of the force plates. The housing fit tightly around the force plates without touching the edges. Thin, aluminum plates of 2.54 cm width and 0.3175 cm thickness and various lengths were wedged between the frame and the force plates at the base of the force plates to ensure no movement of the force plates relative to the frame or to one another. The wooden lifting platform was situated 2.54 cm above the right-side force plate at a 45 degree angle. It was 25 cm wide and 50 cm long. Its base contacted the outside of the frame, but it did not contact either force plate. On top of the lifting platform, Styrofoam padding was attached. The lifting crate was a wooden box (30 cm cubed), with one open face and two handles on opposite faces which were perpendicular to the open face. A peg 2.22 cm in diameter and 10 cm long was attached in the center of the bottom face (opposite the open face). Barbell weights with inner diameter 2.54 cm were placed over the peg to hold them centrally in the bottom of the box. Figures 2.1 and 2.2 below show the lifting task apparatus setup. Note that the subject was required to stand on the force plates and repeatedly lower the box to, and lift the box from, the lifting platform.

Figure 2.1 Lifting task Apparatus with Box Lowered to Platform

Figure 2.2 Lifting task Apparatus with Box Raised

2.2.2 *Data Collection Instruments*

There were three pieces of equipment and one verbal questionnaire used to collect data during the experiment. The equipment used included the force plates which were part of the lifting task apparatus, a Lumbar Motion Monitor (LMM), and a Myopac Electromyography (EMG) recorder and processor. The force plates were used to collect GRF data, and the LMM was used to capture position, velocity, and acceleration of the trunk. The Myopac and questionnaire were used as a part of the fatigue verification process.

2.2.2.1 Force Plates

The force plates (Bertec ®, Columbus, Ohio) contained four three-dimensional load cells which translated forces in the x (lateral), y (anteroposterior), and z (vertical) directions into readable voltages. The load cells were also used by the internal force plate CPU to transform the instantaneous moments about all three axes into voltages. The gain for each of the six channels for both Platforms (twelve channels in all) was set at 20 to provide good resolution. The force and moment data were all collected at 1024 Hz. The twelve output channels from the force plates were connected to an analog-to-digital converter so they could be imported into a computerized oscilloscope data recording system.

2.2.2.2 Lumbar Motion Monitor

The LMM system is a multi-axis electrogoniometer with three potentiometers, which alter the voltage of their respective circuits depending upon lumbar angle in the sagittal, coronal, and transverse planes. These angular values are then differentiated in software to generate measures of angular velocity and angular acceleration of the lumbar region of the torso. Data from the LMM were recorded at 60 Hz. The device was secured to each subject's waist and shoulders and was calibrated based upon each individual's normal vertical standing posture (controls for inter-individual differences in lumbar lordosis). A subject fitted with the LMM can be seen in Figure 2.3, below.

Figure 2.3 Participant Fitted with LMM

2.2.2.3 Electromyography

The electromyographic (EMG) activity of the lumbar erector spinae were recorded using two silver-silver chloride bipolar electrodes and a single pole ground electrode. The electrodes were connected to a portable Myopac EMG recorder, which was then connected to the analog-to-digital converter. EMG data were collected at 1024 Hz, which allowed for frequencies of up to 512 Hz to be visible when the data were transformed into the frequency domain.

2.2.2.4 Verbal Questionnaire

The Verbal Questionnaire consisted of a single question and was presented to subjects 8 through 12 ten times during the lifting bout. It asked the subjects, "on a scale of zero to ten, with ten being complete body fatigue, zero being no body fatigue, and five being a medium amount of body fatigue, how fatigued to you feel right now?" The subjects then reported a number to the experimenter indicating their level of perceived whole body fatigue. It should be noted here that this subjective assessment of fatigue was implemented in response to concerns regarding the ability of the EMG system to provide adequate data documenting subject fatigue. This is why only subjects 8-12 experienced this subjective assessment.

2.2.3 Setup Equipment

The setup, or task preparation, equipment, include all the instruments used to collect data which was needed either to complete the set up of the lifting task or to analyze and process the raw data. The principal piece of setup equipment used was an an Asymmetric Reference Frame (ARF) powered by a KIN-COM® Dynamometer (Chatanooga Group, TN). The ARF provides a static resistance in any sagittal trunk angle. Two one-dimensional load cells measured force tangentially along the arc of the arm's travel. The ARF was used to determine subjects' maximum voluntary exertion (MVE), which was then used to determine the weight of their load during the lifting task, as will be described below. A participant performing an MVE in the ARF can be seen in Figure 2.4, below.

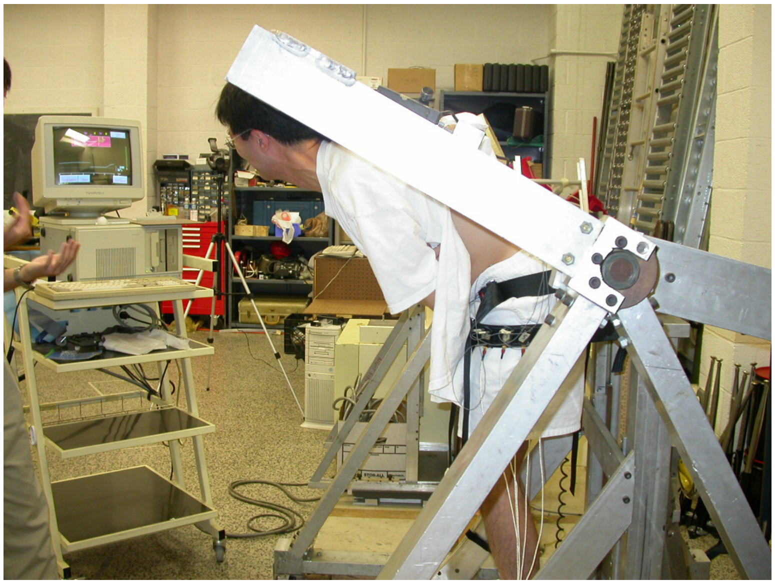

Figure 2.4: Participant Performing MVE in the ARF

For measuring subjects' weights, a standard spring scale was used. It was calibrated with standard barbell weights to ensure its accuracy. An anthropometer was used for measuring the length of various body segments. A standard digital stopwatch was used by the experimenter for tracking subjects' progress through the experiment in order that he could issue the proper lifting commands throughout the trials. The data from the scale and anthropometer were later used in determining subjects' required load as well as data processing.

2.3 Procedure

As mentioned previously, the procedure for the study was divided into two distinct parts: task preparation and lifting task. These two parts are best described in chronological order, beginning with the task preparation and ending with the protocol for the lifting task itself.

2.3.1 Setup

The procedure for the task preparation began with subjects reading and signing an informed consent form, which explained to them the nature of the task and the risks involved (an example consent form can be seen in Appendix A). After the subjects were informed of their role in the experiment, measurements were taken of their weight, height, acromion to acromion shoulder width, and distance from the L5/S1 joint to the height of the right acromion along the line of the spinal column. These measurements were taken so that an appropriate lifting weight could later be determined based upon the generic lifting model used by Shu et al. (2005) The subjects then warmed up by lifting a 111 Newton weight for 15 repetitions and then stretching. There was no instruction given on how to lift the warm-up weight, as the experimenter did not want to later influence the lifting style of the subjects.

After the warm-up, two Ag-AgCl bipolar electrodes were placed one inch apart along the line of the left and right multifidus muscles at L3 height, and the ground electrode was placed over the right iliac crest, using standard preparation procedures. (Marras, 1990). Next, the subjects performed two maximum voluntary contractions (MVC) in the ARF (Mirka & Marras, 1993). The arm of the ARF was set at 60 degrees from vertical. Subjects practiced an MVC exertion and were then instructed to perform two MVCs. Each subject was given verbal encouragement to help ensure that he or she extended to maximum ability. One minute of rest were provided between the two consecutive MVC exertions. Subjects were also allowed to view their force production on a real-time graph, which served as an additional motivational tool.

After the maximum extension force was captured, it was entered into a biomechanical model used by Shu et al. (2005). This model considered weight of the participant's torso and the magnitude of the MVC along with the collected anthropometric dimension of L5 to acromion distance. The model returned with a weight that was equivalent to 40 % of the subject's lifting capacity in the mid-sagittal plane. Since the lifting task to be performed was an asymmetric lifting task, this value was multiplied by 0.6 to generate a load value that was to be lifted in the asymmetric posture (Marras and Mirka, 1989) This procedure was used for each participant to calculate their individual hand-held weight to be used during the lifting phase of the experiment.

The subjects were then fitted with the LMM. As soon as the LMM was attached snugly, a single five-second baseline data set was collected for both the full upright posture (zero degrees from vertical) and the 90^{o} flexed posture. The force plates were zeroed electronically through a built in reset button. The electric power to the force plates was always turned on at least 30 minutes prior to each lifting task to ensure that a minimal drift would occur after they were reset. Next, two stance widths were marked on the force platforms. The width of the narrow stance was equal to each subject's shoulder width, and the wide stance was equal to double the shoulder width. Each stance width dictated the distance from center heel to center heel, with the remainder of the foot being positioned so as it was most comfortable based on individual subject preference. With respect to the axes of the Platforms, the feet heel markers were placed along the same y axis position (anteroposterior) and were equidistant from the midpoint of the dividing frame in the x direction (lateral). Small, wooden blocks were placed to the inside of the feet in the narrow stance and to the outside of the feet in the wide stance so that the subject could more easily locate the correct stance positions during the lifting task. Figure 2.5, below, shows a diagram of the two stances and the wooden blocks used to mark their positions.

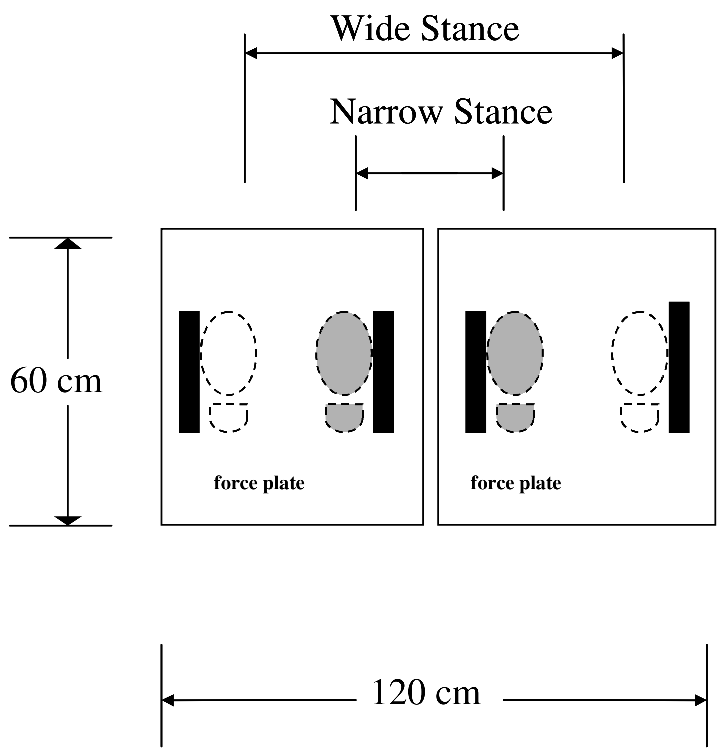

Figure 2.5 Foot Position on Force Plate

As a final preparation for the experiment, the electrodes already attached to the subject were connected to the Myopac EMG system, and all collection software were run in test mode for ten seconds to ensure that signals were being received and that those signals were of an expected magnitude.

2.3.2 Lifting Task

During the lifting portion of the study, the participants repetitively lifted and lowered a load equal to 40 % of their lifting capacity. The load consisted of a box 30 cm on each side with large padded handles cut out of two sides. The load was placed centrally inside the box on the bottom face. Subjects were asked to lift the box once every five seconds for a period of ten minutes. As the subjects began the task in an upright, symmetric position, one lift consisted of first lowering the load (eccentric phase) to the wooden platform 10 cm above the surface of the force platforms and 45 degrees to the right of center in the transverse plane (Figure 2.1). During the second phase of the lift, the subjects returned to the upright, symmetric posture (concentric phase) (Figure 2.2 for upright posture). After each minute of lifting, the subjects were instructed to change stance. While force platform data were recorded continuously throughout the experiment, EMG data were only recorded at specific intervals during the experiment. These data were collected at the beginning of the experiment (before lifting began) and at the end of the experiment (after lifting was completed) as well as during every second break in which the subjects changed stance. During these time periods, the participants were asked to flex the trunk forward to an angle of 60 degrees from vertical in the sagittal plane and zero degrees of deviation in the transverse plane and to hold that posture for two seconds. EMG data were recorded while the subjects' feet were in the narrow stance. With regard to the LMM, data were collected for one 30-second block each minute. LMM data collection began 20 seconds after the change of stance to guard against fluctuating postures caused by the new foot placement. Also during the stance changes for subjects 8 through 12, the subjects were asked to evaluate their overall level of fatigue on a scale from 1 to 10 as described in Section 2.2.2.4. Upon completion of the lifting task, subjects were instructed to stop lifting, were removed of all electrodes and equipment, given a souvenir t-shirt, and instructed to notify the experimenter should any discomfort persist that they believed was associated with the lifting task.

2.4 Independent Variables

Two independent variables were used in this experiment: Stance and Time. The two levels of Stance were the wide stance and the narrow stance. Time, an indicator of the level of fatigue of the subjects, was present in five levels labeled 1 through 5. Each level corresponded to two minutes of lifting such that level 1 consisted of the first two minutes of lifting, level 2 consisted of the third and fourth minutes of the experiment, and so on through level 5. Each level contained one minute of lifting in the narrow stance and one minute of lifting in the wide stance.

2.5 Dependent Variables

Three instruments (LMM, EMG, and force platforms) were used to record data during the lifting trials. The data from the EMG and the survey are not considered dependent variables in this experiment, but instead provide some measure of the fatigue that was developed during the lifting task.

The dependent variables of interest associated with the LMM were maximum angular position and acceleration in both the sagittal and coronal planes during the concentric range of motion. Angular positions were considered because of the associated increase in moment about L5/S1 that deviations in these planes create. Accelerations were collected because of their direct proportionality to force, not only in the spine, but between the feet and floor as well. Data for maximum positions and accelerations identified in the concentric range of each lift, yielding 10 to 12 observations of the peaks of these measures per Time-Stance combination.

In an effort to better assess the effects of the independent variables on the variability in these measures, the modified Levene test was used. This approach required the calculation of the deviations of each datapoint from the median value in the set. Therefore, from those 10 to 12 maximum values, median deviations were calculated for each measure. That is, for each time-stance combination of lifting, the median was taken from the data points recorded from the concentric range of motion. Then, the absolute value of the difference between the median and actual value was calculated for the data during each time-stance combination. This value was labeled the median deviation. This procedure was done for all variables at all Time-Stance combinations. The median deviation was considered important because fatigue-induced increases in variability often result in wider ranges of motion (Parnianpour et al. 1988) and velocities (Spart et al. 1997) although they might have similar average values as unfatigued motion. This is important because when studying slips because it only takes one large trunk acceleration to induce a force between the feet and the floor strong enough to overcome the coefficient of static friction, especially in a low friction environment.

The variables of interest from the force platforms were the maximum horizontal ground reaction forces during the concentric range of motion and measures of variability of these forces. These variables were only considered for the force platform under the right foot because all lifts were performed to the right side and the right foot carried substantially more of the load of the torso and the box. Naturally, larger vertical loads correspond to larger shear forces given the angle between the vector from the knee to ankle and the force plates is the same in both legs. The maximum forces in the lateral (x) and anteroposterior (y) directions were recorded for each concentric lift. The maximum composite force vector, *v*, was also calculated for each concentric lift. The formula for the calculation of the vector, *v*, can be seen in equation (1) below:

$$v = \sqrt{x^2 + y^2} \qquad (1)$$

In equation (1), *v*, is the composite force vector, *x* is the lateral force, and *y* is the anteroposterior force for any 1/1024th second datum. The maximum vector for each concentric lift was extracted for analysis. The median deviations of each of the three forces were calculated in the same manner as the median deviations for the LMM.

2.6 Data Processing

Data for this experiment were collected from three separate sources: LMM, force plates, and the Myopac. In the case, of the LMM and force plates these raw data needed to be processed to derive the dependent variables of interest.

2.6.1 Force Platform Data Processing

Force platform data were processed in a manner similar to that of the LMM data. First, the raw voltage data were passed through a calibration matrix provided by the manufacturer of the force platforms. This yielded three-dimensional force and moment data for the entire duration of the lifting task. The next step was to filter out all data except for that which occurred during the concentric range of motion. This was done in two stages. The first stage involved filtering out all data that were recorded during a time when the subject engaged in any activity other than a lift. This was done by identifying the extreme negative vertical forces associated with the peak downward acceleration during the eccentric range of motion and the point of maximum deceleration midway through the concentric range of motion (Figure 2.7). Only data between these two points were considered further.

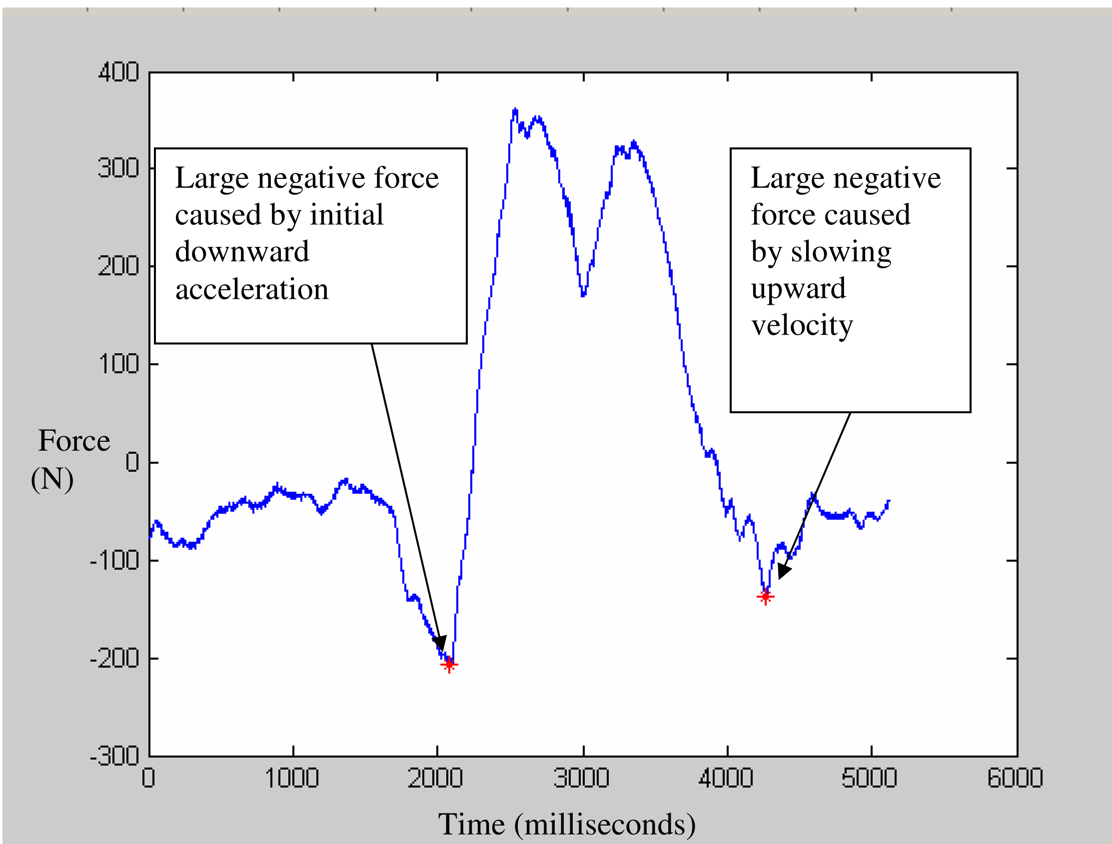

Figure 2.6 Characteristic Lift Curve in the Normal Force Domain

The second part of the filtering process involved separating the eccentric from the concentric phases. This was done by identifying the point on the vertical force lift curve which corresponded to the point in time when the subject touched the load to the wooden platform. The point manifested itself in the vertical force curve in the form of a sharp negative valley located very near the midpoint of the beginning and ending points of the lift identified in the previous processing step (Figure 2.8).

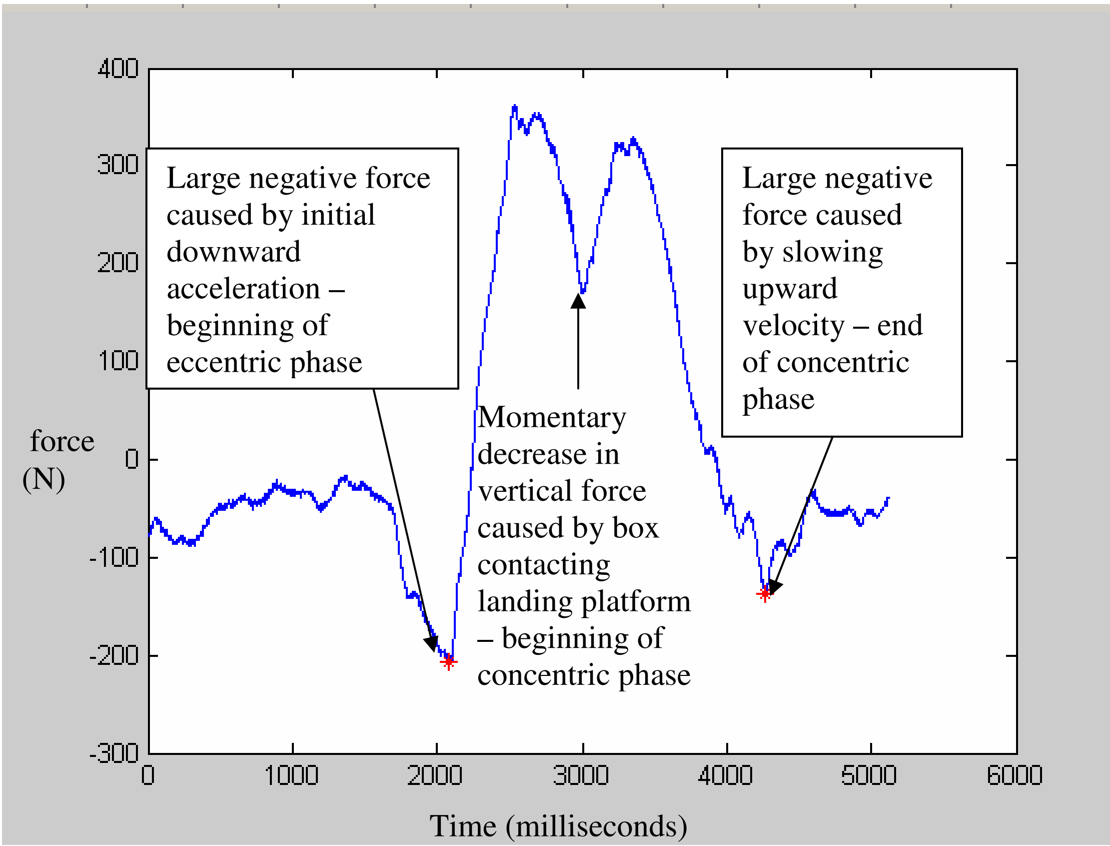

Figure 2.7 Characteristic Midpoint of Lift Curve in the Normal Force Domain

Following the identification of the three negative peaks, only data points between the second and third valleys were considered. The maximum forces in the lateral (*x*) and anteroposterior (*y*) directions were then extracted from each concentric lift. In addition to the maximum x and y directional forces, a composite horizontal force vector, *v*, was created for the concentric lifting phases. The vector for each concentric lift phase datum was equal to the square root of the sum of squares of the two horizontal forces at that particular instant in time. The maximum vector for each concentric lifting phase was recorded for later use. It is important to note that none of the three maximum forces, *x*, *y*, and *v*, ever occurred at precisely the same moment within any concentric lift phase.

Further, median deviations were calculated for *x*, *y*, and *v* for each minute of the lifting trials. This was done by first calculating the median value of the maximum *x*, *y*, and *v* forces for each minute (approximately 11 points). Then, the values of the medians were subtracted from their respective force values to yield a distance from the median.

2.6.2 LMM Data Processing

The LMM software automatically generated 12 text files for each subject: the two references positions (0^{o} and 90^{o}) and one for each of the 30-second lifting trials. The first step in the processing procedure was to normalize the subjects' data realative to their upright relaxed posture. This was done by subtracting the average neutral vertical posture values from each row of actual lift data. The second step in processing was to identify the concentric range of motion. This was done by identifying the points of maximum trunk flexion and the following points of minimum trunk flexion on the sagittal position graph (Figure 2.6). These points corresponded to the point where the subject touched the load to the wooden platform (beginning of concentric motion) and the point where he or she returned to an upright posture (end of concentric motion), respectively.

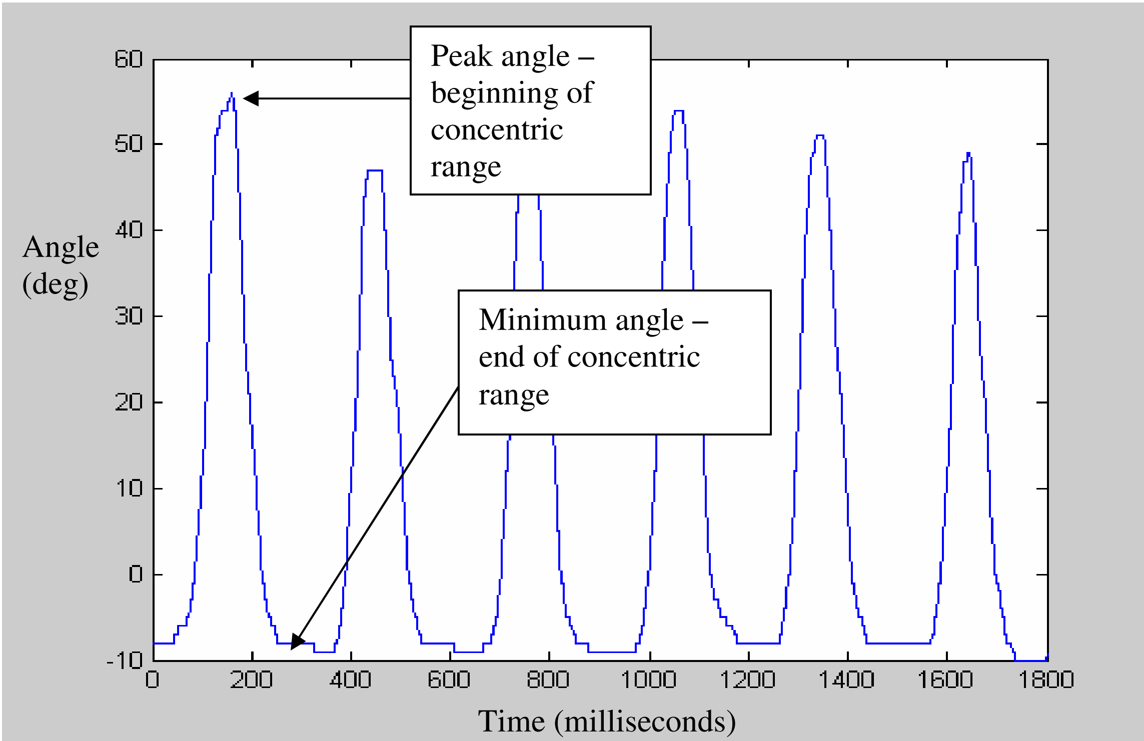

Figure 2.8: Description of Beginning and End of Concentric Lift Phase

Once the timing of the beginning and ending points of the concentric range of motion for each lift were identified, the maximum angular position and acceleration were found in both the sagittal and coronal planes during those time periods. After the extraction of the maximum values for positions and accelerations, the median of the set of the 10-12 maximum values for each Time-Stance combination (each minute of lifting) was found for each dependent measure and then the deviations of each of these 10-12 points from this median value were calculated.

2.6.3 Fatigue Verification

2.6.3.1 Fatigue Verification using EMG

The EMG data that were collected were used for the purpose of verifying fatigue of the multifidus muscles. For each EMG recording (10 per subject), one second, or 1024 data points, were extracted from the middle of the data set. A Fast Fourier Transform (FFT) was then performed on the EMG data so they could be viewed in the frequency domain, and the median frequencies were then extracted for each data set. Noise was filtered out of the signal through the use of a low pass filter at 10 Hz, a high pass filter at 400 Hz, and a notch filter from 59 Hz to 61 Hz to limit the impact of electrical noise on these signals.

2.6.3.2 Fatigue Verification using the Verbal Questionnaire

For participants 8 through 12, the verbal questionnaire was used to corroborate EMG data. The subjective assessments of fatigue, one for each minute of task performance for each participant, were arranged in time order for each subject. Each participant's data were then subjectively assessed by the experimenter to verify that the self-assessment of fatigue increased with time into the task. No further analyses were performed with these data as their purpose was considered supplementary and not primary.

2.7 Statistical Analysis

2.7.1 *Statistical Model*

Due to the time-dependent nature of fatigue, it was not feasible to randomize the order in which each fatigue state was experienced by the subjects. Also, because subject stance was alternated every minute, a combined data set incorporating all subject-stance-fatigue combinations would have taken on a split-split plot personality. The solution, therefore, was to isolate the independent variables, focusing only on the effect of one at a time. As a result, seven data sets and seven statistical analyses were used for the data recorded from both the LMM and the force platforms. (One analysis exploring the effect of fatigue in the wide stance, a second exploring the effect of fatigue in the narrow stance, a third exploring the effect of stance at Time 1, a fourth exploring the effect of stance at Time 2, etc.)

2.7.1.1 Statistical Model for the Assessment of Effect of Time

To determine the effects of fatigue on the selected dependent variables, the original data sets were broken down by stance, yielding one table for data collected during the narrow stance and another for data collected during the wide stance. Both analyses took on a model of the form of equation (2) below:

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \; ; (i = 1\text{-}5, j = 1\text{-}12) \qquad (2)$$

In this model, the stance effect has been eliminated, and only the main effect of Time, τ, is included in the model. The other parameters of the model include the mean of all values of the response, μ, in only one stance, the subject block effect, β, and the error term, ε. Notice that the time effect includes all Time conditions, and the blocking effect accounts for all 12 subjects.

2.7.1.2 Statistical Model for the Assessment of Effect of Stance

Similar to the above model, the effect of stance was determined by performing individual analyses of the two levels of stance at each of the five levels of fatigue. The model used for the analysis is shown below in equation (3). It is nearly identical to the model of the stance effect with only the number of levels of the treatment changed.

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \; ; (i = 1\text{-}2, j = 1\text{-}12) \qquad (3)$$

In this model, μ represents the mean for all responses for a given time block, τ represents the two-level main effect of Stance, β represents the subject blocking variable, and ε again is used as the error term. Notice that the time effect includes both Stance conditions, and the blocking effect accounts for all 12 subjects.

2.7.2 Assumptions of ANOVA

Prior to any analyses, it was necessary to examine the data to verify that the assumptions of ANOVA were not violated. That is, the independence assumption, the assumption of homogeneity of variance, and the normality assumption were all verified. The three assumptions for all variables were examined graphically through JMP ® statistical software by methods advocated by Montgomery (2001). For the verification of the independence assumption, residuals were plotted as a function of trial order. Any trends in the plot (i.e. consistent slope or predictable oscillations) are clear indications of a trend in the data as a function of trial order, which in turn is an indication that the experimental design was not fully randomized or that any restrictions on randomization were not taken into account. The homogeneity of variance assumption was verified by a plot of actual residual values versus their predicted values. As the magnitude of the prediction increases, changes in actual residuals' distribution about the predicted value are indicative of a dependence of the residuals on another variable. This means that the statistical model is incomplete. The assumption of normality of residuals was verified using a normal quantile plot. On the plot, normally distributed populations create a straight line with a slope of 1, while non-normal populations could have any shape and are often nonlinear. It is, however, acceptable for minor deviations from the straight line to occur, as they do not represent a clear violation of the assumption (Montgomery 2001). Sample graphs can be seen in Appendix B. The dependent variables which were found to violate the constant variance assumption (no other assumptions were violated) were then transformed, by use of a natural log transformation, in an attempt to eliminate the expanding variance of residuals as a function of predicted value. Examples of violations of the constant variance assumption and the subsequent natural log correction can also be seen in Appendix B.

2.7.3 MANOVA

Before individual, one-way ANOVAs could be used to test the significance of the effects of the independent variables on each of the dependent variables in each data set, a MANOVA analysis was conducted within each data set to determine if the different levels of the independent variable isolated within each data set affected the dependent variables as a group. In situations where the MANOVA showed no significant differences between levels, no further analysis was done with regard to any variables. Where the MANOVA did find significant variation as a function of treatment level ($p <$

0.05), individual ANOVAs were performed to determine which dependent variables were significantly affected by the independent variables.

2.7.4 ANOVA

One-way analyses of variance were conducted for all recorded variables within data sets where the MANOVA found significant variation. A p-value of less than 0.05 was used as an indicator of significance for all variables. The modified Levene's test was used to test for significant variation in the dependent variables as a function of both Time and Stance. In situations where dependent variables were found to be significantly affected by time, a Tukey-Kramer HSD (Honestly Significant Difference) post-hoc test was performed to determine precisely which pairs of dependent variable-Time combinations were statistically significant. The test was used to determine which pairs of responses were statistically different from one another. There was no need to perform the Tukey-Kramer HSD for dependent variables found to be affected by Stance, as Stance only had two levels.

3.0 Results

The results below are separated by the type of data collected, fatigue assessment, force platform, and LMM. Each sub-section presents charts and graphs relating to the statistical and physical significance of each of the independent variables with respect to the independent variables.

3.1 Fatigue Assessment Data

Table 3.1 shows the average median frequencies across all participants at the beginning of the trial and every two minutes thereafter for both the right and left multifidus muscles. The F ratios for the response of left and right multifidus median frequency based upon time into the study are 12.24 (p-value < 0.0001) and 11.59 (p-value <0.0001), respectively. Therefore, there is a statistically significant median frequency drop related to time, indicating fatigue took place. However, the median frequencies presented are not in the normal range for median muscular frequencies (60-80 Hz).

Table 3.1: Average Median Frequency (Hz) Across Participants at 2-minute Intervals

	side	
time	left	right
beginning	56.3	54.4
after 2 min	43.2	39.3
after 4 min	42.8	37.2
after 6 min	45.1	41.4
after 8 min	40.0	38.0
end	44.9	44.4

These uncharacteristically low median frequencies were a problem throughout the study. Because only two of the first seven participants' median frequency data appeared to be legitimate, the verbal questionnaire was introduced for the remaining five participants. The questionnaire was meant to bolster the argument for fatigue which was not altogether convincing in all participants based upon the electromyographic data alone. The following table shows the results for the verbal questionnaire presented to participants 8 through 12.

Table 3.2: Subjective Rating of Fatigue by Participants

Time into Lifting Bout (minutes)	Subject 8	9*	10	11	12*
1	4	1	1	3	3
2	4	2	2	4	5
3	6	2	3	4	7
4	6	7	4	5	10
5	8	8	5	6	10
6	8	9	5	6	10
7	9	10	6	7	
8	9	10	6	7	
9	9	10	7	8	
10	9		7	8	

Note: * denotes incomplete response due to subject not completing full 10 minute trial.

In Table 3.2, above, are presented the subjective assessment of overall body fatigue (on a scale of 0 to 10) as felt by participants 8 through 12 as a function of time into the lifting task. As can be seen, all participants reported having near maximal or maximal fatigue by the end of the experiment, while only experiencing light fatigue at the beginning. The empty values in the columns for participants 9 and 12 are present because those individuals prematurely ended the lifting task. The subjective fatigue ratings of participants 9 and 12 would suggest that they asked to end the task early because the felt too fatigued to continue.

3.2 Force Plate Data

3.2.1 Effects of Stance on Ground Reaction Forces

Table 3.3 shows the results of the statistical analysis of Stance on the six force platform dependent variables at each of the different levels of Time. Notice that, regardless of fatigue state, peak horizontal slip forces in both the lateral and anteroposterior directions were significantly affected by Stance. Further, the maximum horizontal force represented by the vector was also heavily influenced by Stance throughout the experiment. Very few significant effects were found to exist between the median deviations of the x, y, and v variables and stance. Figure 3.1 shows that for all times into the lifting task, the doubling of foot separation results in the near-doubling of maximum horizontal shear forces, from around 40 N in the narrow stance to around 80 N in the wide stance. It is interesting to note (Figure 3.2) that the maximum anteroposterior force during each lift decreased rather dramatically from the narrow to the wide stance, dropping around 25 %, from near 40 N in the narrow stance to near 30 N in the wide stance. Finally, Figure 3.3 shows that the average maximum shear force experienced by all subjects throughout the experiment increased from around 75 N in the narrow stance to just over 100 N in the wide stance, an increase of approximately 33 %.

Table 3.3: F ratio and p-value for Stance Effect at Different Levels of Time

Time into Lifting Task	MANOVA	Maximum lateral force on right foot	Maximum anteroposterior force on right foot	Maximum combined vector force on right foot	Natural log of median deviation of maximum lateral forces on right foot	Natural log of median deviation of maximum anteroposterior forces on right foot	Natural log of median deviation of combined vector force on right foot
time 1	170.75 (<0.0001)	609.83 (<0.0001)	164.91 (<0.0001)	570.64 (<0.0001)	4.12 (0.0434)	0.86 (0.3539)	2.16 (0.1433)
time 2	131.18 (<0.0001)	355.96 (<0.0001)	123.5 (<0.0001)	551.87 (<0.0001)	0.46 (0.4968)	2.80 (0.954)	1.47 (0.2262)
time 3	117.61 (<0.0001)	294.26 (<0.0001)	123.6 (<0.0001)	313.31 (<0.0001)	0.06 (0.8110)	9.50 (0.0023)	0.25 (0.6170)
time 4	103.53 (<0.0001)	303.62 (<0.0001)	106.83 (<0.0001)	385.55 (<0.0001)	2.84 (0.0934)	6.24 (0.0132)	0.23 (0.6309)
time 5	104.25 (<0.0001)	281.4 (<0.0001)	125.15 (<0.0001)	432.9 (<0.0001)	1.11 (0.2924)	2.52 (0.1136)	2.08 (0.1510)

The following three figures show the magnitudes of the average maximum lateral, anteroposterior, and vector forces as they were affected by stance across participants.

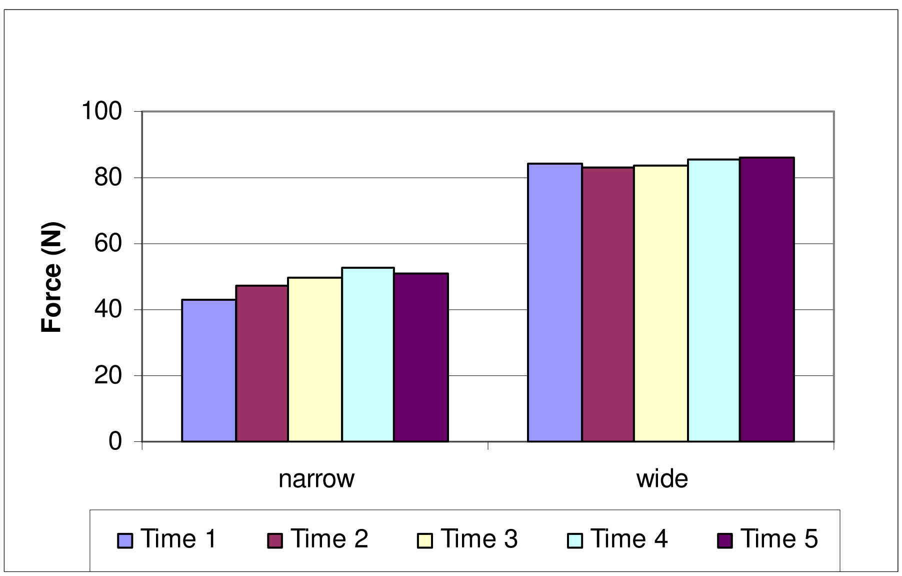

Figure 3.1: Effect of Stance on Maximum Lateral Shear Force

Notice in Figure 3.1, above, that for all times into the lifting task, the doubling of foot separation results in the near-doubling of maximum horizontal shear forces, from around 40 N in the narrow stance to around 80 N in the wide stance.

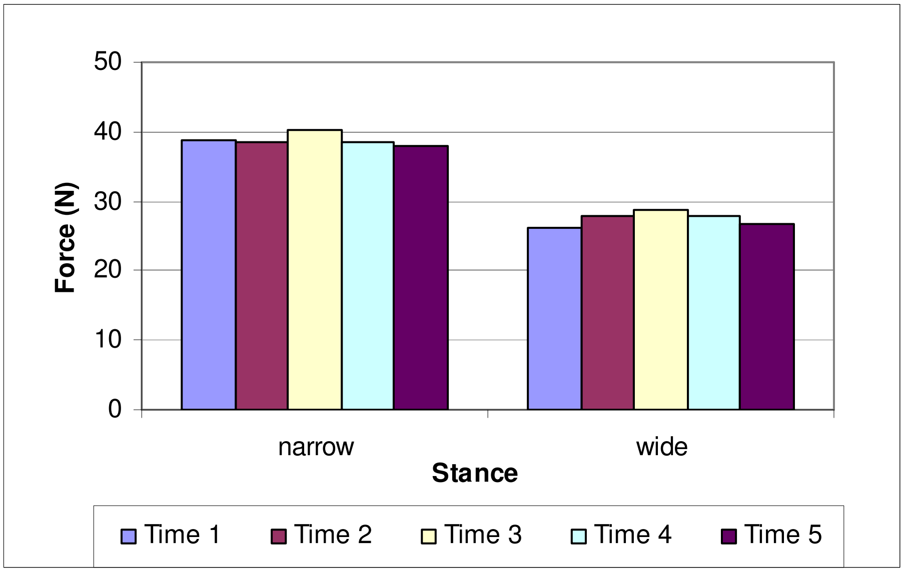

Figure 3.2: Effect of Stance on Maximum A-P Shear Force

It is interesting to note that the maximum anteroposterior force during each lift decreased rather dramatically from the narrow to the wide stance, dropping around 25 %, from near 40 N in the narrow stance to near 30 N in the wide stance.

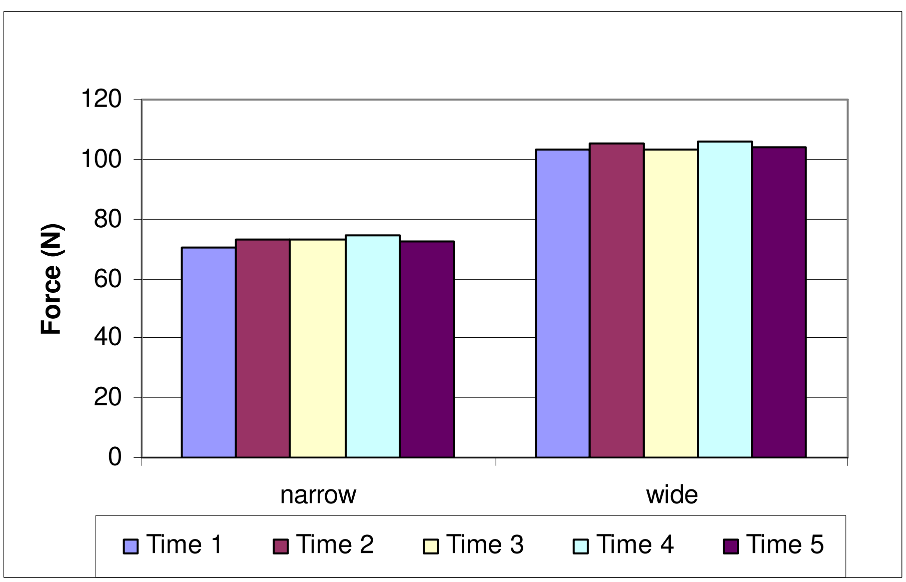

Figure 3.3: Effect of Stance on Maximum Combined Shear Force

Figure 3.3 depicts the maximum shear forces during each lift. Primarily driven by the larger lateral forces, the average maximum shear force experienced by all participants throughout the experiment increased from around 75 N in the narrow stance to just over 100 N in the wide stance, an increase of approximately 33 %.

3.2.2 Effects of Time on Ground Reaction Forces

Table 3.4 shows the results of the statistical analysis of Time on the six force platform dependent variables at each of the different levels of Stance.

Table 3.4: F ratio and p-value for Time Effect at Different Levels of Stance

Stance	MANOVA	Maximum lateral force on right foot	Maximum anteroposterior force on right foot	Maximum combined vector force on right foot	Natural log of median deviation of maximum lateral forces on right foot	Natural log of median deviation of maximum anteroposterior forces on right foot	Natural log of median deviation of combined vector force on right foot
Narrow	3.33 (<0.0001)	12.06 (<0.0001)	1.52 (0.1959)	4.60 (0.0012)	1.21 (0.3034)	1.23 (0.2954)	2.56 (0.0374)
Wide	1.4 (0.093)	--	--	--	--	--	--

During the wide stance, the MANOVA showed that there was no significant difference between any of the dependent variables for the different levels of fatigue. However, for the narrow stance, it was revealed that the maximum lateral force per lift as well as the maximum vector force per lift increased significantly over the course of the lifting task. The magnitude of the right foot shear force response over time in the narrow stance in the lateral direction as well as the composite vector can be seen in Figure 3.4 below. The results of the Tukey-Kramer HSD can be seen in the labels above the columns. Those columns which are labeled with the same letter are not considered statistically significant from one another (note that the columns from the wide stance and the narrow stance should not be directly compared in any of the graphs which illustrate the effect of Time).

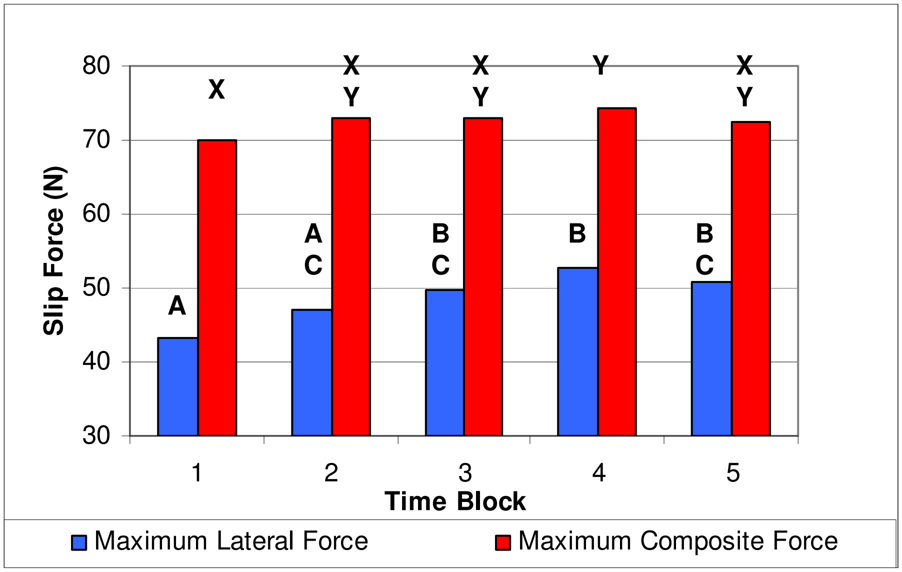

Figure 3.4: Effect of Time on Lateral and Composite Shear Forces of the Right Foot in the Narrow Stance

3.3 LMM Data

Similar to the Force platform data presented above, the LMM data were divided into seven subsets. MANOVAs and subsequent ANOVAs were performed in each of the fatigue levels while varying stance and were then conducted on both of the stance levels while varying fatigue. Below are the statistical results as well as graphs illustrating the physical significance of trunk position and acceleration changes with time and stance.

3.3.1 Significance Effects of Stance on Trunk Kinematics

Table 3.5 shows how the eight dependent LMM measures were affected by stance at each of the five levels of time into the lifting task. At time levels 3 and 5, the MANOVA showed that there was no significant variation as a function of stance for the group of dependent variables as a whole. Only coronal acceleration was found to be strongly affected by stance at the levels where individual ANOVAs were conducted. None of the median deviations was found to change significantly due to stance.

Table 3.5: F ratio and p-value for Stance Effect at Different Levels of Time

Time into Lifting Task	MANOVA	Maximum coronal positon	Maximum coronal acceleration	Maximum sagittal position	Maximum sagittal acceleration	Natural log of maximum coronal position	Natural log of maximum coronal acceleration	Natural log of maximum sagittal position	Natural log of maximum sagittal acceleration
time 1	3.51 (0.0012)	9.80 (0.0022)	18.47 (<0.0001)	0.18 (0.6694)	5.51 (0.0206)	0.09 (0.7670)	0.04 (0.8450)	0.04 (0.8479)	0.00 (0.9680)
time 2	4.62 (<0.0001)	1.40 (0.2390)	11.58 (0.0009)	23.14 (<0.0001)	12.03 (0.0007)	0.01 (0.9245)	0.00 (0.9966)	1.33 (0.2518)	1.75 (0.1881)
time 3	1.99 (0.0533)	--	--	--	--	--	--	--	--
time 4	3.41 (0.0015)	0.00 (0.9975)	7.64 (0.0066)	12.96 (0.0005)	0.16 (0.6928)	0.41 (0.5232)	0.33 (0.5640)	2.41 (0.1230)	1.76 (0.1870)
time 5	1.95 (0.0604)	--	--	--	--	--	--	--	--

3.3.2 Effects of Time on Trunk Kinematics

Table 3.6 shows how the dependent LMM variables were affected by fatigue during each of the two different stances. In contrast to the shear force data, many of the LMM variables were found to be significantly affected by fatigue during both stances. Most notably, coronal acceleration was found to be significantly affected during the narrow stance, and sagittal acceleration was significantly affected by fatigue in both stances.

Table 3.6: F ratio and p-value for Time Effect at Different Levels of Stance

Stance	MANOVA	Maximum coronal positon	Maximum coronal acceleration	Maximum sagittal position	Maximum sagittal acceleration	Natural log of maximum coronal position	Natural log of maximum coronal acceleration	Natural log of maximum sagittal position	Natural log of maximum sagittal acceleration
Narrow	3.31 (<0.0001)	4.34 (0.0020)	2.53 (0.0403)	9.02 (<0.0001)	5.88 (0.0001)	1.28(0.2791)	0.74 (0.5630)	1.92 (0.1074)	1.19 (0.3141)
Wide	2.51 (<0.0001)	9.37 (<0.0001)	0.59 (0.6693)	6.19 (<0.0001)	5.44 (0.0003)	1.04 (0.3878)	0.58 (0.6749)	0.34 (0.8490)	1.81 (0.1268)

Figures 3.5 and 3.6 show the magnitudes of the responses of sagittal and coronal acceleration due to fatigue.

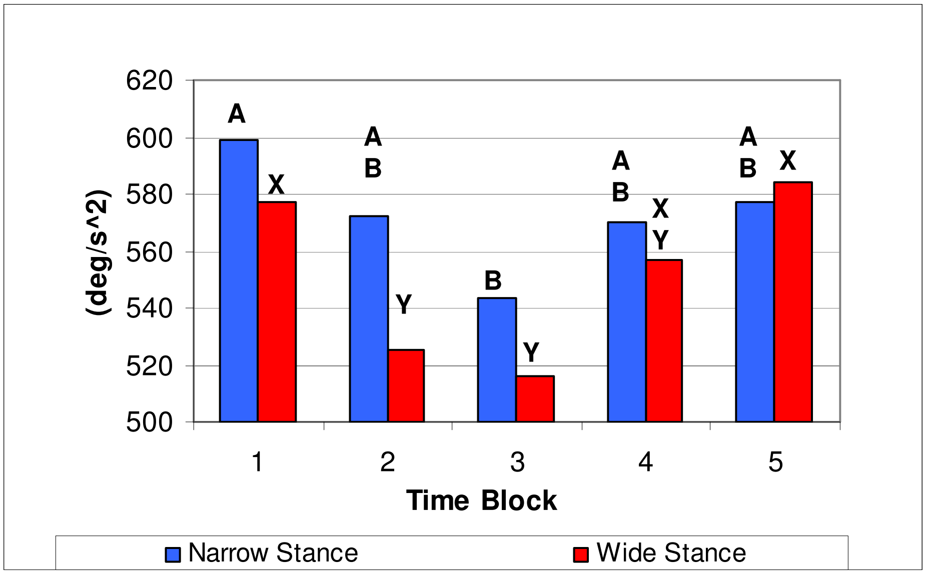

Figure 3.5: Effect of Time on Sagittal Acceleration

Notice that during the first half of the experiment, participants experienced a marked decrease in sagittal acceleration of around 60 deg/s^2 in both stances. During the second half of the experiment, maximum sagittal acceleration increased steadily over time in both stances. The slight significance of the Time effect on coronal acceleration in the narrow stance as determined by the ANOVA was not corroborated by the Tukey-Kramer HSD, as can be seen in Figure 3.6. Despite the questionable statistical significance, the average maximum coronal acceleration per lift increased 11 % from 61 deg/s^2 during the first two minutes of lifting to 68 deg/s^2 during the final two minutes of lifting.

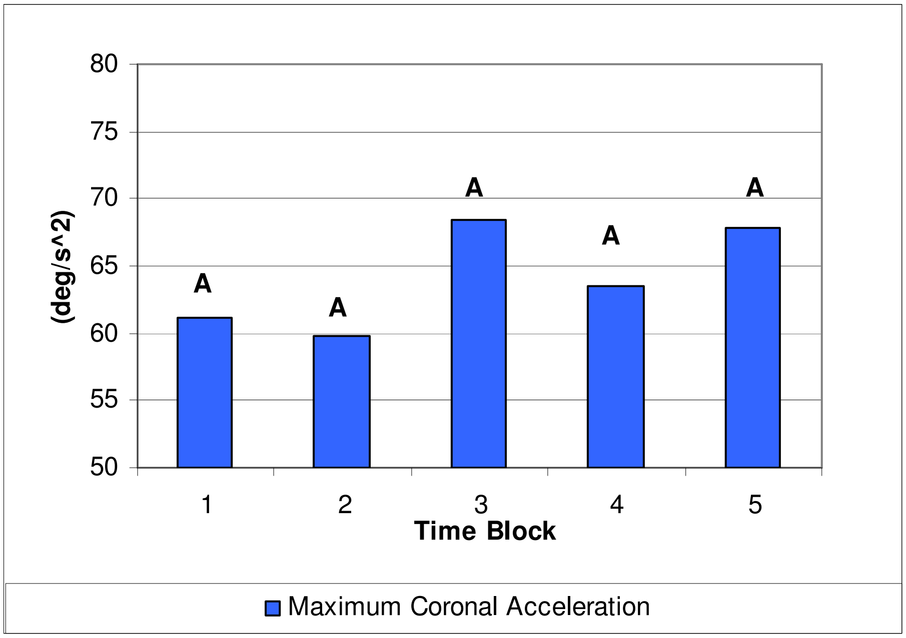

Figure 3.6: Effect of Time on Coronal Acceleration in the Narrow Stance

Coronal and sagittal position were also found to vary significantly with time. The effect of time on coronal position can be seen in Figure 3.7, and the time effect on sagittal position can be seen in Figure 3.8. Notice that both coronal and sagittal position exhibit the same parabolic pattern in the wide stance as time into the lifting task increases. A similar pattern also emerges in sagittal position as a function of time into the task in the narrow stance. Maximum coronal position, however, tends to decrease with time into the lifting task in the narrow stance.

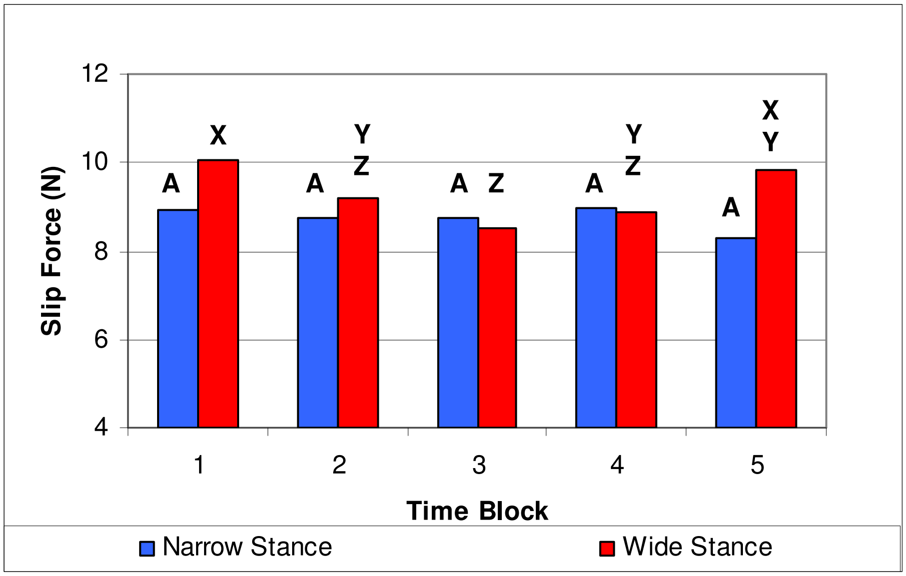

Figure 3.7: Effect of Time on Coronal Position

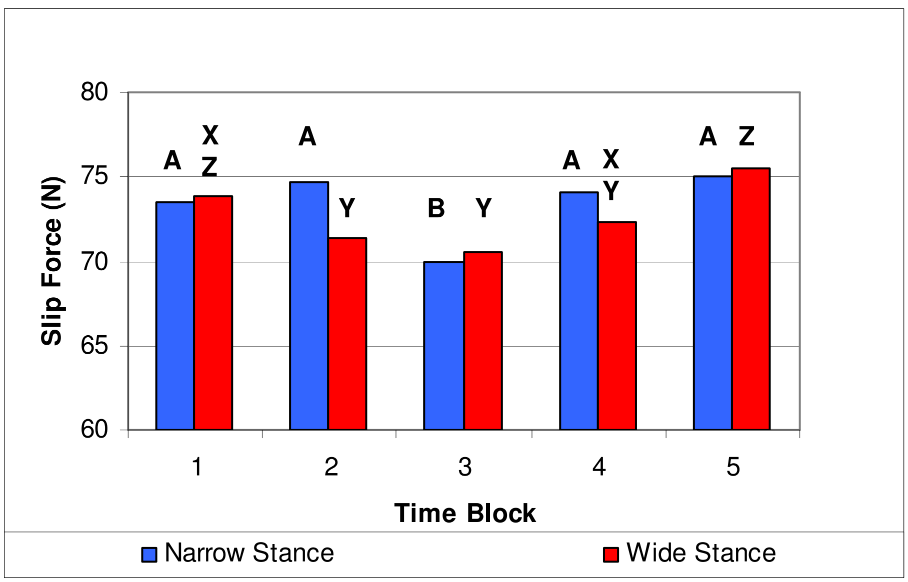

Figure 3.8: Effect of Time on Sagittal Position

4.0 Discussion

The goal of this study was to evaluate the impact of a repetitive, fatiguing, asymmetric lifting task on ground reaction forces and trunk kinematics as a function of time. Also of interest was how the fatigue that was developed would impact the variability in these human performance measures.

The most interesting and important effect noticed in the force platform data was the increase in lateral shear forces as a function of time in the narrow stance. This result could be inferred from the works of Parnianpour et al. (1988) and Sparto et al. (1997), which showed increases in lateral motion as a function of fatigue. It was also in line with the work of Shu et al. (2005), which showed that the net lateral shear force increased as individuals became fatigued while lifting. Building on the work of Shu et al. (2005), the data in this study showed that individual foot shear forces were approximately four times the magnitude of the net forces seen in the previous study. The maximum lateral forces observed here in the narrow stance increased from 43 N at the beginning of the exercise to 51 N at the end of the exercise, an increase of 8 N, but of 18.6 %. An increase of this magnitude could easily lead a person to slip in a fatiguing lifting condition where the required coefficient of friction were very low and the initial shear forces were very close to the coefficient of static friction between the person's feet and the ground.

Also following the hypothesis was the variation of the lateral and overall vector forces with respect to the two stances. This was just as expected. Because the vector from the hip to the ankle of each leg shifted up to 30 cm in the lateral direction, the angle between the vertical line of action of participants' weight and the leg increased substantially. This led to an increased proportion of the participants' weight being transferred to the lateral direction load sensors. The lateral forces, on average, increased from around 40 N to around 80 N as stance was doubled, while combined vector forces increased from near 50 N to over 100 N. As the average subject weighed only 700 N, the maximum shear forces in the wide stance were approximately 14 % of the participants' body weight (RCOF = 0.14). The results of Gronqvist et al. (1993) suggested that the maximum safe RCOF in a walking task for very slippery conditions (oil on steel with rubber shoes) was 0.13. Depending upon the difference between walking and lifting slipping mechanics, the shear forces experienced during this lifting task could be dangerously large in a low friction environment. This calls into question the traditional theory of safe lifting held by Garg et al. (1983), which states that proper lifting technique involves a squat lift with a wide stance so that the load is held between the legs, thus creating a minimal moment about the L5/S1 joint. However, in the presence of a slippery lifting surface, additional erector spinae stress caused by a moderate load would be preferable to a fall, which could lead to substantially higher forces on the spine as well as acute impact trauma as found by Gronqvist et al. (2001).

With regard to variability in shear forces as a function of time, there was no evidence discovered to support the hypothesis that variability would increase as individuals became fatigued. This was unusual, considering the preceding research indicated either increased variability (range of motion or forces) of trunk motion or increased range of trunk motion (implying increased variability and decreased control) as fatigue increased in individuals (Parnianpour et al. 1988, Sparto et al. 1997). This anticipated variability of trunk behavior was expected to result in increased variability of lateral shear forces. One possible explanation for this lack of variability is insufficient fatigue developed in participants. As participants were not constrained in their motion as in the Parnianpour et al. (1998) study, perhaps recruited muscle groups in the back and legs were able to effectively compensate for localized fatigue of the erector spinae. In a free lifting situation where individuals experienced global fatigue, perhaps the results of the Levene's test would be different. An alternative explanation for this is that real variability in terms of a median deviation of dependent measures does not actually change as a function of fatigue. Parnianpour et al. (1988), when referring to variability, simply meant that range of motion increased as a function of fatigue. While this might imply a wider distribution of points around a mean, it could just as easily imply a median shift as a function of fatigue, with the distribution of points around that median remaining the same. In the follow-up work conducted by Sparto et al. (1997), standard deviations were given for all variables recorded at the beginning and end of the fatiguing lifting task, even though they were not analyzed with the Bartlett test for change in variance. However, in subjectively examining the standard deviations reported, there appeared to be little or no change in standard deviation of most dependent variables as a function of fatigue.

The LMM data generally showed trends that were different from the force plate data. One LMM variable, however, did exhibit a slight increase over time was the maximum coronal acceleration. But despite showing a significant trend in the ANOVA, the Tukey-Kramer HSD test found the effect of time on coronal acceleration to be negligible. This discrepancy can be attributed to only a marginal significance of the Time effect on coronal acceleration. Notice that the p-value for the effect is 0.0403 (from Table 3.6), which is on the border of significance. Given the large sample size, it is possible that in a marginally significant case such as this, the ANOVA may lean toward finding significance, whereas the Tukey-HSD may not. Unfortunately, this is not in line with the research of Parnianpour et al. (1988), who showed that trunk coronal motion and velocity increased as a function of fatigue. As the coronal acceleration (or velocity change) is a primary path by which force can be transferred to the feet in the lateral direction, it seemed likely that the two might behave similarly. That is, it was thought that increasing range of motion in the coronal plane would lead to increasing acceleration which would lead to increased lateral shear forces. However, an alternative source for the increasing lateral shear force in the narrow stance could be increasing lateral motion of the load box. It is possible that the fatigue in the shoulders or upper arms could have allowed for this possible increased acceleration of the load.

Also interesting was the change in sagittal position and acceleration of the trunk over time, which followed a very non-linear path. Both indicate a decrease in sagittal motion and acceleration during the first three Time periods. This is similar to the results of Parnianpour et al. (1998), who found decreased trunk motion and velocity in the sagittal plane as a function of fatigue. However, there was an observed increase in sagittal trunk motion and acceleration during the remaining two Time periods, which could possibly be indicative of a change in lifting strategy. That result conforms with the results of Sparto et al. (1997), van Dieën et al. (1998), and Bonato et al. (2003), all of whom found increases in trunk range of motion as a function of time. Specifically in the works of van Dieën et al. (1998) and Bonato et al. (2003), lifters were found to move from a squat lifting strategy to a stoop lifting strategy as they became more fatigued.

Upon recalling the behavior of participants in this study and looking at the pattern of sagittal motion and acceleration, it is possible that this study actually confirms both patterns of motion as a function of fatigue. While the majority of participants did not drastically alter their lifting strategies so that they were easily perceptible by the experimenter, some of the more heavily fatigued participants did noticeably alter lifting strategy not once, but twice during the task. Participants all began lifting with a strategy combining both stoop and squat techniques. However, it appeared that, as the muscles of the back became fatigued from lifting, more of the lifting motion was transferred to the legs. But the legs appeared to eventually become fatigued while the back muscles were granted a partial reprieve from the load burden. Once the legs became too fatigued to continue bearing the burden of the lift, the participants tended to adopt a more stooped posture to remove stress from the legs.

Beyond the fatigue effects on trunk motion, stance appeared to have no consistent effect on trunk kinematics. There is no precedent for this relationship, so it is not conclusive that there is definitely not any stance effect. However, I believe that stance effects will only be seen between stances where either the angle of the pelvis relative to the shoulders changes from one stance to another or one of the two levels of stance puts the lifter in a position where loss of balance is likely. Therefore, the reason for my belief that there was no change in trunk kinematics as a function of stance in this study was that there simply was not enough difference in the stance levels. While the feet were further apart in the wide stance, that distance did not change the angle of the pelvis relative to the shoulders or the lifting platform; the lifting and landing destination remained the same distance from the pelvis in the transverse plane and only slightly closer in the vertical direction. This small change in vertical distance from the L5/S1 joint to the lifting platform between stances was, I believe, much too small to be perceived by the participants. Consequently, their trunk behavior was very similar between the stances. Further, despite the small foot separation in the narrow stance, the foot positions were still sufficiently wide to keep the system (box and human) center of gravity well within the trapezoidal envelope marked by the feet and to allow the participants to generate large counter moments which kept them from losing balance in the presence of large trunk accelerations. However, if the feet were so close together that the center of gravity of the system routinely reached the edge of the foot envelope or if the musculature of the legs were too weak to generate a large enough force for a top-lifting-speed counter moment, I believe it quite likely that differences would be seen from that stance to one of the stances used in this study. More research should be done to confirm or challenge the results presented here.

Again, with regard to the predicted variability of trunk motion and acceleration as seen in previous works, no significant trends were unveiled. This could be the result of a variety of factors, including how the data were recorded and calculated or simply that the participants in this experiment were not as variable as other groups for some reason or other (i.e. age, athletic ability, or some unknown factor). Subjectively, I do not believe that the lack of variability was a result of extreme fitness or athletic training on the part of the "average participant." Some lack of variability could be due to the relatively young age of all of the participants, as younger persons have been found to be somewhat less variable in their motion control (Okada et al. 2001). It is also unlikely that the lack of perceived variability is a product of the way variability was measured and calculated in terms of the median deviation. While it is true that the peak values from which the median deviations were calculated could have occurred at any point during the concentric range of motion, they were not randomly dispersed within that time frame. All peak positions occurred at the point where the participants touched the load to the load platform, and all peak accelerations were found to take place very near the peak position. Therefore, any variability would have been found for the same point in each participant's lifting pattern. Ultimately, I think that the most likely reasons for the absence of increasing variability as a function of Time into the study are the same as for the lack of variability found in the GRF data, i.e. either a lack of fatigue or no real dependency exists.

Ultimately, the results from the force plates and the LMM combine to indicate that lower body position as well as fatigue and repetition impact lifting kinematics and ground reaction forces. During a lifting task, workers' feet are the only conduit for friction which can keep the lower part of the body in place while the torso is accelerating in any of the three planes of motion. Therefore, as trunk acceleration changes as a worker performs more lifts, so too do the shear forces between his feet and the ground. Here, as is consistent with Sparto et al. (1997) and Dolan and Adams (1998), individuals experience less control and increased spinal accelerations the longer they progress into a fatiguing task. In both studies, participants lifted moderately heavy loads for a large number of lifts similar to that of the current study. Sparto et al. (1997) documented increases in trunk flexion and deviation of load from the starting point as a function of time into the task. Dolan and Adams (1998) found similarly increasing trunk flexion as a function of fatigue which was accompanied by increasing spinal moment. In the current study, this increase in trunk motion, along with increase in acceleration in time, led to the increase of lateral ground reaction forces in the narrow stance.

However, it is not understood why the participants' maximum trunk acceleration behavior was not mimicked by the maximum anteroposterior shear forces. One possible explanation is that in the anteroposterior directions, individuals' lower body inertia manages to counteract the inertia of the upper body, as the trunk and upper legs rotate in opposite directions in the sagittal plane. The body has no neutral posture limbs to counterbalance in additional accelerations in the coronal plane; therefore, even the seemingly minute changes in coronal acceleration can create significant shifts in lateral ground reaction forces.

One last point that is not fully understood is why the lateral shear forces were not affected by lifting time in the wide stance. It was first thought that this could simply be a masking effect, due to the substantially increased lateral GRFs created by the change in leg angle. However, as the torso did not experience a similar pattern of coronal acceleration as a function of time in the wide stance as the narrow stance, this seems less likely to be the culprit. It appears more likely that stance may perhaps, itself, be a cause of some variability. It has been shown that factors such as asymmetry and velocity can affect muscular forces in the back (Granata et al., 1998), which would then impact the magnitude of the compensatory ground reaction forces. Hypothetically, it seems possible, then, that extreme stances such as the one used in this experiment could create similar variations in lifting performance such that any effect of time or fatigue could well be masked.

The limitations present in this study were those that plague many laboratory studies and a few that do not. Firstly, real-world adaptability is not guaranteed. While there are many occupations that require use of asymmetric lifting, stooping postures, or both (harvesting, construction), they are likely not so intensive that some individuals would not even be able to perform them for 10 minutes. Secondly, this task targeted only the muscles of the erector spinae group to be fatigued. In an occupation where an individual performed steady lifting tasks for a period of many hours, other types of fatigue would be present, such as fatigue of viscoelestic structures due to prolonged stooped postures, whole body fatigue due many hours in harsh outdoor environments, or mental fatigue due to boredom or an excess of objects to track and lift. These types of fatigue could contribute further to increases of magnitude seen in ground reaction forces as they could cause additional loss of control of body motion.

A second limitation in terms of applicability to real world scenarios involves my claim that increased shear forces as a function of either time or stance would cause an individual to slip in a situation where the coefficient of friction was sufficiently low. In the event where friction were indeed low enough for the shear forces determined in this study to allow sliding, it is possible that people could change their lifting stance or behavior in anticipation of slipping in order to decrease the required coefficient of friction to prevent a slip (Cham & Redfern 2002). Despite the ability of individuals to decrease required coefficients of friction, a point of combined whole body, localized, mental, and viscoelastic fatigue may be reached where motor control is impinged to the point that careful motion and force control is not possible. In such intensely fatiguing occupations such as these, this particular limitation is not likely to come into play.

A final limitation with the study is the frequent changes of stance. While they were necessary due to the rapid nature of the experiment and the heavy loads lifted, they also interrupted steady state lifting. Those interruptions broke the rhythm of steady state lifting in a given stance, which could have affected the ground reaction forces recorded for lifts after the stance changes. However, because so many data points were used per time period, and the data were all averaged for each minute of lifting, any transitional effects should have been muted.

Despite the limitations present in this study, the lessons learned can be used and built upon for future research. While the effects of fatigue on the musculoskeletal system are fairly well understood, much less in understood, or even known, about the external effects of fatigue on the body and the potential they have for causing injury. One area of interest would be to determine the effects of fatigue from a more realistic occupation, such as harvesting crops. This would involve introducing additional forms of fatigue, which would require lighter loads lifted for longer periods of time under perhaps more extreme circumstances. However, if this were to be investigated, more sophisticated methods of quantifying, or at least verifying, the multiple types of fatigue would be needed. One possible method of verifying whole body fatigue would be to record EMG data from multiple muscle groups, possibly including some groups that are known to be recruited after primary muscles become fatigued. Another, simpler method would be to have participants rate various types of fatigue during breaks.

Another area for future research to explore is lifting on surfaces which have low coefficients of friction. Realistic surfaces such as icy, muddy, or wet soil should be simulated to more fully understand lifting behavior in a realistic environment where the worker has knowledge of the state of the ground. If friction could be varied along with stance and angle of asymmetry, very interesting results could be discovered, and realistic probabilities of injury could be determined. Hopefully, the effects of asymmetry, fatigue, and stance could be evaluated at multiple levels of realistic coefficients of friction. The problem with this type of experimentation, however, is the ethical dilemma of collecting real slip data and preventing participants from actually falling and hurting themselves. Much work would have to go into the design of safe apparatus before such studies could be performed.

Ultimately, I would propose a study involving a prolonged lifting trial lasting two to four hours with four levels of asymmetry, two levels of stance, and at least two difference coefficients of friction. I would record trunk motion data with a magnetic tracking system instead of the LMM, and I would use force plates with a removable slick, plastic cover and calculate the RCOF during lifting. I would record EMG data of the multifidus and vastus medialis, as they would bear the burden of the lifting. I would also include a verbal survey used to assess whole body fatigue and localized fatigue of the back and quadriceps. A study of this magnitude would not only require fit participants, but also two or three experimenters just to set up the apparatus and record data properly.

Such a redesigned study, though complicated, could be important to assessing the realities of the fatigue effect on ground reaction forces and slip potential in a realistic scenario. Fatigue has too long been restricted to confined apparatus and motor behavior. Only recently has research been conducted to examine the external effects of fatigue, which can include back injuries or slips, falls, and much more serious injuries. Only through expanded, more realistic studies can more accurate determinations be made about the dangers or likelihood of fatigue related GRF behavior.

5.0 Conclusion

A study was conducted in the ergonomics lab at North Carolina State University. The goal of the study was to assess the effects of fatigue on ground reaction forces and trunk motion during a repetitive lifting task. participants were involved in a 10-minute fatiguing lifting bout during which they lifted and lowered a weighted box at a rate of one cycle every five seconds. The load lifted was equal to 40 % of participants' maximum voluntary contraction.

It was observed that lateral shear forces were significantly affected by time in the narrow stance, which resulted in an increase in average peak shear force from 43 N to 51 N over the course of 10 minutes. Stance was also found to affect lateral shear forces, resulting in an increase from about 40 N to about 80 N as stance width doubled. Anteroposterior shear forces were only found to be affected by stance, which induced a decrease in force from about 40 N to about 30 N as stance width was doubled.

Trunk position and acceleration in both coronal and sagittal planes were found to be affected by time in the narrow stance. The relationship between these variables and time into the task appeared to be parabolic in nature, with a minimums occurring during the third time period. Maximum sagittal position varied in both stances from near 75 degrees at the beginning and ending of the task as compared with only around 70 degrees during the middle lifting phases. Coronal position followed a similarly parabolic curve in the wide stance, ranging from around 10 degrees at the beginning and end of the task to around 8.5 in the middle lifting time block. Coronal position in the narrow stance, however, followed a general decreasing pattern, moving from 9 degrees maximum flexion during the first time block to 8 degrees during the final lifting period. Also following the general parabolic trend were accelerations in the sagittal plane. In the wide stance, sagittal acceleration peaked at 580 deg/s^2 during the first and last time periods, while seeing a low maximum of 520 deg/s^2 during the middle time segment. A similar pattern existed for sagittal acceleration in the narrow stance, with the range being from 600 deg/s^2 during the first lifting period, 540 deg/s^2 during the middle period, and 580 deg/s^2 during the final period. Coronal acceleration was not found to be affected by time in the wide stance, but it did generally increase with time in the narrow stance from 61 deg/s^2 during the first time period to 68 deg/s^2 during the final time period. The effects of stance on trunk position and acceleration varied greatly from time period to time period, not resulting in any clear trend. Interestingly, none of the dependent measures of variability was found to be significantly affected by time, as would have been expected.

The results of the study show clear, but small, increases in shear forces due to time into task, but only in the narrow stance. Larger increases in shear forces are shown as stance width increases from shoulder width to twice shoulder width. In order for the recorded shear forces to indeed cause a slip, the coefficient of friction would have to be very low. Industries such as agriculture and construction, who frequently work on wet, icy, or muddy ground, should take caution to help limit employees' fatigue and teach proper lifting techniques with a shoulder-width stance.

Ultimately, this research can be used to further expand the information base on the effects of fatigue on external forces. These results are largely consistent with similar studies, and it is hoped that, with those studies, more accurate and safe lifting techniques and guides may be developed.

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United States Bureau of Labor and Statistics. Construction Laborers http://www.bls.gov/oco/ocos248.htm#nature.

Appendix A

Informed Consent Form

North Carolina State University
INFORMED CONSENT FORM for RESEARCH

Title of Study: *The Effect of Fatigue on Asymmetric Lifting*

Principal Investigator: Jonathan Drum Faculty Sponsor (if applicable): Dr. Gary Mirka

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We are asking you to participate in a research study. The purpose of this study *is to discover how fatigue of the muscles of the lower back impacts an individual's ability to perform a stable lift which is asymmetric over a period of time.* YOU MUST BE 18 YEARS OF AGE OR OLDER to participate in this study.

INFORMATION

If you agree to participate in this study, you will be asked to participate in a fatigue experiment involving a freestyle lifting task. The procedure is as follows: (1) you will warm up by lifting 30 pounds and then stretching, (2) you will have five sensors placed on different muscles of the lower back, (3) you will be asked to push maximally with your back against a stationary bar in an apparatus similar to a piece of exercise equipment (you will perform this exertion twice), (4) motion sensors will be placed on the sections of the upper and lower back (5) you will then be asked to lift a load equal to 40% of your personal capacity for 120 repetitions. You will start in a standing position with the load in your hands. Every five seconds, you will be asked to bend over and touch the load to the ground and stand up again Every minute, you will change your foot separation distance from shoulder width to a measured distance of two times the shoulder width or vice versa. (6) You will again be asked to lean over so that the load is at the level of the top of the kneecap and you will hold this position for five seconds. This step will be performed twice.

RISKS

The lifting task will induce muscle fatigue and some discomfort in the muscles of your back and/or legs. This is normal. If you have any chronic problems or recent injury or pain in your low back, knees, or hips, you should not participate in this experiment. If you have not had such an injury or condition, please mark your initials here: _____. If you experience any numbness, tingling, or sharp pains during the study please stop immediately and notify the researcher. If the researcher determines that it is in your best interest to stop, he will remove you from the study. There is some risk of skin irritation to people with very sensitive skin, even though all adhesive tapes used in the experiment are hypoallergenic. If you have very sensitive skin, please tell the researchers now. If you do not have such sensitivities, please mark your initials here: _____. Finally, you may experience some muscle soreness for a couple days after the experiment similar to that felt after a heavy workout.

BENEFITS

While there is not direct benefit to you from the study, this experiment could benefit the workplace by lowering the number of low back injuries due to constant lifting. By discovering how stability and posture vary as a function of fatigue, new training and lifting procedures can be implemented which will help reduce instability and limit forces placed on the spine.

CONFIDENTIALITY
The information in the study records will be kept strictly confidential. Data will be stored securely in a folder locked up in a filing cabinet in the ergonomics lab. No reference will be made in oral or written reports which could link you to the study. Videotapes of the experiment will be destroyed after the study is finished.

COMPENSATION (if applicable)
For participating in this study you will receive a T-shirt from Ergolab.

EMERGENCY MEDICAL TREATMENT
If you need emergency medical treatment during the study session(s), the researcher(s) will contact the University's emergency medical services at 515-3333 for necessary care. There is no provision for free medical care for you if you are injured as a result of this study.

Initial Here________

CONTACT
If you have questions at any time about the study or the procedures, you may contact the researcher, Jonathan Drum**, at** 3232 H Shire Lane Raleigh, NC 27606**, or** [919-515-7210]**. If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Matthew Zingraff, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/513-1834) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)**

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT
"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time."

Subject's signature____ Date _________________

Investigator's signature___________________________________ Date _________________

Appendix B

Assumptions of ANOVA and Data Transformation

B.1 Independence Assumption

The independence assumption was tested graphically through the use of a plot of residual versus time as advocated by Montgomery (2001). An example of a typical plot can be seen below in Figure B-1. Notice that there do not appear to be any trends in the residual as a function of the order in which the points were recorded

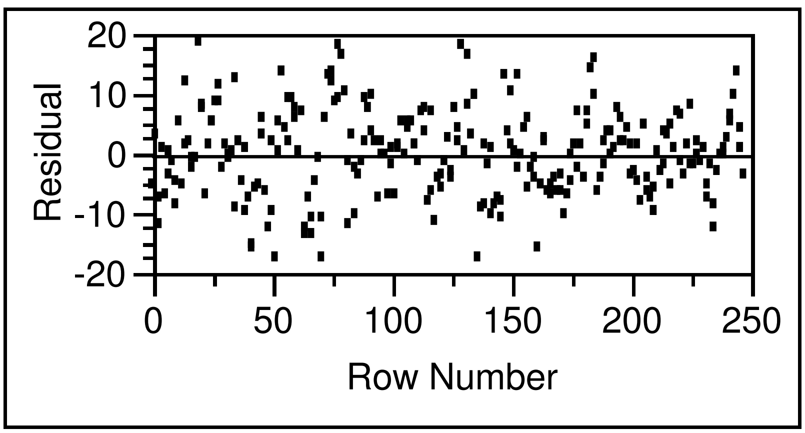

Figure B.1: Residual as a Function of Collection Order

B.2 Assumption of Constant Variance

The assumption of constant variance was tested graphically through the use of a plot of residual versus predicted value of each variable as described by Montgomery (2001). An example of a typical plot can be seen below in Figure B-2. Notice that the distribution at each level of predicted value does not appear to vary in magnitude.

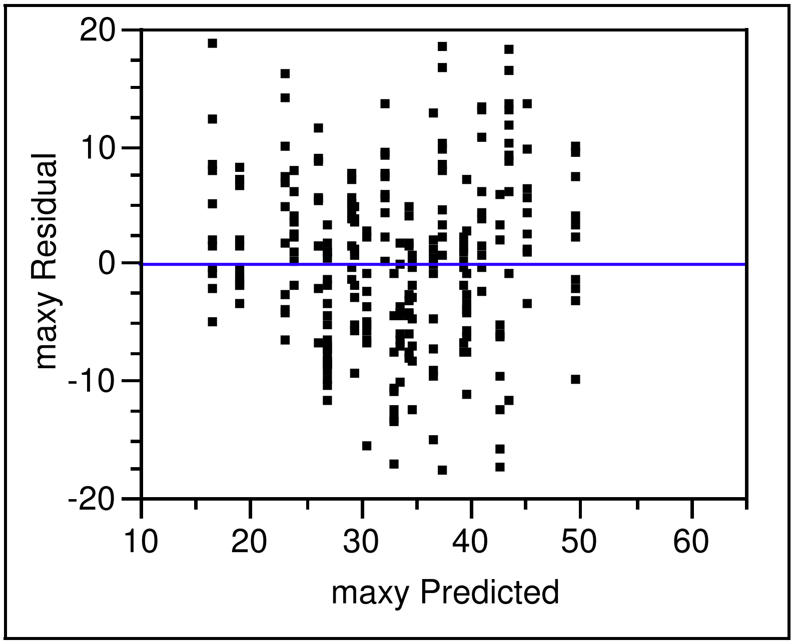

Figure B.2: Residual by Predicted Value

B.3 Normality Assumption

The assumption of normality was verified graphically through the use of a normal quantile plot of the residuals as advocated by Montgomery (2001). An example of a typical plot can be seen below in Figure B-3. Notice that the distribution of the residuals approximates a straight line with slope equal to unity. Notice also that the bar graph distribution resembles the bell-shaped curve associated with a normal distribution.

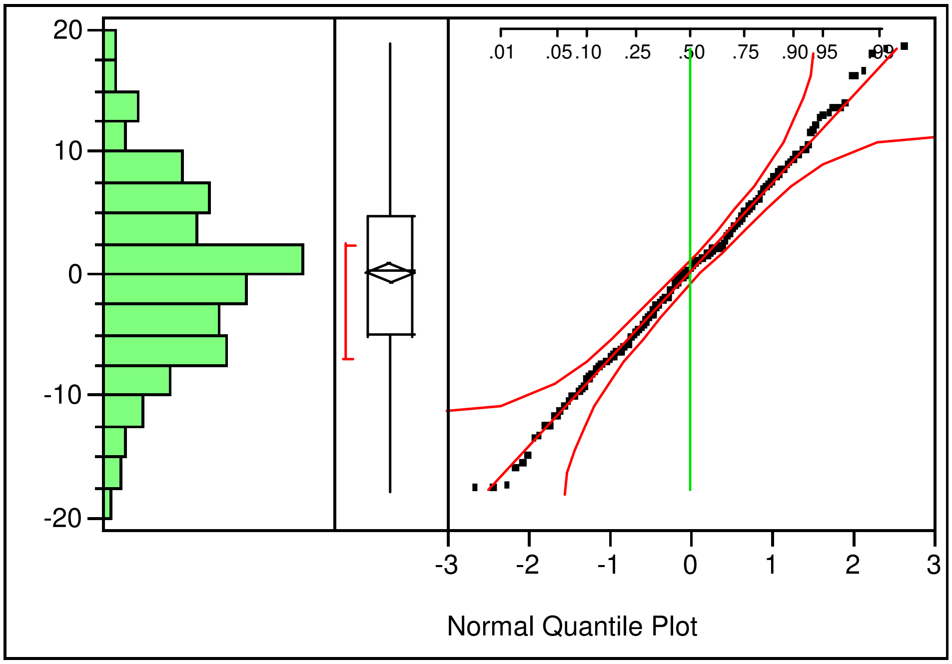

Figure B.3: Normal Quantile Plot of Residuals

B.4 Logarithmic Transformation

In the case of the median deviation data, the nature of Levene's test required that individual ANOVAs be performed on each of the median deviation variables. Because median deviations can never be negative, the assumption of constant variance was violated in all those data. To compensate the data were transformed using the natural log function as seen below in Equation B.1.

$$md_{ij} = \ln\left(md_{ij} + 1\right) \qquad \text{(B.1)}$$

In Equation B.1, md_{ij} is the i^{th} column, j^{th} row of median deviation data. All median deviations were increased by one before the natural log was used in order to avoid null set responses resulting from the natural log of zero. The results of the transformation can be seen in the following three sections.

B.4.1 Transformation Effect on the Independence Assumption

In Figures B.4 and B.5, below, the before and after effects of the natural log transformation of median deviation can be seen in the plot of residual versus time. Notice there is no real change from untransformed to transformed data, with the exception of the reduction in magnitude of the outliers. Therefore, no problems with independence assumption resulted from the transformation.

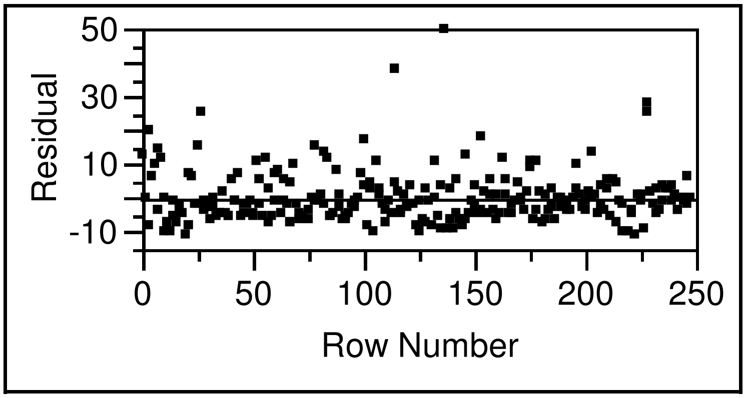

Figure B.4: Residual by Row prior to Natural Log Transformation

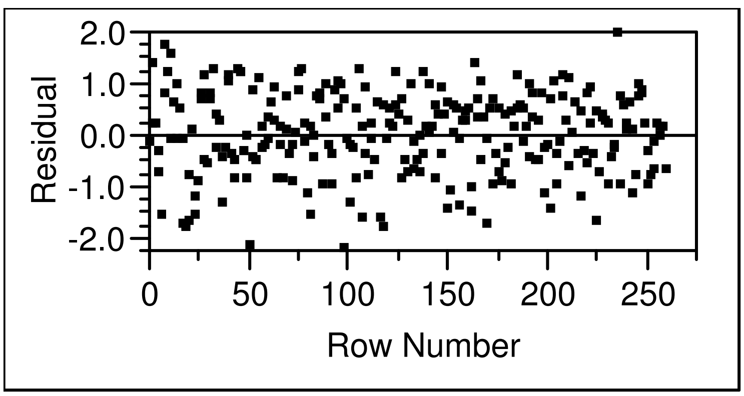

Figure B.5: Residual by Row (Time) after Natural Log Transformation

B.4.2 Transformation Effect on the Assumption of Constant Variance

In Figures B.6 and B.7, below, the before and after effects of the natural log transformation of median deviation can be seen in the plot of residual versus predicted value. Notice there is a dramatic change in variance from the untransformed to the transformed data. The variance in the untransformed data continually increases as a function of predicted on both the tope and the bottom of the graph. The increased variance in the upper bounds is eliminated by the transformation. The only-positive nature of the data, however, prevents the elimination of the hard boundary at lower magnitudes on the residual axis. Therefore, the violation of the constant variance assumption was remedied as much as possible.

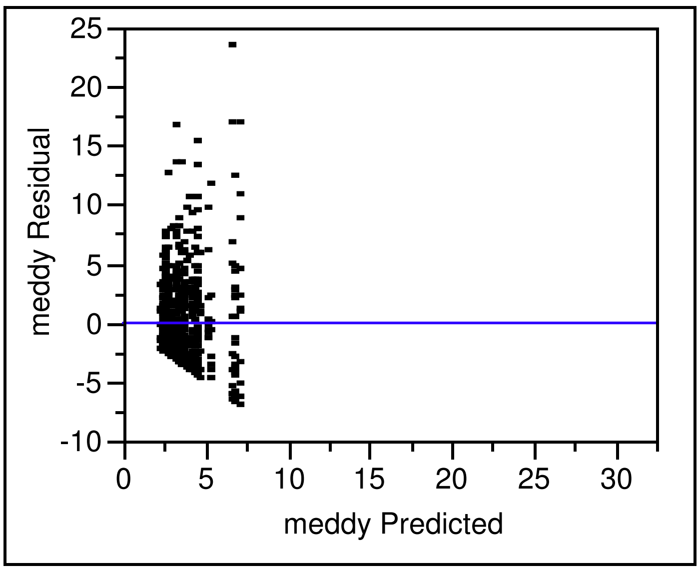

Figure B.6: Residual by Predicted prior to Natural Log Transformation

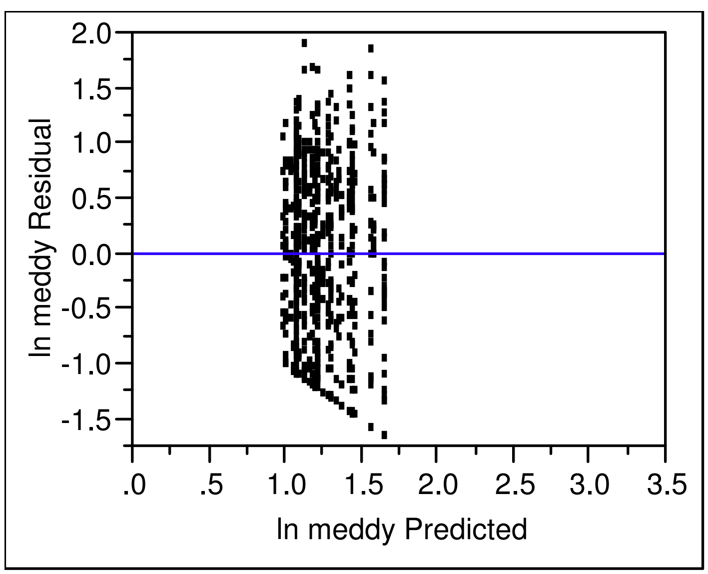

Figure B.7: Residual by Predicted after Natural Log Transformation

B.4.3 Transformation Effect on the Normality Assumption

In Figures B.6 and B.7, below, the before and after effects of the natural log transformation of median deviation can be seen in the normal quantile plot of residuals. Notice there is no dramatic change in the results of the plot; however, the residuals do develop a more normal distribution as a result of the transformation.

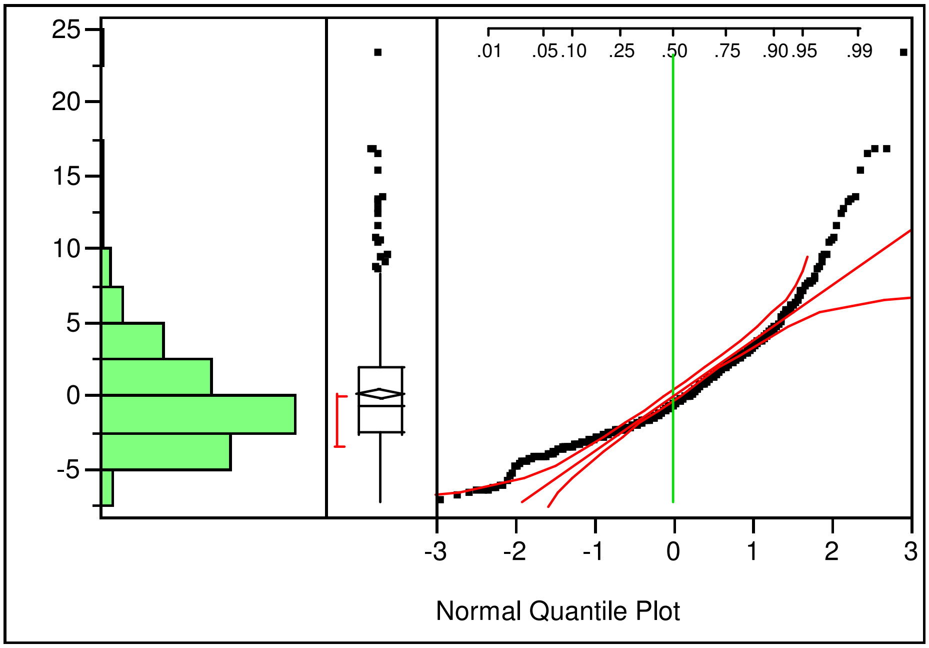

Figure B.8: Normal Quantile Plot of Residuals prior to Natural Log Transformation

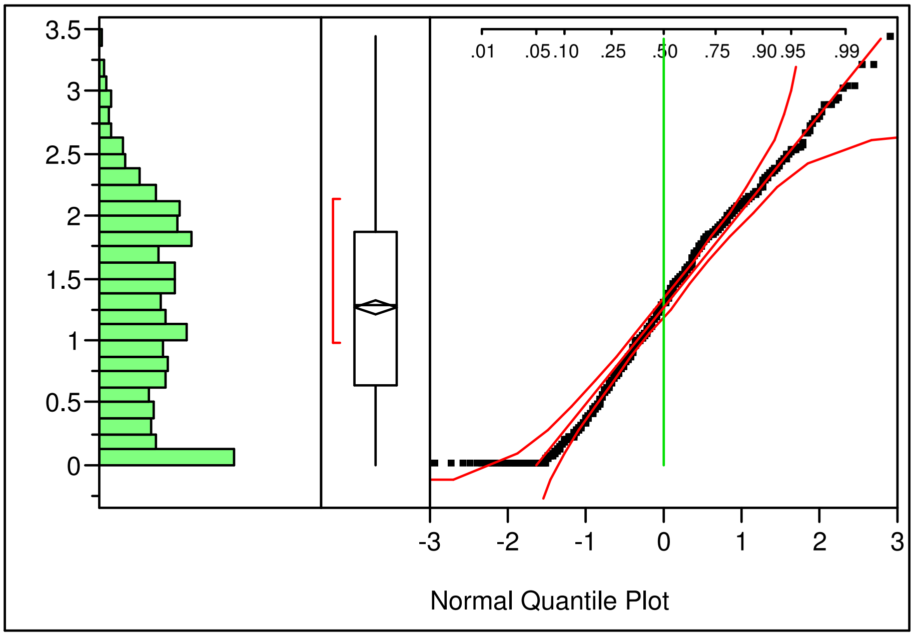

Figure B.9: Normal Quantile Plot of Residuals after Natural Log Transformation