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BIOMECHANICAL INVESTIGATION OF LIFTING SPEED

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A laboratory study was conducted to explore the effects of lifting speed on several predetermined biomechanical variables including total lifting time, peak speed of load, total net muscle work, total absolute net muscle work, work done to the load, time integral of sum of squared ratio of joint moment and strength, total absolute joint moment, and the time when the peak speed occurs. Five subjects performed lifts at five lifting speeds labeled as the slowest, slow, normal, fast, and fastest, and three weights, 50%, 65%, and 80% of their maximum acceptable weight of lift. The speed at each level was determined individually by each subject according to their capability. Measures of the total net muscle work, total absolute net muscle work, work done to the load, and time integral of sum of squared ratio of joint moment and strength decreased significantly as the lifting speed increased ($p<.05$, $<.001$, $<.001$, $<.001$, respectively). This indicates that lifting at a faster speed tends to reduce the work the body has to do. The peak speed of load occurred at 70% of total lifting time for the slowest lifts, but at 30% of total lifting time for other lifting speeds. Performing lifts at their minimum speeds changed the usual speed coordination technique the subjects used. The study suggests that slow lifting may not necessarily be of advantage to the body.

INTRODUCTION

When evaluating stresses on the body from a lifting task, static models completely ignore the importance of inertial forces; hence true stresses are underestimated. Studies involving dynamic modeling of manual lifting have shown that in estimating stresses on the body, inertial forces could be substantial (for example, Freivalds et al., 1984); therefore, dynamic models are usually recommended for more accurate estimation of stresses on the body. Studies of manual lifting have tried to estimate individual or population capacity or investigate safe lifting limits. In the search for a safe lifting limit, whether it is an estimation from dynamic biomechanical models or a collection of empirical data from psychophysical studies, the effects due to variation in lifting speed were usually neglected. Most studies tended to assume a natural lifting speed from the subjects without controlling the variation of speed within the same lifting condition. The assumption that one performs a lift within a small variation in speed seems true, yet there is no study to substantiate this observation. Further, studies of lifting techniques have done very little to understand the role of lifting speed in movement coordination. Fast and jerky lifts are usually thought to be potentially harmful to the body and should be avoided. Smooth and slow lifting is usually recommended in the field of ergonomics. However, the potential biomechanical disadvantages from slow lifting have not been investigated thoroughly. The question to be raised is to what degree we have to slow down when performing a lift. If there are indeed biomechanical disadvantages from slow lifting, how slow should the lift be performed so that our body can still tolerate those stresses? Are we still able to finish a lift without undue stresses if the lift is performed too slowly? How sensitive is the body in reacting to the changes in lifting speed? It seems that slow lifting techniques should not be unconditionally practiced before these questions are addressed.

In an unpublished study, Hafez and Ayoub (a,b) investigated the moment stresses in relation to lifting speed in a lifting activity. In the study, the subjects lifted a horizontal weighted bar. The movement of the bar was vertically guided and constrained. They calculated the sum of absolute static and inertial components of the moments over the body joints and found that the sum of static moments decreased with the increase of lifting speed; however, the sum of inertial moments increased with the increase of lifting speed. The study also found that the subjects preferred to lift at a speed where the sum of the static and inertial moments approached minimum. This finding, although with an artificial lifting activity, seemed to support the idea that there was an optimal lifting speed at which the overall moment stress was minimized. In other words, lifting too slowly may not be advantageous in terms of the overall moment stress.

Hall (1985) studied the effects of attempted lifting speed on mechanical stresses on the spine, using 3 weights and 3 lifting speeds. The study found that lifting at a faster speed dramatically increased the moment at L5/S1 and compression force on the lumbar spine. This finding tended to support a slow lifting technique by minimizing the stresses on the lumbar spine.

Bush-Joseph et al. (1988) studied the effects of lifting speed and lifting method. They used 3 lifting speeds and 3 lifting methods, leg, back, and free-style lifts. The study found that the peak moment at L5/S1 increased linearly with lifting speed. The study also found that in fast lifting, the differences of peak moment between lifting techniques disappeared. In slow and normal lifting, back lift resulted in the smallest peak moment. These findings support the use of back lift at a slow lifting speed.

Since relatively few studies were available which directly address the problems of lifting speed, the present study attempted to investigate biomechanical changes at different lifting speeds. Several biomechanical variables other than the spinal stress were selected in the study, most of which were related to whole-body work.

Biomechanical variables

Variables under investigation were total lifting time, peak speed of load, total net muscle work, total absolute net muscle work, work done to the load, time integral of sum of squared ratio of joint moment and strength, total absolute joint moment, and the time when the peak speed of load occurs. To calculate the values of these variables, a 5-joint sagittal dynamic lifting model was used. The model and its basic assumptions are described in Chaffin and Andersson (1991). The kinematics and kinetics of lifting motion were calculated based on the 5-joint model. The 5 joint landmarks were the hand, elbow, shoulder, hip, knee, and ankle. Definitions of these variables are described as follows.

1. Total lifting time: This is the time elapsed between the beginning and ending of a lift. The beginning of a lift is defined as the point in time when the container leaves the floor. The ending of a lift is defined as the point in time when the container is completely placed on the shelf. Naturally, average lifting speed is the inverse of total lifting time.

2. Peak speed of load: This is the maximum magnitude of velocity of the center of the load.

$$\text{peak speed of load} = \max\left(\sqrt{v^2_{x,load} + v^2_{y,load}}\right)$$

3. Total net muscle work: At a given joint, muscle power is the product of net muscle moment and angular velocity (Winter, 1990). The net mechanical work done by the muscles is the integral of the power over the entire period of a lift. Total net muscle work is defined here as the sum of the net mechanical work done by the muscles over the 5 joints. The following equations were used to calculate the total net muscle work.

$$P_j = M_j w_j; \quad W_j = \int_{t=0}^{T} P_j dt;$$

$$\text{Total net muscle work} = \sum_{j=1}^{5} W_j$$

where P_j = net muscle power, in watts

M_j = net muscle moment, in Nm

w_j = joint angular velocity, rad/s

W_j = work done by muscles at joint j

T = total lifting time

4. Total absolute net muscle work: Since positive and negative work at different joints may cancel each other in the numerical summation over the 5 joints, the sum of absolute work of the joints was used to avoid underestimating the total net muscle work. The equation is:

$$\text{Total absolute net muscle work} = \sum_{j=1}^{5} |W_j|$$

5. Work done to the load: This is the mechanical work done to the external load during the period the box travels from the floor to the shelf. The equation is:

$$\text{work done to the load} = \int_{t=0}^{T} (F_{x,load} V_{x,load} + F_{y,load} V_{y,load}) dt$$

6. Time integral of sum of squared ratio of joint moment and strength: This variable was previously used in the simulation model in Hsiang (1994) and Lin et al. (1994) as an objective function. The simulation model assumed that during a lift, the body minimized the objective function. This function is calculated as:

$$\int_{t=0}^{T} \sum_{i=1}^{5} \left(\frac{M_i(t)}{S_i(t)} \right)^2 dt$$

where M_i = moment at joint i

S_i = moment strength of joint i

The static strength prediction equations developed by Stobbe (1982) were used to predict the moment strength of each joint at different angles.

7. Total absolute joint moment: This is the sum of absolute moments of the 5 joints aggregated over the entire period of a lift. This variable represents the overall physical stress not weighted by the joint strength. The equation is:

$$\text{Total absolute joint moment} = \sum_{i=1}^{50} \sum_{j=1}^{5} |M_{ij}|$$

where

M_{ij} = moment of joint j at time frame i, noting that the moment was reinterpolated into 50 frames for the entire period of lift

8. Time of peak speed: This is the time when the peak speed of load occurs during a lift. The time is expressed as a percentage of the total lifting time.

$$\text{peak speed time} = \frac{t}{T} \times 100\%$$

where t = time when peak speed occurs

T = total lifting time

OBJECTIVES

The objectives of the study were:

1. To investigate the effects of lifting weight on voluntary speed variation. It was hypothesized that as the weight of the load increased, the subject's capability to freely vary lifting speed was limited. For one to smoothly complete a lift of heavier load, it seems that a minimum speed will be required. Also, at very heavy weights, one's capability to lift very fast is limited by joint strength. As a result, the difference between the minimum and maximum speeds that allow one to complete a lift might become smaller under heavier loading conditions.

2. To explore biomechanical changes due to different conditions in lifting speed and weight. The biomechanical variables listed in the previous section were investigated.

METHODS

Subjects

Five paid healthy male subjects were used in the study. They were all graduate students in the department of Industrial Engineering at Texas Tech University. Their heights range from 1.66 m to 1.9 m and weights from 51 kg to 93 kg. None of them had any history of low back injury.

Apparatus

A 12x12x12 inch^3 plywood box with metal handles was used for loading at different weights. A lifting shelf adjusted at a height of 32" was used. Motion Analysis System (Trade Mark) was used for collecting film data of the lifting motion. Reflective markers were attached to the body landmarks at the hand, elbow, shoulder, hip, knee, and ankle joint on the right side of the body.

Procedure

Prior to data collection, one hour maximum acceptable weight of lift (MAWL) was estimated by each subject. The MAWL was estimated for floor-to-knuckle (32" high) lifts at 1 lift/min. Subjects were instructed to lift for an hour. During the hour, they could freely increase or decrease the content of the box until they felt that the load in the box represented their capacity for the aforementioned lifting condition. A second one-hour MAWL session was administered the next day for each subject. If the two MAWL estimates differed more than 15%, new MAWL sessions were administered until the last two MAWL estimates differed less than 15%. The last two MAWL estimates for each subject were presented in Table 1. The average of the last two estimates was used as their MAWL.

TABLE 1. MAWL estimates for each subject (kg)

subject	1st	2nd	average
1	15.6	17.0	16.3
2	20.0	17.3	18.7
3	21.8	18.2	20.0
4	29.3	25.2	27.3
5	27.3	24.1	25.7

Three lifting weights (50%, 65%, and 80% of the MAWL) and five lifting speeds (slowest, slow, normal, fast, and fastest) were considered. In the data collection, the subjects were asked to perform 5 consecutive lifts at 1 lift/min. for each of the 5 lifting speeds and each of the 3 weights. For each lifting weight, the subjects started from the slowest speed. There was no external cue for speed control. The subjects were instructed to lift as slowly as possible while keeping a smooth and uninterrupted motion. Each subject determined his own slowest speed. After completing 5 lifts at the slowest speed, they were instructed to lift at their preferred speed. This speed was labeled as the normal speed. Again, 5 such lifts were performed. The experiment then continued with the slow speed for which the subjects were instructed to lift at a speed between the slowest and normal speeds. Following the slow speed, subjects lifted at the possibly fastest speed of their own. Finally, the fast speed, i.e., the speed between the normal and fastest, was performed. For each lifting weight, the performance of the lifts at different speeds followed this order. The reason that this order was used was that complete randomization would have confused the subjects in performing different speeds of lifts, making a large variation within each speed category. Filmed data were collected on the 3rd and 4th trials of the 5 lifts for each condition and the subjects were not aware of which trial was being collected.

Statistical analyses

In the first objective to investigate the effects of lifting weight on voluntary speed variation, analysis of variance was carried out using the difference in total lifting times between the slowest and fastest lifts as the dependent variable and the lifting weight as the independent variable, blocked on the subject. Similarly, the difference in peak speed between the two extreme lifting speeds was analyzed against the lifting weight.

For the second objective, the dependent variables were the total lifting time, peak speed of load, total net muscle work, total absolute net muscle work, work done to the load, time integral of sum of squared ratio of joint moment and strength, total absolute joint moment, and the time when the peak speed occurs. The independent variables were the lifting weight with 3 levels, 50%, 65%, and 80% of the MAWL, and the lifting speed with 5 levels, the slowest, slow, normal, fast, and fastest lifts. Due to the randomization restriction in the order of the lifts performed by the subjects, the analysis of variance was done using a split-plot factorial design with repeated measures on subjects. Two observations were available within each cell of treatment combination. Table 2 summarizes the treatments used in the analyses.

TABLE 2. Treatment combinations for each subject

	weight (%MAWL)		
speed	50%	65%	80%
very fast	**	**	**
fast	**	**	**
normal	**	**	**
slow	**	**	**
very slow	**	**	**

RESULTS AND DISCUSSION

Voluntary speed variation and lifting weight

It was hypothesized that the voluntary variation in lifting speed would become smaller under heavier loads, that is, as the weight of lift increased, the speed difference between the two extreme speeds would become smaller. Surprisingly, the difference in the total lifting time and that in the peak speed of load between the two extreme speeds were not significantly different under different lifting weights at the 5% confidence level. The hypothesis that the subject's capability to vary lifting speed is reduced under heavier weight was not supported by the study.

Effects of lifting speed and weight on biomechanical variables

The results from the statistical tests for the effects of lifting speed and weight on each of the biomechanical variables are shown in Table 3. Most main effects were significant but interactions were not. The discussion of each dependent variable follows.

TABLE 3. Statistical test results

variables	weight	speed	spd*wt
total lifting time	ns	***	ns
peak speed of load	ns	***	*
total net muscle work	*	*	ns
total absolute net muscle work	***	***	ns
work done to the load	***	***	ns
time integral of sum of squared ratio of joint moment and strength	*	***	ns
total absolute joint moment	*	ns	ns
time at which the peak speed of load occurs	ns	***	ns

(* p<.05; ** p<.01; *** p<.001;ns: not significant)

1. Total lifting time and peak speed of load

Total lifting time indicates the average speed of lifting. As shown in Figure 1, with the increase of lifting speed, the total lifting time decreased (p<.001) and the peak speed of load increased (p<.001). The effects of weight and its interaction with speed were not significant on the total lifting time. The fact that the weight of load did not affect the total lifting time significantly indicates that heavier loads do not necessarily make the lift slower. There is a minimum speed required for a lift below which the lift will not be completed. Figure 2 shows the mean lifting time and peak speed of load at the three weights. Although non-significant, when the weight increased from 50% to 65% of MAWL, the lifts seemed to slow down, but the decrease of lifting speed leveled off when the weight increased from 65% to 80%. One may project that when weight of lift further increased to 100% MAWL, the speed of lift would not further decrease if the lift is to be completed. To verify this point, further experiments will have to be conducted. The interaction between speed and weight was significant on the peak speed of load (p<.05). Figure 3 shows the interaction. The difference in peak speed due to lifting weight was greater when the lifts were performed at a relatively faster speed. As the lifts went slower, the difference disappeared. The peak speeds approached a value close to 0.35 m/s for all three weights. This supports the idea that when performing slow and heavy lifts, one needs to get the load to a certain peak speed during the lift in order to complete it.

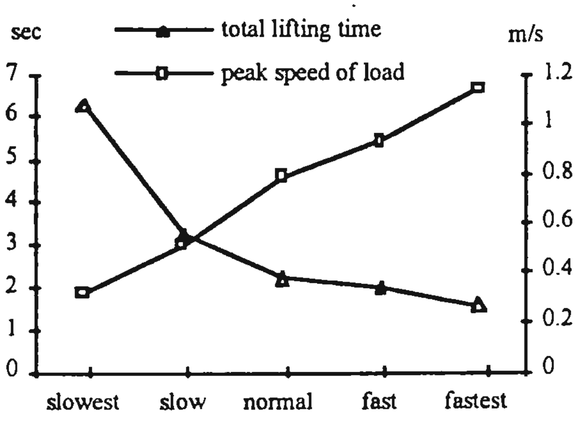

Figure 1. Mean total lifting time and peak speed of load at 5 lifting speeds

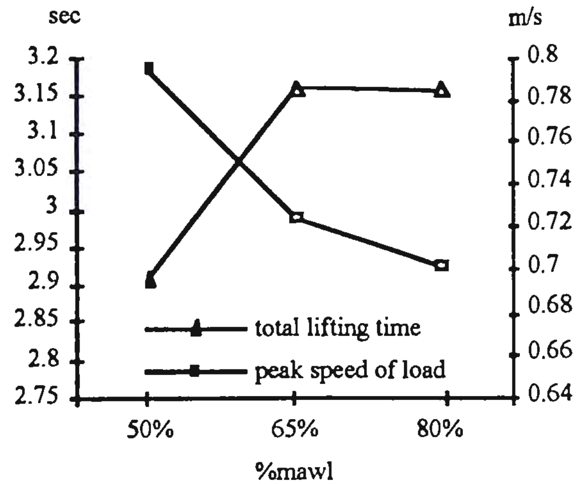

Figure 2. Total lifting time and peak speed of load at 3 weights

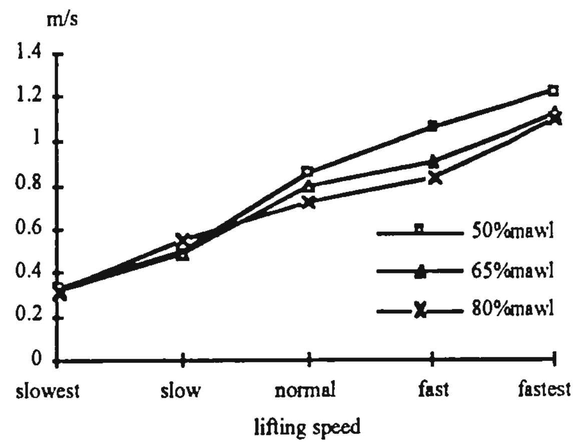

Figure 3. Peak speed of load a t 3 weights and 5 speeds

2. Total net muscle work, total absolute net muscle work, and work done to the load

The total net muscle work, total absolute net muscle work, and work done to the load were all significantly different due to the change in lifting speed (p<.05, p<.001, and p<.001, respectively). They all decreased as the speed of lift increased, as shown in Table 4. From the standpoint of reducing work, the subjects might feel less stressful to lift at a faster speed.

The effects of weight of lift on work were all significant for the 3 types of work. The fact that work increased with weight was expected.

TABLE 4. Total net muscle work (TW), total absolute net muscle work (TAW), and work done to the load (WL) at the 5 speeds (in joules)

	slowest	slow	normal	fast	fastest
TW	129.4	126.5	124.1	123.6	119.3
TAW	221.9	214.5	210.3	207.0	194.8
WL	49.13	48.01	47.44	46.84	45.68

3. Time integral of sum of squared ratio of joint moment and strength and total absolute joint moment

The effect of speed on the time integral of sum of squared ratio of joint moment and strength was significant (p<.001); however, it was not significant on the total absolute joint moment. Figure 4 shows the mean values of the time integral of sum of squared ratio of joint moment and strength at different speeds of lift. Comparing the 2 measures, the time integral of sum of squared ratio of joint moment and strength seems to be a better indicator of overall physical stress than the total absolute joint moment because it takes into account the strength capability of each joint. The time integral of sum of squared ratio of joint moment and strength decreased with the increase of lifting speed, consistent with what happened in the 3 types of work variables described earlier. Lifting at a faster speed seems to reduce the work the body has to do. If the subjects performed the lifts in a way to reduce work, why was the fastest speed not the preferred speed? Notice that the degree of decrease in the time integral of sum of squared ratio of joint moment and strength leveled off as the lifts went faster. Using the time integral of sum of squared ratio of joint moment and strength as a stress index, the leveling of the stress index at faster speeds seems to indicate that when the speed continues to increase, one does not gain any more advantage by lifting faster. Previous studies (Hall, 1985 and Bush-Joseph et al., 1988) have shown that increasing lifting speed might be potentially dangerous due to the dramatic increase in hip moment and L5/S1 compression force. Perhaps the subjects chose the speed according to the tradeoff between reducing work to do and preventing potential injuries.

The effects of weight were significant on both the time integral of sum of squared ratio of joint moment and strength and the total absolute joint moment. The results were expected because the weight of lift directly affected the calculation of moments in these variables.

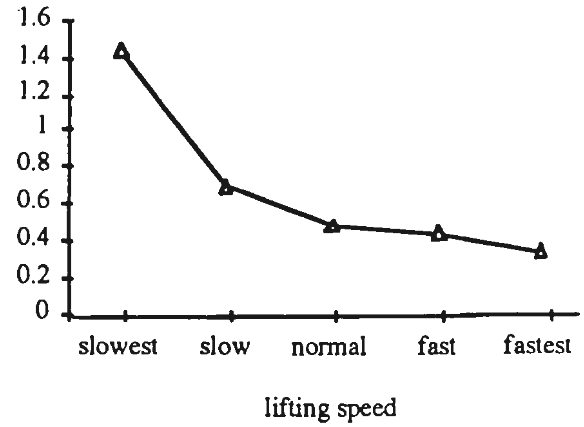

Figure 4. Time integral of sum of squared ratio of joint moment and strength at 5 lifting speeds

4. Time when the peak speed of load occurs

The effect of lifting speed on the time when the peak speed occurs was significant (p<.001). As shown in Figure 5, this was mainly due to the case in the slowest lifts. In the slowest lifts, the peak speed did not necessarily occur early in the lift. It occurred close to the end of the lift, i.e., at 70% of total lifting time. In the other four speeds of lift, peak speed occurred at 30% of total lifting time. During the experiments, the subjects tended to lift faster at the beginning of the lift and then slowed down when the load was already away from the floor. However, when instructed to lift as slowly as possible, the subjects lifted very slowly at the beginning. As the load was moved close to the shelf height, the subjects began to increase the speed to place the load on the shelf. This speed coordination was opposite to the

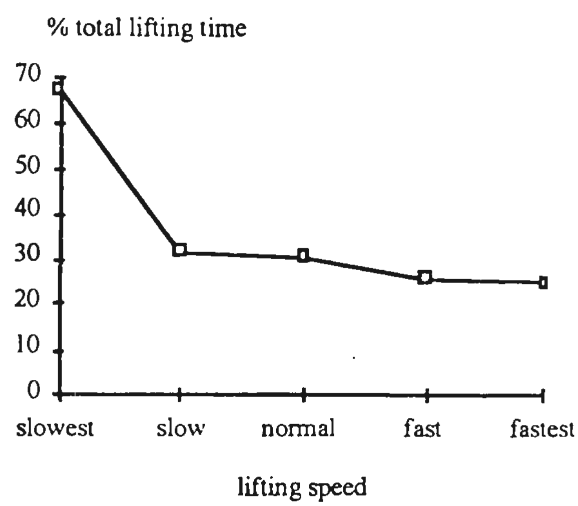

Figure 5. Time of peak speed of load at 5 lifting speeds in % of total lifting time

lifts performed in the other four speeds. It is felt that in extremely slow lifts, the subjects could not stand the stress likely to occur at the final stage of the lift. The subjects had to speed up to finish the lift because at that stage, the load was farther away from the body, imposing greater stress on the body due to the increased moment arm between the load and the body. When the lifts were performed at a speed closer to the subjects' normal speed, they created a peak speed for the load early in the lift. It is believed that one needs to initiate enough power early during the lift to generate sufficient momentum for the load so that the load can be easily carried and moved onto the shelf at the later stage of the lift, when the weaker upper extremities are being used to finish the lift. Such speed coordination is critical to the success of a lift, especially for heavy loads. From this, it seems that lifting at a very slow speed may not be of advantage to the body, especially during the final stage of the lift.

CONCLUSIONS

The study showed that the total net muscle work, total absolute net muscle work, work done to the load, and time integral of sum of squared ratio of joint moment and strength were all sensitive to the changes in lifting speed. For dynamic biomechanical studies of lifting, the variation of speed should be considered. The use of these variables as indicators of overall physical stresses imposed on the body from lifting tasks are encouraged for future studies concerning the speed of lifting.

Very slow lifting may not be of advantage to the body. The study showed that as the lifts were slower, the work-related measures increased. Lifting faster tends to reduce the work the body has to do. Normally, the peak speed of load occurred very early in the lift. For very slow lifts, the peak speed occurred later in the lift. At normal speeds, the subjects tended to initiate large force at the beginning of the lift to create sufficient momentum for the load needed later in the lift. Lifting too slowly may change such speed coordination critical to the success of the lift. It may also cause difficulty for one to finish the lift at the later stage when the load is far away from the body and begins to lose its momentum. When the lifts were performed slowly, the subjects seemed to sustain great stresses due to the slow motion and large moment arm between the load and the body at the final stage of the lift. Although peak compression force at L5/S1 might be larger in faster lifts, very slow lifts could impose greater cumulative compression force due to the longer holding of the load. It is not clear whether the peak or cumulative compression is more likely to cause injuries. Future studies are recommended to address this problem.

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