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ABSTRACT

Lifting loads that have a horizontal velocity (e.g., lifting from a conveyor) is often seen in industry and it was hypothesized that the inertial characteristics of these loads may influence lifting technique and low back stress. Seventeen male participants were asked to perform lifting tasks under conditions of four horizontal load speeds (0 m/s, 0.7 m/s, 1.3 m/s, and 2.4 m/s) and two lifting frequencies (10 and 20 lifts/minute) while trunk motions and trunk muscle activation levels were monitored. Results revealed that increasing horizontal load speed from 0 m/s to 2.4 m/s resulted in an increase in peak sagittal angle (73 vs. 81 degrees) but lower levels of peak sagittal plane angular acceleration (480 deg/s/s vs. 420 deg/s/s) and peak transverse plane angular acceleration (200 deg/s/s vs. 140 deg/s/s) and a consistent increase in trunk muscle coactivation. Participants used the inertial of the load to reduce the peak dynamics of the lifting motion at a cost of increased trunk flexion and higher muscle activity.

Relevance of the findings for ergonomics research and practice:

Conveyors are ubiquitous in industry and understanding the effects of horizontal load speed on the lifting motions performed by workers lifting items from these conveyors may provide some insight into low back injury risk posed by these tasks.

Keywords: load speed; frequency; lifting; electromyography; trunk kinematics

Introduction

The impact of occupation-related low back pain (LBP) is considerable. Murphy and Volinn (1999) estimated that $8.8 billion was spent on occupational LBP pain claims in US in 1995, and the rate of LBP claims was 1.8 per 100 workers per year. A number of epidemiologic studies have shown an association between low back disorders (LBD) and occupational requirements, including heavy lifting, awkward trunk postures, trunk dynamics during lifting, and whole-body vibration (e.g. Andersson 1981, Bigos *et al*. 1986, Marras *et al*. 1993, Punnett *et al*. 2005). Exploring the relationship between these high-risk occupational requirements and the underlying low back biomechanics can provide insight into the mechanism of injury and can provide clues as to appropriate ergonomic intervention for the prevention of occupation-related low back pain.

Previous research has demonstrated that the dynamics of a lifting motion influence the loading on the spine and the risk of occupational LBD (e.g. Bush-Joseph *et al.* 1988, Lindbeck and Arborelius 1991, Marras *et al*. 1993). In its simplest form, the influence of a rapid lifting motion (i.e. trunk extension) can increase the effective load force (F=ma) and thereby have a direct impact on moment about the spine and spine loading (e.g. Freivalds *et al.* 1984, Lindbeck and Arborelius 1991). In a more complicated relationship, three-dimensional trunk kinematics have been shown to influence risk of low back disorders (Marras *et al*. 1993). In this study of more than 400 repetitive industrial lifting tasks, these authors demonstrated that three, three-dimensional trunk kinematic parameters (average twisting velocity, peak lateral velocity, and peak sagittal flexion angle) influenced the risk of LBD. Based on these results, factors that could influence lifting strategies, and thereby lifting kinematics, should be considered. Participant-dependent factors such as lifting technique (Hsiang *et al*. 1997, Kingma 2004, Marras and Davis 1998), lifting experience (Chany *et al*. 2006, Marras *et al*.

2006), gender (Marras *et al*. 2003), and obesity (Xu *et al*. 2008) can significantly impact lifting kinematics and therefore may affect LBD risk. Likewise, task dependent factors including load magnitude (Lavender *et al*. 2003), load size and stability (Lee and Lee 2002, Marras *et al.* 1999, Ciriello 2007), coupling character of load (Davis *et al*. 1998), lifting origin and destination (Davis and Marras 2005, Lavender *et al*. 2003), lifting speed (Lavender *et al.* 1999, Lin *et al*. 1999), lifting frequency (Hagen *et al*. 1995), and ground surface characteristics (Faber *et al*. 2008, Jiang *et al.* 2005, Matthews *et al.* 2007) have been shown to alter trunk kinematic patterns and influence the risk of LBP. One task-related characteristic that has not been explored relative to lifting kinematics/biomechanics is the effect of horizontal load speed.

Conveyors (both gravity-fed and belt-powered) are ubiquitous in many industrial settings, being used to move loads in automated distribution, baggage handling and warehousing scenarios (Mital 1999). Working with a conveyor typically involves two tasks: loading objects onto the conveyor (loading) and taking objects from the conveyor (unloading). For loading, the lifting task is similar to a basic lifting task because the worker simply lifts the object from a static location to a static position on the conveyor. However, the unloading task is different. As the lifter seeks to gain control of the load while on the conveyor, the load has a horizontal velocity which must be considered by the lifter. Depending on the work area configuration, this inertia may be utilized by the lifter (if the direction of load motion is consistent with the direction of the destination of the load) or may need to be absorbed by the lifter (if the direction of load motion is contrary to the destination of the load). Hence, the horizontal motion of the load can alter the lifting strategy of lifter as compared to lifting a static load. In addition to the simple inertial characteristics of the load, the motion of the load and the limited reach of the lifter mean that the lifters have a relatively short window of opportunity to take the objects from the moving surface. The goal of the current study was to quantify the effects of horizontal load speed and lifting frequency on lifting kinematics and biomechanics.

1. Methods

1.1. Participants

Seventeen males from the university undergraduate and graduate student population of the Iowa State University participated in this study. All were fully informed volunteers and were screened for chronic back problems and current back pain. Each participant signed an informed consent form approved by the Iowa State University Institutional Review Board. The average (standard deviation) of age, stature and whole body mass of participants were 25.3 yr (3.9), 179.2 cm (7.5), and 80.8 kg (19.7).

1.2. Experimental setup apparatus

The experimental setup was designed to simulate the working environment of jobs that require lifting from a conveyor. Two connected gravity roller conveyors (3m each) were used in this study. One conveyor was horizontal (top surface 40 cm above the ground), while the other was connected to this flat conveyor and was angled 8.9 degrees relative to horizontal (Figure 1.) The load was released from a varied location on the tilted conveyor to achieve the required load speeds at the lifting location. These release points were determined through pilot experimentation wherein two infrared photoelectric sensors (Lafayette Instruments Co.) provided precise measures of the load speeds and the release locations were varied until the designated speeds were achieved. Once the unloading points for different speeds were found, markers were placed on the conveyor to make sure the load would be released from the same heights to obtain the designated speeds. Before data collection, pilot tests (15 trials each) to confirm each releasing height were conducted. The speeds (and standard deviations) obtained in this pilot testing were 0.70 m/s (0.11) for the 0.7 m/s condition, 1.29 m/s (0.15) for the 1.3

m/s condition, and 2.37 m/s (0.16) for the 2.4 m/s condition. The variability in these numbers represents the variable interaction between the wheels of the skatewheel conveyor and the underside of the load.

Insert Figure 1 about here

Five plastic milk crates (handles with good coupling 18 cm from base of crate) were used as the load. The size of crates was 33 cm (L) × 33 cm (W) × 28 cm (H), and the total mass of the loaded crates was 10 kg. When performing in the lifting task, the participant faced the conveyor, and the load always came to the participants from their left hand side (Figure 1.) A 69 cm high table was set 50 cm right to the center line of the lifter and 60 cm from the center line of conveyor and was the location of the destination of the load. This configuration resulted in a hand height of 58 cm at the origin of the lift and a hand height of 87 cm at the destination.

1.3. Data collection apparatus

A force platform was used to capture the three-dimensional ground reaction forces and moments (Bertec, Columbus, OH). The sampling frequency was set to 1024 Hz. The direction of the positive ground reaction force and moment vectors are shown in Figure 1.

To capture trunk kinematics, the lumbar motion monitor (LMM) (Chattanooga Group Inc., TN) was used (Marras *et al.* 1992). The LMM provided continuous measures of position, velocity and acceleration in the three cardinal planes of motion: sagittal, coronal (lateral), and transverse (twisting). The raw data generated by the LMM was captured at a rate of 60 Hz.

To capture muscle activation levels, the participants were fitted with 8 pairs of surface electrodes (Model DE-2.1, Bagnoli™). The bilateral muscles sampled and their sampling locations were as follows: (1) erector spinae: 3.5 cm from the vertebral midline at L2 level, (2) rectus abdominis: 5 cm above the umbilicus and 3 cm from the midline, (3) external oblique: about 15 cm lateral to the umbilicus and in the midpoint between the 12th rib and iliac crest, and (4) deltoids: 8 cm lateral from the acromion and centre of the muscle.

1.4. Experimental design

The experimental design included two independent variables: SPEED (0 m/s, 0.7 m/s, 1.3 m/s and 2.4 m/s) and FREQUENCY (10 lifts/min and 20 lifts/min). Both independent variables were within-participant variables. Each combination was replicated twice (total 16 trials per participant). The order of trials was fully randomized.

The dependent variables included measures of ground reaction forces, muscle activation levels and three-dimensional trunk kinematics. These were captured during the concentric lifting motion that began when the participant first touched the box and ended when it was released at the destination. The start and end of each lifting was defined by two trigger signals manually controlled by one investigator during data collection. The values of the dependent variables described as “average” were the average observed during the concentric lifting motion. Dependent variables described as “Max” or “Min” were the instantaneous maximum or minimum values observed during the concentric lifting motion. The dependent variables captured from the force platform were the maximum and average forces in the anterior-posterior direction (MaxFx and AvgFx), the maximum and average forces in medial-lateral direction (MaxFy and AvgFy), and the maximum and minimum moment about the centre of pressure (MaxMz and MinMz). The dependent variables captured from the EMG system were the average, normalized (to maximum) EMG of the eight selected trunk and shoulder muscles with direct influence on these three-dimensional lifting tasks: erector spinae (RES, LES), rectus abdominis (RRA, LRA), external oblique (REO, LEO), and deltoid (RDELT, LDELT). The specific dependent variables describing trunk kinematics were chosen because of their direct impact on spinal loading. They were the minimum sagittal angle (MinSagAng), the maximum sagittal angle (MaxSagAng), the maximum sagittal acceleration (MaxSagAcc), the maximum transverse angle (MaxTranAng), and the maximum transverse acceleration (MaxTranAcc). The MaxSagAng was the greatest degree of sagittal trunk flexion while MinSagAng referred to the most upright posture, both found during the concentric range of motion. MaxSagAcc was the peak acceleration observed during the commencement of the lifting motion (typically occurred near the time of the peak sagittal angle.) MaxTranAng referred to the peak rightward rotation angle of the shoulders relative to the pelvis. MaxTranAcc referred to the peak rightward acceleration of the torso relative to the pelvis (i.e. accelerating the load toward the destination not decelerating the load when it had reached its destination.) For all dependent variables, the values of each measure for each of the five consecutive lifting repetitions during a single trial were averaged into one value to represent that trial (i.e. values described as "Avg" were the average of the five averages, values described as "Max" were the average of the five maximums, and values described as "Min" were the average of the five minimums.) There were eight conditions and two repetitions of each condition resulting in 16 observations of each dependent variable for each participant.

1.5. Task and procedure

Before beginning data collection, a five minute warm up was provided to stretch and warm up the muscles of the low back and upper extremities. Eight surface EMG electrodes were secured on the skin over specific muscle groups to be sampled. The participant then performed a series of isometric maximum voluntary contraction (MVC) exertions designed to elicit maximum muscle activity from the sampled muscles. To capture the MVC EMG of the erector spinae the participants performed the isometric maximum voluntary contraction against the resistance provided by a lumbar dynamometer (Mirka and Marras, 1993) while the participant assumed a sagittally symmetric, ~30° forward flexion trunk angle. Similarly, the participants used the resistance provided by the dynamometer (through a strap that was wrapped over the shoulders) to achieve an MVC for the trunk flexors (rectus abdominis and external obliques) while the participant was in a sagittally symmetric ~30° forward flexion trunk angle. Finally the MVC exertions of the deltoid muscles were performed using static resistance of the arm of the dynamometer with the shoulder in a 60 degree abduction posture. These maximum EMG signals were used to normalize the task EMG signals from the experimental trials.

After completing the MVC trials, participants moved to the lifting trial area. The LMM was secured to the back of participant and two LMM calibration trials were performed with the participant standing upright and bending forward 90-degrees while the LMM output was recorded. The participant then performed the series of lifting tasks wherein they were required to stand on the force platform and lift five boxes in sequence from the conveyor and place the boxes onto the table. For each speed level, the boxes were released from the appropriate fixed position on the tilted conveyor at the designated frequency. An electronic metronome was used to assist the experimenter in releasing the boxes at the appropriate frequency. During the 0 m/s trials the experimenter simply placed the box on the lifting location and then said "lift" at the required frequency. On the participant side, when a box approached (or when he was told to "lift"), the participant lifted the box and placed the box on the table, and the box was immediately cleared off the table by another experimenter. Between trials 30 seconds resting time was provided to the participants.

1.6. Data processing

1.6.1. Electromyographic data

The raw data were band-pass filtered at a low-pass frequency of 500 Hz and a high-pass frequency of 10 Hz. A notch filter was also applied that eliminated 60 Hz and its aliases and then these filtered signals were full-wave-rectified. The EMG signals from the MVC trials were reduced to 1/8th second windows and the maximum of these 1/8th second windows was the value used as the denominator in order to normalize the EMG data from the experimental trials. The EMG data collected during the five concentric lifting motions from each trial were averaged and were used as the numerator for the calculation of the average normalized EMG.

1.6.2. LMM data

The sagittal angle data collected during the lifting tasks were normalized with respect to sagittal angle data collected during the 0 and 90 degree, pre-lifting calibration trials for each subject.

1.6.3. Forceplate data

The point of application of the force vector (i.e., centre of pressure) was calculated and the free moment about this centre of pressure was found (Mz). It should be noted that data collection problems led to the elimination of the data from the first two participants.

1.7. Statistical analysis

All statistical analyses in this study were conducted using SAS®. Prior to formal statistical analysis, the assumptions of the ANOVA procedure (normality of residuals assumption, non-correlation of residuals (i.e. independence) assumption, and constant variance of residuals assumption) were tested (Montgomery 2005, pp.76-79). Dependent variables that violated one or more assumption were transformed so that the ANOVA assumptions were no longer violated (Montgomery 2005, p.80).

Three multivariate analyses of variance (MANOVAs) tests were conducted on EMG, LMM, and forceplate data respectively to control the experiment-wise error rate. Only those independent variables found to be significant in the MANOVA were pursued further in the univariate ANOVA. Bonferroni post-hoc tests were then performed on the significant main effects to further explore the nature of these significant effects. A criteria p-value of 0.05 was used in all statistical tests.

2. Results

MANOVA results revealed significant effects of SPEED and FREQUENCY for all three sets of dependent measures (Tables 1, 2 and 3), but the interaction between SPEED and FREQUENCY was not found to be significant (EMG: p=0.06; LMM: p=0.61; forceplate: p=0.45). Consequently, the interaction between SPEED and FREQUENCY was not considered further in the univariate analysis.

Insert Table 1 about here

The results of the analysis of the lumbar kinematics variables provided insight into the changes in lifting strategy employed by the participants (Table 1). In the sagittal plane the results showed that at higher load speeds the participants tended to maintain a greater sagittal angle during the lifting motion – they tended to bend down further at the beginning of the lift (11% greater MaxSagAng) and not come as upright at the end of the lift (26% greater MinSagAng) (Figure 2). Similarly, the effect of FREQUENCY showed significantly higher MinSagAng at the lower lifting frequency indicating that the participant came to a more erect posture during lifting under the low frequency conditions (Table 1 and Figure 2). There was a statistically significant effect of SPEED on MaxTranAng but the difference from the highest to lowest value was just under one degree and was not deemed physically significant. The values of peak acceleration (both MaxSagAcc and MaxTranAcc) decreased with increasing load speed (Table 1 and Figure 3), indicating that the participants were likely utilizing the inertia of the load to assist in the movement of the load from origin to destination.

Insert Figures 2 and 3 about here

The results of the analysis of the muscle activity data revealed consistent and significant trends for increasing activity of all trunk muscles with increasing SPEED (Table 2 and Figure 4). The result that all trunk muscles, both those that are considered primary agonists for this lifting motion (RES, LES, LEO) and those that are considered antagonists for this motion (RRA, LRA, REO) showed this response, indicates a significant level of increasing co-activation was used to control the inertia of the load. While the trunk kinematics data from the LMM indicates that the lifter utilized the inertia of the load to reduce the peak angular accelerations in both the sagittal and transverse planes, these muscle activation results indicate that this benefit came at the cost of increased trunk muscle co-activation.

Insert Table 2 and Figure 4 about here

The results of the analysis of the ground reaction forces and moments provide an interesting perspective on the "accelerating" and "braking" requirements of the lifter relative to the control of the moving load. First of all, the effects in the anterior-posterior direction were quite small, but the medial-lateral ground reaction forces clearly describe the role of the lifter in controlling the moving load (Table 3 and Figure 5). This can be clearly seen in the responses AvgFy and MaxFy measures to varied speed levels. In the case of the 0 m/s speed the AvgFy shows a negative value indicating the leftward push of the feet on the force platform to initiate the movement of the load to the destination. This is as compared to the AvgFy for the higher load velocities as well as the response of the MaxFy measures that reflect the braking motion when slowing the load at destination. It is interesting to note that the 2.4 m/s value for MaxFy was significantly higher than the other load speed levels which would seem to indicate that some threshold of inertial force might have been reached. Consistent with these results are the results relative to MinMz and MaxMz (Table 3 and Figure 6). MinMz is the Mz moment that reflects the moment that is required to initiate the twisting motion and is clearly greatest in the 0 m/s condition. MaxMz, on the other hand, is the ground reaction moment that results in a slowing of the load at the destination, and this value increased steadily with increasing load speed.

Insert Table 3 and Figures 5 and 6 about here

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3. Discussion

The purpose of this study was to investigate the effect of the load speed and lifting frequency on lifting biomechanics. The three-dimensional nature of the lifting task involved both sagittal plane and transverse plane movements. Sagittal plane movement included bending to reach the load on the conveyor and unloading the load onto the table. The transverse plane movement involved rotating the torso to move the load from the mid-sagittal plane to a destination approximately 90 degrees from this position. The task in the current study considered a dynamic object which had inertia in the direction along the line from origin to destination (i.e. the inertia of the load would be "helping").

Regarding trunk kinematics, the differences in both maximum and minimum sagittal angles with load speed suggest that individuals tend to maintain a more flexed trunk posture during the concentric lifting motion under higher load speed conditions. The data with regard to acceleration in both the sagittal and transverse planes indicate that the participants chose to utilize the inertia of the load to reduce the lifter initiated accelerations. By combining the sagittal angle results with these acceleration results, it would appear that a strategy under the dynamic load conditions would be to maintain a relatively flexed trunk posture and utilize the arms and shoulders in a pendulum-like fashion to accept the load and then utilize the inertia of the load to reach the destination. By comparison, when lifting in the static condition the lifter would perform a lift primarily in the sagittal plane and then rotate as much as necessary to place the load at the destination. Taken in isolation, this strategy of utilizing the inertia of the load to reduce required accelerations of the torso might appear advantageous.

Activation levels of the muscles of the torso tended to show a different and more negative perspective. First, the more flexed trunk posture adopted by participants during higher speed conditions resulted in a greater moment of the trunk mass and load during the lifting motion as is evidenced by a higher activity of the erector spinae. Likewise, the results showed a general increase in the activation levels of the antagonist muscles which would be activated to increase the trunk stability as this inertial load is accepted and carried to destination. Even the left external oblique whose line of action would seem to indicate the greatest potential benefit from the vector of the inertial load, had its highest activation level with the greatest load speed. Collectively, these results indicate that the internal biomechanical co-activation strategy did not make use of the inertial characteristics of the load to reduce the stress during the transfer task. Finally, the data from the average and peak medial-lateral ground reaction forces would support the view that these lifts saw the load motion as something that required braking as opposed to being an opportunity to reduce the stress during lifting. On balance it would appear that for this group of participants the effects of the load motion negatively impacted the stress in the low back.

Previous studies that have considered the effects of load velocity have focused on the effects of changes in the vertical load velocity, primarily through the directions to the participants (e.g. Lavender *et al.* 1999, Lavender *et al.* 2003) or through urgency from the required lifting frequency (e.g. Hagen *et al.* 1995). Because these previous studies had the lifter moving quickly primarily in the vertical direction (against gravity) it was clear that these tasks were going to generally increase muscle activation values and biomechanical stress measures just as one might expect with increased load weight. In the current study, this was not quite as clear. With a horizontal load speed and a requirement for the load transfer to take place in the direction of the velocity of the load, it was possible that the lifters could make use of the inertia of the load to achieve the performance requirement. In terms of trunk kinematics, it appears that the lifters did, in fact, make use of the motion of the load, however, this came at the cost of increasing trunk muscle coactivation (an thereby spine loading) of both agonist and antagonist muscle groups.

There are several limitations of the current study that limit the generalizability of the results. First, the participants in this study were physically fit, male college students with relatively limited experience in manual materials handling tasks. Previous studies have demonstrated that gender (Marras *et al*. 2003) and obesity (Xu *et al*. 2008) influence lifting kinematics and these factors may play a role in the response to lifting from a conveyor system through differences in strength and inertial characteristics of the lifter. In addition, Marras *et al*. (2006) found that inexperienced subjects generally demonstrated more compressive force on their spines than experienced manual material handlers when the moment exposure was the same. Were this experiment to be performed on warehouse workers with experience lifting to and from conveyor systems, strategies developed through years of experience might have an impact on the biomechanical responses. Even in this current participant group, there were indications that the inertia of the moving load was being utilized in terms of several of the trunk kinematics variables. With training and strategy development it is conceivable that the muscle activation responses could show similar trends. Future research employing workers with this type of experience could provide valuable insight into training/experience effects. Second, this study controlled many variables that could have interaction with load speed and lifting frequency such as load weight, handle couplings, and standing position orientation. Varying these factors might result in different lifting strategies. Future research could provide insight into the interaction between these factors and load speed. Finally, this study is limited in that a linear relationship between muscle force and EMG was assumed without considering the force-length and force-velocity relationships and only the biomechanical responses were investigated. Musculoskeletal models are needed in future study to determine if these biomechanical differences induce changes in spine loading. Those alternate approaches might provide a more complete understanding of the underlying strategies employed when lifting these moving loads.

4. Conclusion

In this study horizontal load speed and lifting frequency have been shown to modify the lifting strategy adopted by the load handler, and hence change the lifting biomechanics including muscle activity and trunk kinematics and kinetics. Under higher load speed conditions participants maintained a more flexed trunk posture and utilized the inertia of the load to reduce the peak accelerations of the torso as compared to lifting a static load. Analysis of the trunk muscle activation profiles and ground reaction forces revealed that significant effort was exerted to control the inertia of the load to allow the lifter to place the load at the destination. These changes in lifting biomechanics indicated greater potential of low back injury during lifting loads with higher horizontal speeds.

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Table 1. ANOVA results for trunk kinematics data

Independent Variables	MANOVA	Dependent Variables				
		Sagittal Plane			Transverse Plane	
		MaxSagAng	MinSagAng	MaxSagAcc	MaxTranAng	MaxTranAcc
Speed	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.02$**	**$p < 0.01$**
Frequency	**$p < 0.01$**	$p = 0.46$	**$p < 0.02$**	$p = 0.09$	$p = 0.79$	$p = 0.07$

Table 2. ANOVA results for muscle activity data

Independent Variables	MANOVA	Dependent Variables							
		RES	LES	RRA	LRA	REO	LEO	RDELT	LDELT
Speed	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	**$p < 0. 01$**	**$p < 0.01$**	$p = 0.15$	**$p < 0.01$**
Frequency	**$p < 0.01$**	$p = 0.42$	$p = 0.14$	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	$p = 0.64$	**$p < 0.01$**	**$p < 0.03$**

Table 3. ANOVA results for ground reaction data

Independent Variables	MANOVA	Dependent Variables					
		Average		Peak			
		AvgFx	AvgFy	MaxFx	MaxFy	MinMz	MaxMz
Speed	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**	$p = 0.65$	**$p < 0.01$**	**$p < 0.01$**	**$p < 0.01$**
Frequency	**$p < 0.02$**	$p = 0.63$	$p = 0.22$	$p = 0.55$	**$p < 0.02$**	**$p < 0.01$**	$p = 0.71$

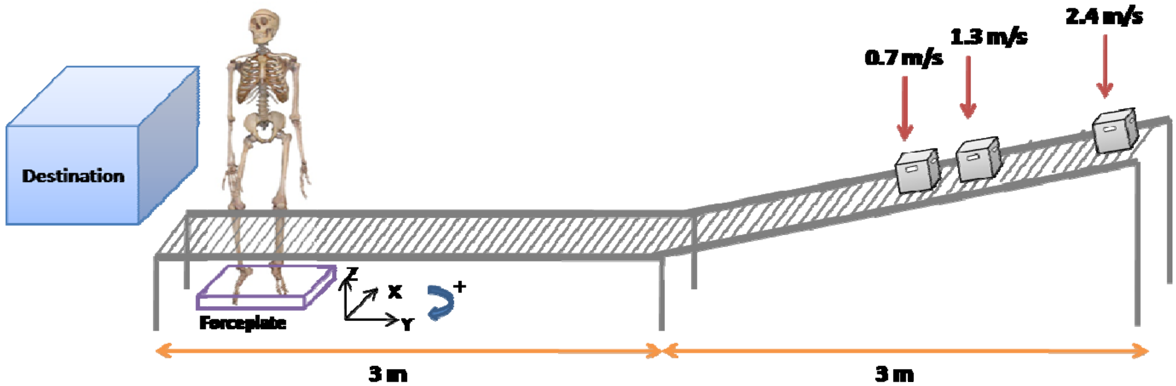

Figure 1. Experimental setup for the conveyor lifting task

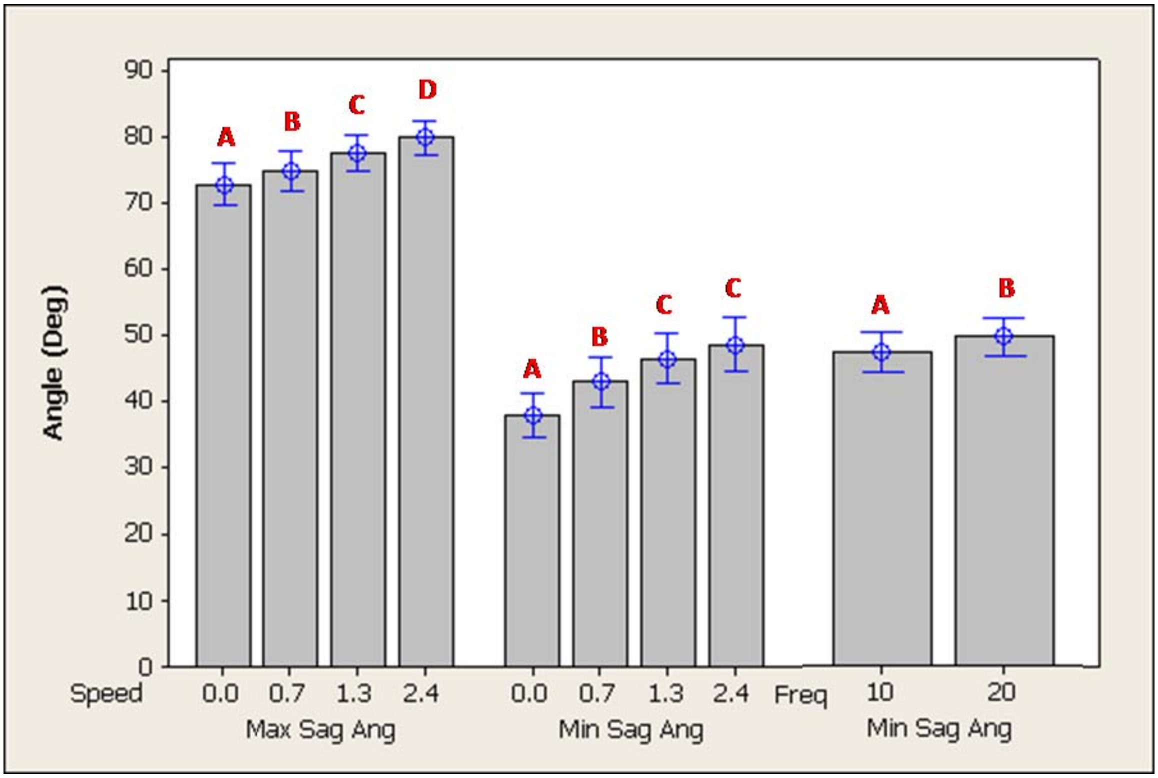

Figure 2. Effect of load speed and frequency on angular trunk movement in sagittal and transverse plane. Error bars represent the 95% confidence interval for the mean. Columns with the same letter were not found to be significantly different in the post-hoc tests.

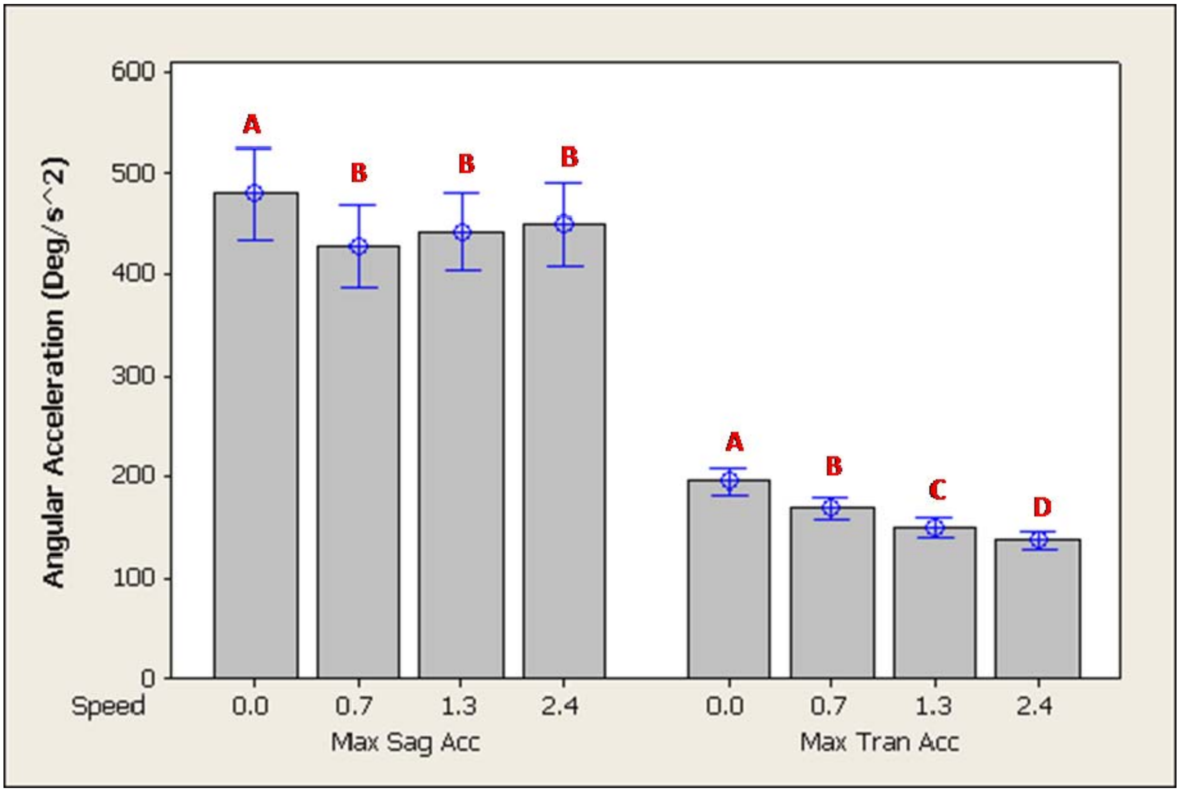

Figure 3. Effect of load speed on angular trunk acceleration in sagittal and transverse plane. Error bars represent the 95% confidence interval for the mean. Columns with the same letter were not found to be significantly different in the post-hoc tests.

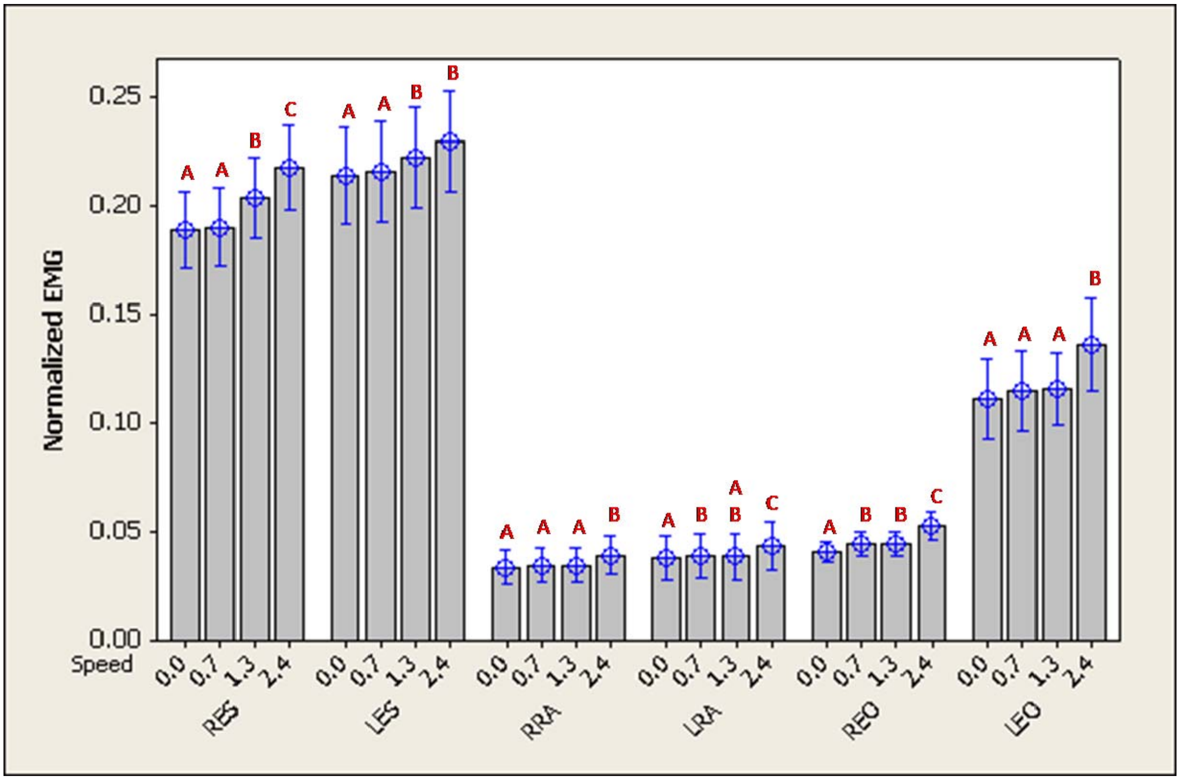

Figure 4. Effect of load speed on average normalized EMG. Error bars represent the 95% confidence interval for the mean. Columns with the same letter were not found to be significantly different in the post-hoc tests.

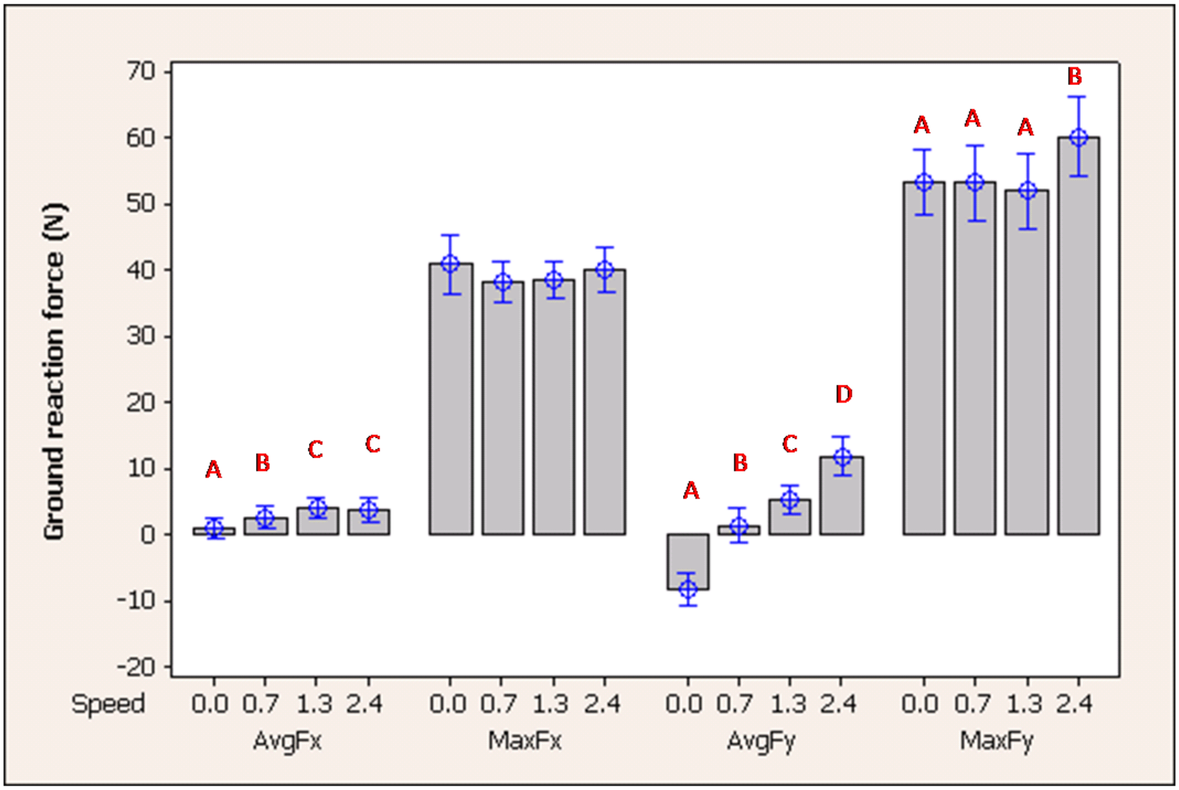

Figure 5. Effect of load speed on A-P and M-L ground reaction forces. Error bars represent the 95% confidence interval for the mean. Columns with the same letter were not found to be significantly different in the post-hoc tests.

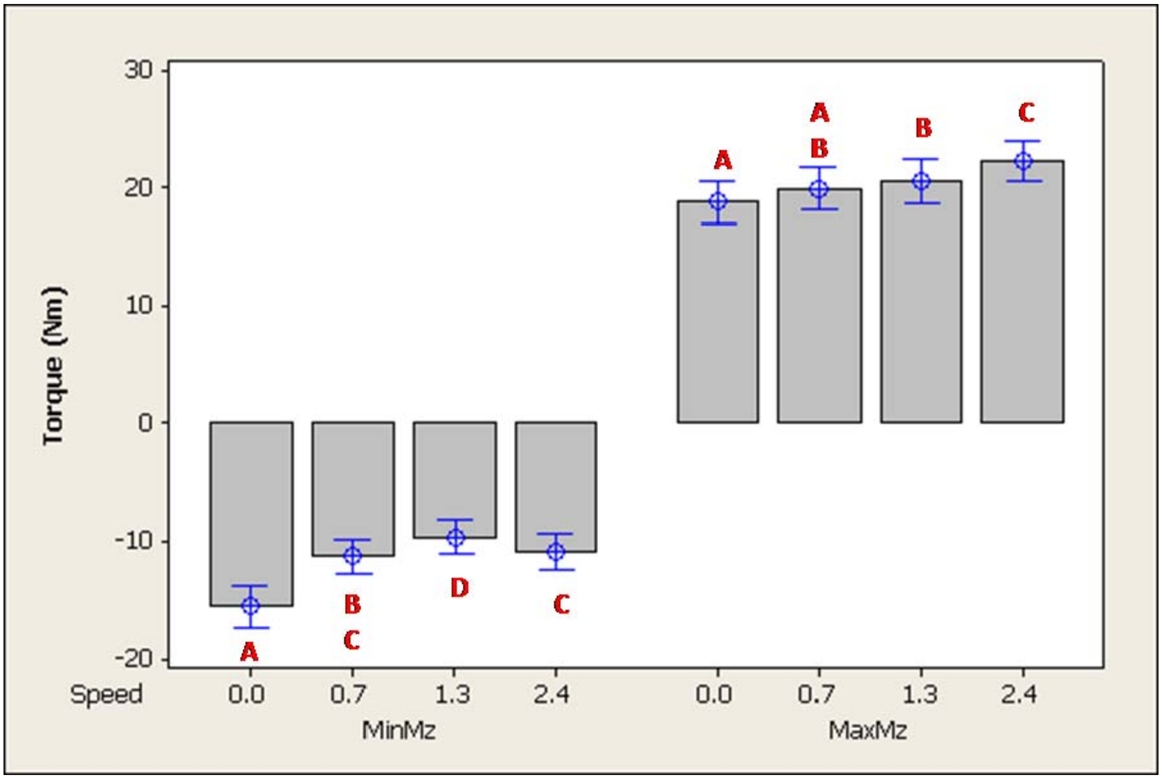

Figure 6. Effect of load speed on the free moment about the centre of pressure. Error bars represent the 95% confidence interval for the mean. Columns with the same letter were not found to be significantly different in the post-hoc tests.