

A biomechanical evaluation of lifting speed using work- and moment-related measures

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A biomechanical evaluation of lifting speed was conducted in the laboratory. The study investigated the effects of lifting speed on several predetermined biomechanical cost functions. The lifting tasks consisted of five lifting speeds labelled 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. The study found that work-related measures, including the total net muscle work, total absolute net muscle work and work done to the load, decreased significantly as the lifting speed increased ($p < 0.05$, < 0.001 and < 0.001 , respectively). The time integral of sum of squared ratio of joint moment and strength also decreased significantly ($p < 0.001$). 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 the minimum speeds changed the usual speed coordination technique the subjects used.

1. Introduction

Numerous studies of manual lifting have attempted to establish safe limits for a working population. In the biomechanical approach, such limits are usually established based on the emphasis in the lumbar spinal stresses. Dynamic lifting analysis has been reported to estimate more accurately spinal stresses, due to the consideration of inertial forces inherent in the dynamic lifting activities (e.g. Freivalds *et al.* 1984). Since fast and jerky lifts may increase inertial forces significantly, slow and smooth motion is usually recommended for heavy load lifting to minimize the stresses on the lumbar spine. Such a recommendation has been substantiated by several studies in which lifting speeds were manipulated so that lumbar spinal stresses could be estimated at different speeds. Hall (1985) found that lifting at a faster speed dramatically increased the moment at L5/S1 and compression force on the lumbar spine. Bush-Joseph *et al.* (1988) and De Looze *et al.* (1994) both

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found that peak moment at L5/S1 increased significantly with the increase in lifting speed. In addition to the increase of lumbar spinal stresses at high-speed lifting, Garg and Beller (1994) found that isokinetic lifting strength decreased with the increase of lifting speed.

With these findings that strongly support the slow lifting method, a question may be raised regarding the degree of slowness at which the lift should be performed. Are there any disadvantages to the body when a person lifts slowly? Garg and Beller (1994) found that their subjects perceived high-speed lifting as less stressful than slow-speed lifting, contradictory to the isokinetic strength decrease at high speed lifting found in the same study. The inconsistency between the higher lumbar spinal stress and less stressful feeling at high-speed lifting leads to a suggestion that a person may lift in a way not to minimize the stress at L5/S1, but to minimize some other costs which benefit from higher lifting speed. To verify this hypothesis, a biomechanical investigation was conducted. The objective of the study was to evaluate the responses of several predetermined biomechanical cost functions due to changes in lifting speed.

2. Methods

2.1. Subjects

Five paid, healthy male subjects participated in the study. Ages were 25, 25, 26, 27 and 36 years; heights ranged from 1.66 to 1.9 m (mean = 1.768 m, SD = 0.121 m); weights ranged from 51 to 93 kg (mean = 74.86 kg, SD = 15.574 kg). None of them had any history of low back injury.

2.2. Apparatus

A plywood container ($30 \times 30 \times 30$ cm³) with metal handles was used for loading at different weights. The lifting shelf was adjusted at 82 cm from the floor. Motion Analysis System (Motion Analysis Corp.) was used for collecting the lifting motion data. The motion system consisted of three cameras and a video processor. Reflective markers were attached to the subject's joint landmarks during data collection. While the subject performed a lifting task, the coordinates of each joint were recorded on a computer using the motion system.

2.3. Individual strength determination

Prior to data collection, the subjects were asked to determine their maximum acceptable weight of lift (MAWL) for lifting at 1 lift/min for 1 h. 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 1 h MAWL session was administered the next day for each subject. If the two MAWL estimates differed > 15%, new MAWL sessions were administered until the last two MAWL estimates differed < 15%. The mean of the last two estimates was used as their MAWL.

2.4. Procedure

The lifting tasks comprised different lifting speeds and weights. Five levels of speed were used and were labelled as the slowest, slow, normal, fast and fastest lifts. The speed at each level was determined individually by each subject according to their capability. Three levels of weight were used with respect to each subject's individual strength: 50, 65 and 80% of their MAWL.

In the data collection, each subject was asked to perform five consecutive lifts at one lift/min for each of the five lifting speeds and the three weights. For each weight, the subject started from the slowest lift of their own. There was no external cue for speed control. The subject was instructed to lift as slowly as he could while keeping a smooth and uninterrupted motion. After completing five lifts at the slowest speed, the subject was instructed to lift normally at their preferred speed. Again, five such normal lifts were performed. The experiment then continued with the slow speed at which the subject was instructed to lift between the slowest and normal speeds. Following the slow lifts, the subject lifted at the fastest possible speed of his own. These lifts were labelled as the fastest lifts. Finally, five fast lifts at a speed between the normal and fastest lifts were performed.

For each weight, the performance of the lifts at different speeds followed the above order. The reason that this order was used was that randomization would have confused the subjects in performing different speeds of lifts, making a large variation within each speed level. Filmed data were collected on the third and fourth trials of the five lifts for each condition and the subjects were not aware of which trial was being collected.

2.5. Dependent variables

Since the authors hypothesized that a person preferred to lift in a way that reduced overall body work or stress, most variables considered in the study were related to total body work or moment, in contrast with the traditional focus within the lower lumbar area. The dependent variables under investigation were 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. To calculate the values of these variables, a five-joint sagittal dynamic lifting model was used. The model and its basic assumptions are described in Chaffin and Andersson (1991). The five-joint landmarks were the hand, elbow, shoulder, hip, knee and ankle. The total net muscle work (Winter 1990) and total absolute net muscle work were calculated as follows:

$$P_j = M_j \omega_j \quad (1)$$

$$W_j = \int_{t=0}^T P_j dt \quad (2)$$

$$\text{Total net muscle work} = \sum_{j=1}^5 W_j \quad (3)$$

$$\text{Total absolute net muscle work} = \sum_{j=1}^5 |W_j| \quad (4)$$

where P_j = net muscle power at joint j , in watts

M_j = net muscle moment at joint j , in Nm

ω_j = joint angular velocity, in rad/s

W_j = work done by muscles at joint j

T = total lifting time

The work done to the load was the mechanical work done to the external load during the period the load travelled from the floor to the shelf. It was calculated as:

$$\int_{t=0}^T (F_{x,load} V_{x,load} + F_{y,load} V_{y,load}) dt \quad (5)$$

where F_{load} = force applying to the load and V_{load} = velocity of the load.

The total sum of squared ratio of joint moment and strength was calculated as follows:

$$\int_{t=0}^T \sum_{j=1}^5 \left(\frac{M_j(t)}{S_j(t)} \right)^2 dt \quad (6)$$

where M_j = moment of joint j

S_j = moment strength of joint j

This variable was previously used in the simulation model in Hsiang and Ayoub (1994) and Lin *et al.* (1994) as an objective function. The simulation model assumed that during a lift, the body minimized the objective function. The static strength prediction equations developed by Stobbe (1982) were used to predict the moment strength of each joint at different angles. The total absolute joint moment was calculated as:

$$\sum_{i=1}^{50} \sum_{j=1}^5 |M_{ij}|, \quad (7)$$

where M_{ij} = moment of joint j at time instant i .

To calculate this variable, the moment of the entire lifting period was interpolated at 50 equally spaced time instants. Finally, the time when the peak speed of load occurs was expressed as a percentage of the total lifting time. Statistical analyses were carried out using these dependent variables against lifting speed and weight. Due to the randomization restriction in the order of lifts performed for the speed levels, analysis of variance was done using a split-plot factorial design with repeated measures on subjects.

3. Results

3.1. Lifting capacity

Table 1 lists the psychophysical lifting capacity of each subject. As described above, the capacity data shown in the table were the results of a series of MAWL estimates where the last two estimates differed <15%. The mean was used as the individual capacity.

Table 1. MAWL estimates for each subject (kg).

Subject	MAWL1	MAWL2	MAWL (mean)
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

3.2. Lifting speed

Since the load was lifted to a standard height (82 cm), the mean lifting speed was expressed as the lifting distance divided by the total lifting time. Figure 1 shows the increase of both the mean lifting speed and peak speed of load with the increase of speed levels. The increase in both was statistically significant ($p < 0.001$). The effects of weight on both the mean and peak speeds were not significant.

The interaction of weight and speed levels was not significant on the mean speed, but was significant on the peak speed. Figure 2 shows the interaction. The difference in peak speed due to lifting weight was greater when the lifts were performed at a

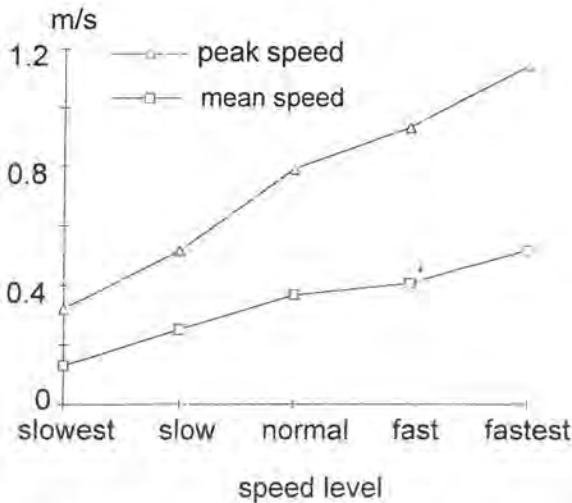


Figure 1. Mean lifting speed and peak speed of load at the five speed levels.

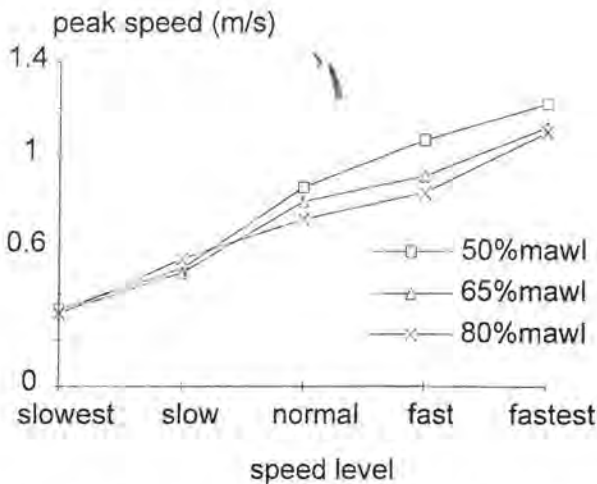


Figure 2. Peak speed of load at three weights and five speed levels.

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 at the slowest lifts.

3.3. Time when peak speed occurs

The effect of lifting speed on the time when the peak speed of load occurs was significant ($p < 0.001$). As shown in figure 3, the peak speed occurred earlier as the lift went faster. In the slowest lifts, the peak speed occurred very late in the lift, at $\sim 70\%$ of total lifting time. In the other four speeds of lift, the peak speed occurred at $\sim 30\%$ of total lifting time. The effects of weight and speed-weight interaction were not significant on the peak speed occurrence time.

3.4. Work-related measures

The total net muscle work, total absolute net muscle work and work done to the load decreased significantly as the lifting speed increased ($p < 0.05$, < 0.001 , < 0.001 , respectively). Table 2 shows the means of these measures at the five lifting speeds. The effects of weight of lift on work were all significant for the three types of work measures. The fact that work increased with weight of lift was nothing but re-examination of law of physics. The effects of speed-weight interaction were not significant on all three types of work measures.

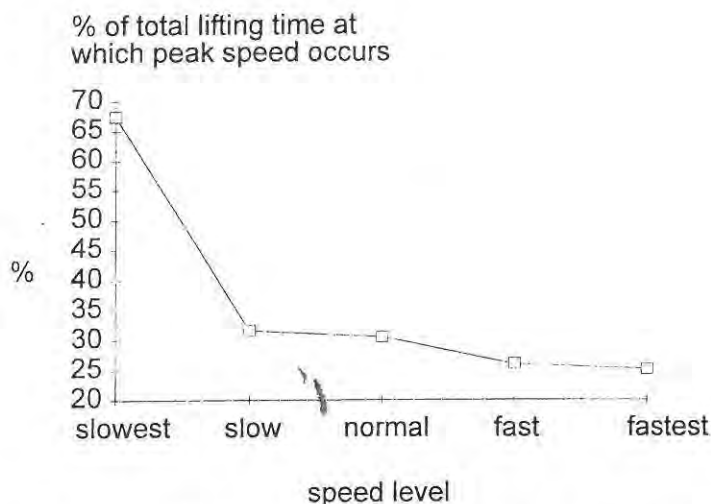


Figure 3. Time when the peak speed occurs at the five levels of lifting speed.

Table 2. Total net muscle work (TW), total absolute net muscle work (TAW), and work done to the load (WL) at the five 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

3.5. Moment-related measures

The effect of lifting speed on the time integral of sum of squared ratio of joint moment and strength was significant ($p < 0.001$); however, it was not significant on the total absolute joint moment. Figure 4 shows the means of the time integral of sum of squared ratio of joint moment and strength at different speeds of lift. The decrease of the time integral of sum of squared joint moment and strength levelled off toward the end of higher speeds. The effects of lifting weight was 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 moments increased directly with the weight of lift. The speed-weight interaction was not significant on these two moment-related measures.

4. Discussion

The control of lifting speed at different levels is usually a major difficulty in studies that wish to manipulate lifting speed. Previous studies investigating the effects of lifting speed usually manipulated speeds at two or three levels. The method used in the study appeared to be reliable in achieving up to five different levels of lifting speed. Both peak and mean speeds increased linearly with the attempted speed levels.

4.1. Minimum speed required for lifting

The result was surprising in that the weight of load did not affect lifting speed significantly. Heavier loads did not necessarily make the lift slower. This seems to imply that there is a minimum speed required for a lift below which the lift will not be completed. It is believed that when a considerably heavy load is lifted, a person needs to get the load to a certain peak speed during the lift in order to complete it. Figure 2 shows that at the slowest speeds, the peak speeds of load approached 0.35 m/s for all three weights. Possibly, this speed was the minimum peak speed required by lifts of at least 50% of a person's maximum capability.

time integral of sum of squared moment and strength

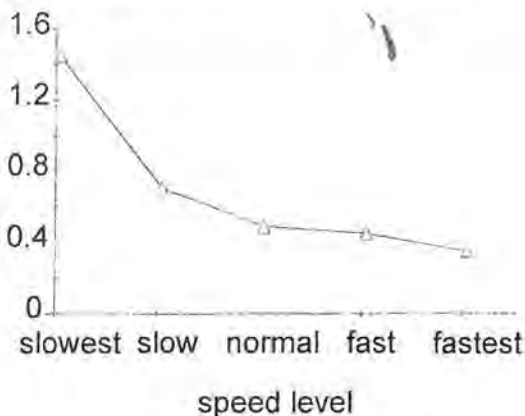


Figure 4. Time integral of sum of squared ratio of joint moment and strength at five lifting speeds.

4.2. *Speed coordination*

The results showed that as the lift went faster, the peak speed occurred earlier. Normally, the subjects would create a peak speed for the load early in the lift at ~30% of total lifting time (figure 3). When instructed to lift as slowly as possible, the subjects lifted very slowly at the beginning. As the load was lifted to the shelf height, it began to lose its momentum. Also, the load began to travel away from the body when it was being placed on the shelf. At this stage, the moment arm between the load and the body began to increase. The subjects had to speed up to finish the lift as soon as possible to avoid holding the load at this stressful posture. As a result, the peak speed of load occurred at 70% of total lifting time for the slowest lifts. This speed coordination for very slow lifting was opposite to the normal lifts.

It is felt that a person needs to initiate enough power early during the lift. This will help generate sufficient momentum for the load so that it can be easily moved onto the shelf at the later stage of the lift, when the weaker upper extremities are being used to finish the lift. Such a speed coordination technique is believed to be critical to both the success and safety of a lift, especially for heavy loads. The loss of load momentum at the later stage of a lift can create very stressful situation for the lower back.

4.3. *Work- and moment-related measures*

The work measures used in the study cannot completely represent the total work done by the body; however, they reflect the degree of effort attempted by the body in performing the lift. All three types of work decreased as the speed of lift increased, implying a reduction of physical effort for faster lifts. It is possible that a person's perceived exertion may be related to the total work the body has to do. If so, this provides some explanation for the inconsistency found in Garg and Beller's (1994) study that their subjects felt less stressful in high-speed lifting, but the lifting strength was in fact smaller and the estimation of lower back stress was higher (Hall 1985, Bush-Joseph *et al.* 1988, De Looze *et al.* 1994).

The time integral of sum of squared ratio of joint moment and strength decreased with the increase of lifting speed, consistent with what happened for the three types of work measures. The total absolute joint moment, however, did not vary with the change of lifting speed. Comparing the two measures, the time integral of sum of squared ratio of joint moment and strength takes into account the strength capability of each joint, making it a better indicator of whole-body moment stresses.

The decrease of both work- and moment-related measures for faster lifts supports the idea that there exists an optimal lifting speed. On the one hand, lifting at a faster speed seems to reduce the work the body has to do. On the other hand, stresses at the lower back and other joints can increase considerably with the increase of lifting speed. Perhaps the subjects chose the speed according to the trade-off between reducing work to do and preventing from discomfort and potential injuries.

5. **Conclusions**

The study showed that when the lifts were slower, the work- and moment-related whole-body stress measures increased. Lifting faster tends to reduce the work the body has to do. For extremely slow lifts, the peak speed occurred later in the lift, different from the usual speed coordination where the peak speed occurred very early in the lift. At normal speeds, the subjects tended to initiate large power at the beginning of the lift to create sufficient momentum for the load early in the lift.

Lifting too slowly changed such speed coordination critical to the success and safety of the lift. It could cause difficulty for a person to finish the lift at the later stage when the load is far away from the body and begins to lose its momentum. At the final stage of the lift, the body seems to sustain great stresses due to the slow motion and large moment arm between the load and the body.

The study has demonstrated a few possible disadvantages to the body due to slow lifting. 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. It seems that slow lifting techniques should not be unconditionally practised before a complete understanding of the role of speed coordination in lifting.

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