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The Effect of a Repetitive, Fatiguing Lifting Task on Horizontal Ground Reaction Forces

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There are many outdoor work environments that involve the combination of repetitive, fatiguing lifting tasks and less-than-optimal footing (muddy/slippery ground surfaces). The focus of the current research was to evaluate the effects of lifting-induced fatigue of the low back extensors on lifting kinematics and ground reaction forces. Ten participants performed a repetitive lifting task over a period of 8 minutes. As they performed this task, the ground reaction forces and whole body kinematics were captured using a force platform and magnetic motion tracking system, respectively. Fatigue was verified in this experiment by documenting a decrease in the median frequency of the bilateral erector spinae muscles (pretest-posttest). Results indicate significant ($p < 0.05$) increases in the magnitude of the peak anterior/posterior (increased by an average of 18.3%) and peak lateral shear forces (increased by an average of 24.3%) with increasing time into the lifting bout. These results have implications for work environments such as agriculture and construction, where poor footing conditions and requirements for considerable manual materials handling may interact to create an occupational scenario with an exceptionally high risk of a slip and fall.

Key Words: slip, agriculture, lumbar injury

Low back pain (LBP) is a considerable health problem worldwide. It has been estimated that LBP affects up to 85% of the population at some point during their lifetime (Andersson, 1998; Korff, Dworkin, LeResche, & Kruger, 1988). In 2002 the incidence rate for nonfatal occupational illness and injuries affecting the lower back was 39.1 out of 10,000 full-time workers in private industry—a higher rate than for any other body segment. The direct costs (treatment costs, lost wages, disability costs) paid annually in the United States for workers' compensation benefits for work related LBP was estimated to be over $11 billion during 1989 (Webster

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& Snook, 1994). The recognized work related risk factors for the development of LBP include heavy physical work, lifting, forceful movements, bending and twisting (awkward postures), whole-body vibration, and long-term static work postures (Chaffin & Park, 1973; Dept. of Health & Human Services, 1997; Liles, Deivanayagam, Ayoub, & Mahajan, 1984).

Muscular fatigue of the primary trunk extensor muscles, the erector spinae muscle group, is often a response to long-term or repetitive exposure to many of the aforementioned risk factors and has also been considered a risk factor in its own right. The exact mechanism that leads from fatigue to injury has not been completely described, but it is believed that there are multiple pathways through which fatigue can contribute to the development of LBP. Some have argued that the fatigue of back and leg muscles (and resulting muscular discomfort) due to repetitive lifting will induce conscious changes in lifting techniques and sagittal plane lifting kinematics. They reason that these changes will ultimately fundamentally affect the anterior/posterior (A/P) shear and compression loading of the spine. For example, Sparto, Parnianpour, Reinsel, and Simon (1997a, 1997b) found that fatigue was associated with decreased knee and hip motion, increased lumbar flexion, and increased migration of whole-body center of pressure. More generally, others have found that the lifting strategy changes from a predominately squat-lifting strategy (bending of the knees) to a predominantly stoop-lifting strategy (bending of the trunk) with fatigue (Bonato, Ebenbichler, Roy, et al., 2003; van Dieën, van den Burg, Raaijmakers, & Touissaint, 1998).

Others have shown that fatigue can induce changes in the amount of off-plane motion (motions in the coronal and transverse planes) leading to changes in the lateral shear and torsional loads in the spine (Parnianpour, Nordin, Kahanovitz, & Frankel, 1988; van Dieën et al., 1998). Parnianpour et al. (1988) illustrated an increase in these off-plane motions during a sagittally-symmetric, fatiguing, trunk flexion/extension exercise performed in an Isotechnologies B200 dynamometer apparatus. They attributed these off-plane motions to a significant loss in motor control of the low back muscular system and expressed concern that this loss of neuromuscular control may diminish the system's ability to protect the weakened viscoelastic elements of the spine.

One aspect of this fatigue-induced reduction in motor control that has not been addressed in the literature is how the resulting kinematic variability impacts the horizontal ground reaction forces. It has been shown that slips and falls are a major concern in the workplace and a leading source of occupational injuries (Courtney, Sorock, Manning, Collins, & Holbein-Jenny, 2001). Much of the research on slips and falls has focused on the potential for these events during gait (Cham & Redfern, 2002; Hsiang & Chang, 2002; Lockhart, Woldstad, & Smith, 2003; Redfern, Cham, Gielo-Perczak, et al., 2001), and these studies have shown that the most influential biomechanical factor to a potential slip event is the horizontal shear force at the point when the sole of the shoe makes contact with the surface. This factor is particularly important when the static coefficient of friction is small enough to be easily overcome by a small shear force.

The literature on gait also highlights the negative results that these slip events have on the impact loading of the musculoskeletal system, both from the perspective of the high muscular forces exerted in an attempt to prevent the fall once the slip has been initiated and on the physical impact when the body hits the ground (e.g., Marigold & Patla, 2002). While these slip events are often studied during gait, there are a number of work environments that provide environmental conditions with sufficiently low coefficients of friction in the footing which make nonambulatory work tasks (lifting and other materials-handling activities) risky for a slip and fall event. This scenario makes the off-plane motions shown by Parnianpour et al. (1988) an important response, and one that may be controlled somewhat by adjusting the width of the stance of the lifter, as illustrated by Wu and MacLeod (2001).

The aim of this experiment was to evaluate the effects of fatigue of the low back musculature on the ground reaction forces during a repetitive lifting task. It was hypothesized that the compromised neuromuscular control induced through a fatiguing, repetitive, free-dynamic lifting task will increase the magnitude of the horizontal (lateral and A/P) ground reaction forces, and that the nature of this response may be influenced by the stance width of the lifter. The relevance of the results of this work to outdoor occupational settings is considerable and may lead to a more fundamental understanding of this mechanism of acute back injury and potential work practices interventions.

Methods

The participants in this experiment were 8 male and 2 female college students ranging from 22 to 31 years of age (mean = 26 yrs). Means and standard deviations of relevant anthropometric characteristics were as follows: stature 174.3 cm (±13.1); mass 72.8 kg (±24.5); shoulder width (acromion-acromion) 34.8 cm (±3.5). Potential participants were excluded if they had current or chronic problems with their back or lower extremities. This relatively homogenous group of participants was chosen to reduce the influence of variability due to age, injury history, etc. It is recognized that this approach somewhat limits the generalizabilty of the results, but as an initial examination of this phenomenon this approach allowed for an exploration of the stated hypotheses. Each participant provided written informed consent (IRB approved) prior to taking part in the study.

Upon arriving at the laboratory, the participants were familiarized with the experimental procedures and performed a short warm-up exercise. Then Ag-AgCl surface electrodes were secured over the right and left pairs of the erector spinae muscles to collect the activity data from these muscles (processing characteristics: total amplification 55,000x, 10–500 Hz band-pass filter, and 59–61 Hz notch filter). This data was used exclusively to document fatigue of these muscles from the beginning (pretest) to the end (posttest) of the experimental procedures.

Prior to the lifting task, each participant performed a maximum voluntary isometric trunk extension with the back flexion angle at 60° from upright in the sagittal plane. The maximum voluntary exertion (MVE) was performed in a lumbar dynamometer apparatus and the peak extension moment was recorded (Mirka & Marras, 1993). Using this information, a participant-specific hand-held load was calculated such that each person was exerting 45% of his or her maximum moment capacity when holding a load in the 60° trunk flexion posture during the experimental trials.

Upon completing the MVE, the participant was moved to the lifting task station and four motion sensors from the magnetic motion tracking system were applied (Ascension, Burlington, VT). Three sensors were placed on the participant: one in the center of the back at the T9 level, one on the right upper arm 5 cm above the lateral epicondyle, and one on the lateral side of the right thigh at the midpoint of the greater trochanter and the center of rotation of the knee. A fourth motion sensor was placed in the center of the right face of the load box. This 0.3m × 0.3m × 0.3m wooden box (cut-out handles 14 cm from the bottom of the box) containing a centrally positioned load was then handed to the participant (total load 45% of his or her personal capacity). The participant was then asked to maintain an isometric exertion at 60° of trunk flexion (sagittally symmetric) while holding this box with arms hanging vertically from the shoulders. He or she held this posture for 5 seconds while EMG data were collected (1,024 Hz) to create a baseline (unfatigued) median frequency for the left and right erector spinae muscles.

After the EMG measurements were recorded, the participant was asked to stand on the force platform (Bertec, Columbus, OH) whereupon small wooden blocks were placed to designate his or her foot positions for a wide or a narrow stance. The wide stance was defined as the interfoot distance (from second toe to second toe) of 150% of the interacromion distance of each participant, while the narrow stance was defined as an interfoot distance of 75% of the interacromion distance. The force platform captured the time-dependent forces in the x, y, and z directions as well as moments about the three axes. Once properly positioned on the platform, the participants then undertook the fatiguing lifting task, during which they lowered the box from standing height to the floor (eccentric motion), touched the bottom of the box to a reference cushion, then it raised back up to the vertical position (concentric motion) (Figure 1). They were told that they could use any lifting style they preferred and were allowed to change technique during the lifting bout.

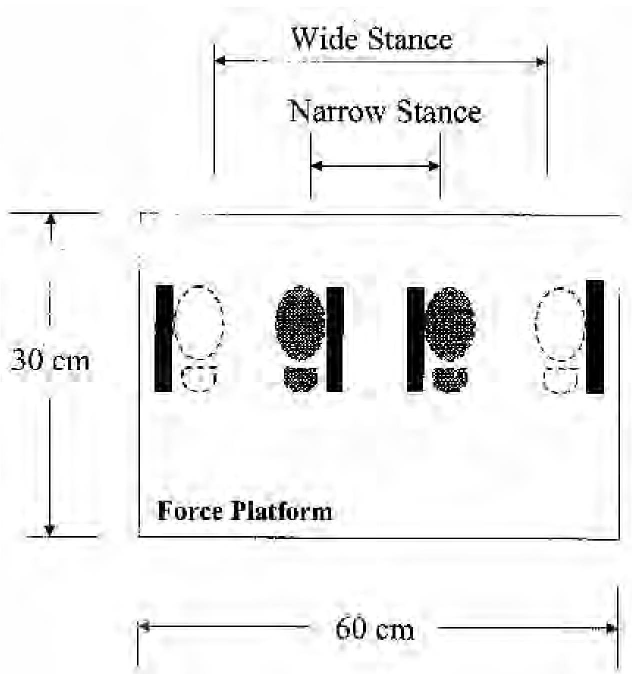

Figure 1 — Layout of the top surface of the force platform showing both stance conditions. Actual distances between the feet were defined by the inter-acromioclavicular distance (AC-AC) as described in the text.

The eccentric/concentric lifting cycle was performed once every 5 seconds for 8 minutes (participant was always holding the load). The initial stance was selected as either wide or narrow (presentation order balanced across participants). At the top of each minute the participants were instructed to change their stance style from "wide" to "narrow" or vice versa. In order to allow them enough time to change stances, 5 extra seconds were given for movement at the beginning of each minute, thus limiting the number of lifts per minute to 11. The body motion and force platform data were collected during the last 30 seconds of each minute. Upon finishing the 8-min lifting task, the participants reassumed the static 60° trunk flexion posture and the EMG signals for the left and right erector spinae muscles were recorded for the postexercise (fatigued) median frequency to verify that these muscles were fatigued by the experimental procedures.

The independent variables in this experiment were Stance (two levels, wide and narrow) and Time (four levels—1,2,3,4—one for every other minute due to the alternating stance width throughout data collection). The dependent variables were peak leftward ground shear force, peak rightward ground shear force, peak anterior ground shear force, peak posterior ground shear force, lateral range of motion of the T9 magnetic sensor, and lateral range of motion of the magnetic sensor on the box. These measures were identified for each lifting cycle (the full concentric/eccentric motion), eliminating the quiet standing time between lifts. The median frequency was used to confirm the effectiveness of the protocol in developing fatigue in the extensor musculature of the low back. The median frequency of these data was calculated using the fast-Fourier transform (FFT) procedure.

Once all relevant data were reduced to these dependent measures, the ANOVA procedure was used to evaluate the effects of Stance and Time on these dependent measures. However, before conducting this analysis, the assumptions of the ANOVA procedure (assumption of normality of residuals, independence assumption, and homogeneity of residuals) were evaluated using the graphical techniques advocated by Montgomery (2001). Significant ANOVA results were followed by post hoc analysis (Tukey's HSD) to further explore the nature of the significant responses.

Results

After the assumptions of the ANOVA procedure were verified, the median frequency data were analyzed to confirm that fatigue was developed through the procedure. Fatigue was confirmed in the erector spinae muscles by showing a consistent median frequency shift across participants: 26% reduction in the left erector spinae ($F = 12.84$, $p < 0.01$) and 22% reduction in the right erector spinae ($F = 37.76$, $p < 0.01$).

The ANOVA of the force platform variables and body segment motion variables revealed no significant interaction effects between Stance and Time. Time was found to have a significant ($p < 0.01$) effect on both the peak lateral and peak A/P ground reaction forces. This significant effect was seen for both the anteriorly directed ($F = 20.14$) and posteriorly directed ground reaction force ($F = 17.46$) as well as the leftward ($F = 10.76$) and rightward lateral forces ($F = 20.14$) (Figures 2 and 3). These increases averaged 18.3% and 24.3%, respectively. A further post hoc test revealed all the ground reaction forces in Time Segment 4 were significantly larger than those in Time Segment 1, while there were some overlaps between Time Segments 2 and 3. Stance had a small but statistically significant effect on the lateral shear forces ($F = 4.14$, $p < 0.05$, for leftward shear force, and $F = 15.6$,

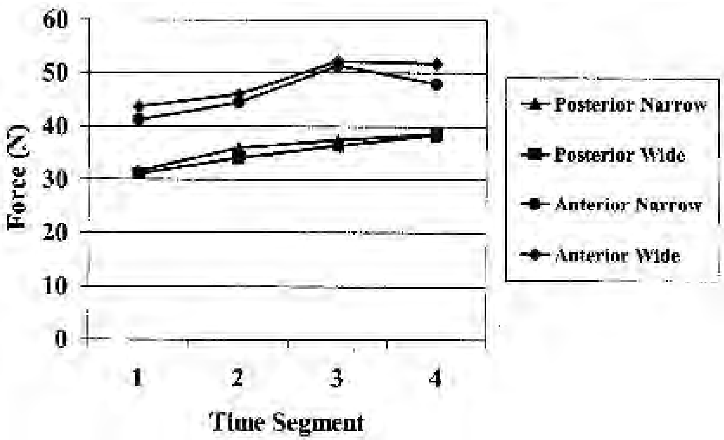

Figure 2 — Effect of Time and Stance on the A/P ground reaction force.

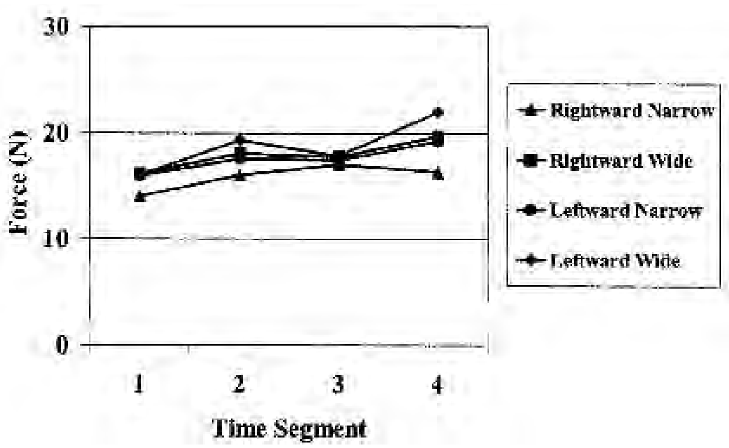

Figure 3 — Effect of Time and Stance on the lateral ground reaction force.

$p < 0.01$, for rightward shear force) (Figure 3), with the wider stance exhibiting on average 10% greater lateral force.

With regard to the motion of the body torso and load, both the A/P and lateral range of motion of the magnetic sensor at the T9 position and the lateral motion of the magnetic sensor on the box also showed increases as a function of Time (14%, 32%, and 21%, respectively) (Figure 4). The post hoc test revealed that these response variables at the end of the lifting period (Time Segment 4) were significantly larger than those at the beginning of the period (Time Segment 1), while there were overlaps during the period (Time Segments 2 and 3).

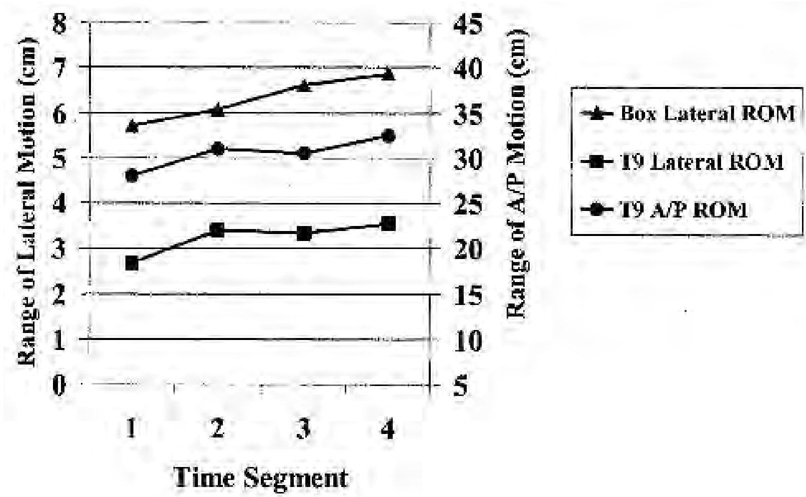

Figure 4 — Effect of Time on the sagittal range of motion of the torso sensor and the lateral range of motion of the box and torso sensor.

Discussion

Force platforms have been used extensively in ergonomics research to aid in the evaluation of different lifting scenarios. Often the data from these instruments have been used as input into inverse dynamics modeling techniques to predict the spine reaction forces during lifting (Dolan, Kingma, De Looze, et al., 2001; Gagnon, 2003; Gagnon, Larrive, & Desjardins, 2000; Gagnon & Smyth, 1992; Granata, Marras, & Fathallah, 1996; Lariviere & Gagnon, 1998; Lindbeck & Arborelius, 1991; Schipplein, Reinsel, Andersson, & Lavender, 1995; van Dieën, Kingma, & van der Bug, 2003), while other researchers have used these data to evaluate the instantaneous center of pressure (Chow, Cheng, Holmes, & Evans, 2003; Heiss & Pagnacco, 2002; Heiss, Shields, & Yack, 2002; Toussaint, Commissaris, van Dieën, et al., 1995).

Fewer studies (Chiou, Bhattacharya, & Succop, 2000; Gagnon, Plamondon, & Gravel, 1993; Kollmitzer, Oddsson, Ebenbichler, Giphart, & Deluca, 2002; Toussaint, Commissaris, Hoozemans, Ober, & Beek, 1997) have considered the importance of horizontal ground reaction forces, as most often the coefficient of friction between the feet and the ground surface is enough to make a slip event unlikely during lifting. Some outdoor work environments, however, have a significant potential for slip during lifting tasks, and it was this scenario that motivated the current work.

The results of this study have illustrated fatigue effects in both the peak A/P and lateral ground reaction forces, but the results also indicate that the underlying biomechanics of the changes are of two fundamentally different origins. First, changes in the A/P ground reaction forces are related to sagittal plane torso movement, a response closely related to the lifting strategy employed by the participants. The anterior and posterior forces both clearly increase as a function of time into the fatiguing lifting task (Figure 2). This is supported by the result of increased

A/P motion range of the lifter's center of mass (Figure 3). It is hypothesized that the increase of A/P ground shear force and torso motion range was brought on by a fatigue-induced change in lifting technique. This hypothesis is supported by the findings of van Dieën et al. (1998) and Sparto et al. (1997a; 1997b) which showed increasing trunk flexion with fatigue. In an occupational scenario it is informative to recognize this increase in the peak A/P ground reaction force in moving from a squat to a stoop lift, and further to consider the impact of this transition on the A/P slip potential.

The changes seen in the lateral ground reaction forces are less reflective of changes in strategy, but more a result of changes in neuromuscular control. The fatigue-induced changes in neuromuscular control demonstrated in previous works (e.g., Parnianpour et al., 1988) have been shown to generate significant increases in peak lateral ground reaction forces in this experiment. Consistent with these previous results, our results have shown significant increases in the lateral range of motion of both the torso and load as a function of time into the lifting bout (Figure 4). These increases in lateral movement of the torso will typically generate greater lateral accelerations of the mass of the torso, resulting in greater lateral ground reaction forces to create these accelerations.

The results of the current work empirically describe the magnitude of these shear forces. In most industrial environments, the coefficient of friction provided by the interaction between a leather, rubber, or composite sole shoe and a dry floor surface are such that this would not result in a significant increase in slip potential. However, in outdoor work environments such as farm fields or construction sites, the "floor" surface is often wet/muddy/icy, and the kinds of changes shown in this study could increase the risk of slip and injury. Further, in most of these environments it is not only the low back musculature that is being fatigued—as was the case in the current study with the focused fatiguing exertions—but also the extremities. This would imply that not only is there more risk of a slip event, but the quick response mechanisms for correcting for the slip are compromised.

Another aspect of the current study that could have an impact on the design of lifting tasks in the agriculture environment is the result found with regard to stance width. A logical solution to increasing stability during a lift is to increase the stance width, thus giving the lifter a wider foot envelope and increasing the lateral distance the torso would have to travel to induce a loss of balance. Further, a wider stance often allows the lifter to move the load closer to the spine (because the load can be held between the knees without interference from the knees), thereby reducing the moment about the spine created by the load. However, the results of the current study show that the wider stance also has the effect of increasing the peak lateral ground reaction force.

In the current lab study the high coefficient of friction between the shoe and the surface of the force platform created a lifting scenario wherein the potential for a lateral slip of one foot or both feet was minimal. But in the agriculture environment, for example, the angle at which the leg intersects the ground defines the degree to which body weight will contribute to the lateral forces at the feet, so not only will there be a greater net lateral shear force, as shown in the current study, but the lateral shear forces for the individual feet will increase, thereby increasing the risk of the feet inadvertently slipping further apart ("doing the splits"). Thus the reasonable recommendation of widening the stance may need to be reevaluated in light of the potential for a slip event.

There are some limitations to the generalizabilty of the current results to the broader occupational setting. First, while our goal was to understand the effects of fatigue on these shear forces and slip potential, the participants in this experiment were not standing on a slippery surface. Workers who are standing on a slippery surface may in fact lift more carefully, focusing some of their attention on these slip forces—a result similar to that shown by Cham and Redfern (2002) in the gait scenario. While we view this as a limitation of the generalizability of our specific results, it should also be noted that the reduction of neuromuscular control is not something within the capability of the individual to overcome, and therefore the trends observed should still hold true.

Second, since only one force platform was used in this study, the lateral ground reaction forces captured by the force platform system refer to the *net* horizontal reaction forces from two feet. The individual forces collected for each foot would likely be considerably higher than those seen here, due to elimination of the canceling effect the two feet had on each other in this experiment. Since the net shear force was shown to increase as time progressed, it is reasonable to say that the shear force on each foot should experience an increase similar in slope and larger in magnitude than those shown here as people become fatigued. Evaluation of the shear forces produced by each foot is an ongoing area of research in our laboratory, and preliminary results show considerable differences between the net ground reaction shear force and the ground reaction shear force experienced by one foot (27 N difference in narrow stance and 45 N difference in wide stance).

Finally, the fatigue that we developed in our pool of participants was very focused in nature, aiming to fatigue the active extensor mechanism in the low back in a short period of time. Other kinds of fatigue are prevalent in agriculture, and to a lesser extent in construction, such as fatigue of the viscoelastic structures of the spine due to prolonged stooped postures, more central fatigue due to boredom and physiological fatigue, and global fatigue due to long-term exposure to a hot working environment. All of these other sources of fatigue can play an additional role in increasing the slip potential beyond that described in the current study.

In conclusion, the results of this work have shown that fatigue does in fact have an impact on the nature of the ground reaction forces. These results show that fatigue produced an average increase in the lateral ground reaction forces of 24.3% and an average increase in the peak A/P ground reaction force of 18.3%. These results can have direct application in agriculture where workers perform strenuous manual-materials handling under slippery footing conditions.

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