Industrial Health 2017, **55**, 27–34 **Original Article**

Lifting speed preferences and their effects on the maximal lifting capacity

Chiuhsiang Joe LIN[1]* and Chih-Feng CHENG[1]

[1]Department of Industrial Management, National Taiwan University of Science and Technology, Taiwan

Received February 19, 2016 and accepted June 29, 2016
Published online in J-STAGE July 5, 2016

Abstract: The objectives of this study were to evaluate how lifting capacity and subjective preferences are affected by different lifting speeds. The maximum lifting capacity of lift was determined with three independent variables, lifting speed, lifting technique, and lifting height. Questionnaires were evaluated after the experiment by the participants for the lifting speed preferences. This study found that the lifting speed was a significant factor in the lifting capacity ($p<0.001$); and the lifting height ($p<0.001$) and the interaction of lifting speed and lifting height ($p=0.005$) affected the lifting capacity significantly. The maximal lifting capacity was achieved around the optimal speed that was neither too fast nor too slow. Moreover, the participants' preferred lifting speeds were consistently close to the optimal lifting speed. The results showed that the common lifting practice guideline to lift slowly might make the worker unable to generate a large lifting capacity.

Key words: Lifting speed, Lifting pace, Lifting capacity, Low back pain

Introduction

Low back pain is a common chronic occupational disease[1, 2]. Not only do workers suffer, but it also increases medical costs, causes lost working time, and lowers productivity[3]. Lifting is an important task in manual material handling. It has been identified as the critical cause of occupational low back pain[4].

In the static biomechanical model, the compression force on the lumbar vertebrae is consistent during the whole lifting duration. However, the compression force on the lumbar vertebrae varies with lifting speed. It was underestimated by 100% to 200% as compared to the dynamic biomechanical model[5, 6]. Lumbar stress is changed not only by changes in posture but also by variations in lifting speed during the lifting duration[7]. In terms of physiology, a fast lifting speed increases muscle recruitment in the earlier phase and decreases it in the later phase of lifting[8]. However, underestimation of the increased demand in the earlier phase of fast lifting can cause an imbalance between the biomechanical demand and muscle recruitment, which can instantaneously cause back injuries[9, 10]. Accordingly, lifting speed is a critical factor that cannot be neglected in evaluating the risk of lifting tasks.

The work practices guide for manual lifting published by NIOSH[11] suggests that lifting tasks should be smoothly executed to avoid the increasing moment generated by the inertial force caused by acceleration of the body. Biomechanical analysis has indicated that jerky, fast lifts may increase the stresses on the lumbar vertebrae, since the inertial force increases with lifting speed[12]. Hall[13] investigated the effects of the attempted speed of lift and the lifting load on the peak and average compression forces, shear force, and moments at the L5/S1 vertebral joint. It was concluded that when the lifting speed was relatively fast, the compression force, the shear force, and the moments in the lumbar region increased significantly. Fathallah *et al.*[14] developed an assessment of spinal loads. The participants were asked to perform tasks involving 2 lifting types (symmetric and asymmetric), 3 lifting speeds

*To whom correspondence should be addressed.
E-mail: chiuhsiangjoelin@gmail.com

(performed in 1, 1.5, and 2 seconds), and 3 weights (22, 67, and 156 N). Spinal loads were assessed by the maximal magnitude and rate (differentiating to time) of compression force, anteroposterior shear, and mediolateral shear force. In spite that lifting speed was not a significant factor in maximum spinal loading, lifting speed was a significant factor in maximum spinal loading rates. In most instances, the loading rates under the fastest speed conditions were double those under the slowest speed conditions. Lavender *et al.*[15] investigated the effects of lifting speed (normal and fast, as perceived by the participants themselves), initial lifting height (floor, knee, and knuckle), and load magnitude (20, 100, 200, 300 N) on peak L5/S1 moments. The lifting speed was reported as a significant factor for the L5/S1 flexion moment. Many studies have reported that, as compared to novices, experienced workers lift faster[16–19] and are less prone to injury[20–22]. It seems that experienced workers prefer to employ a faster speed for lifting, handling, pushing, and pulling loads[16–19]. Supporting this observation was a report that workers felt less stress during faster lifting than during slower lifting[23].

However, Konz and Johnson[24] indicated that acceleration during lifting could counteract the body weight and the inertia of the load. Bernard *et al.*[25] investigated the effects of lifting speed by simulating realistic lifting. The lifting speed was very slow, slow, normal, fast, and very fast perceived by the participant. The dependent variables were the average absolute moments summed across all joints (static, inertial, and dynamic) using the biomechanical model employed in the study of Kroemer[26]. To evaluate muscular contribution, the time integral of absolute moments (static, inertial and dynamic) was applied. The results showed that the effect of lifting speed was significant for all average moments. With increases in lifting speed, the average absolute static moment increased, but the differences were very small. Yet the average absolute static moment increased dramatically as the lifting load increased. The average absolute inertial moment increased only when the lifting speed increased. From the results of the average absolute variables, it was suggested that the lifting speed should be slower than the normal speed. For the effects on the time integral of the absolute moments, the cumulative moments decreased as the lifting speed increased. Such results indicate that the muscular contribution decreased at a fast lifting speed, which would benefit workers. Nevertheless, the peak lifting speed (0.73 m/s) in the realistic simulation was not sufficiently fast. Consequently, the U-shaped relationship between the lifting speeds and the time integral of the absolute dynamic moment was not representative, suggesting that the optimal lifting speed did not occur in their study. However, that study is notable for its completely opposite conclusions for the average absolute moments and the time integral of absolute moments. Lin *et al.*[12] conducted a further investigation based on that previous study by incorporating several biomechanical cost functions. The analysis showed that the total net muscle work, the total absolute net muscle work, the work done to the load, and the time integral of the sum of the squared ratio of joint moment and strength decreased significantly as the lifting speed increased. It was verified in that study that lifting at a faster speed reduces the work the body has to do. Yoon *et al.*[8] investigated the effects of muscle recruitment on the trunk and upper extremities when the lifting pace was perceived by the participants themselves. They suggested that workers should be educated about the biomechanical advantage of a fast lifting speed if they can afford the increase in muscle recruitment demand in the earlier phase. A biomechanical study conducted by Greenland *et al.*[27] investigated the effects of lifting speed on peak and cumulative back compression force (BCF) and shoulder moment (SM) loads. The lifting speeds employed were slow, medium, and fast. Their results showed that the peak and cumulative BCF and the cumulative SM loads were significantly affected by the lifting speed. For the peak BCF, increasing the lifting speed increased the value, and the maximum value was at the fast speed. Conversely, the cumulative BCF and SM decreased with increases in lifting speed, and the minimum value was at the fast speed. They argued that a slow lifting speed was at least as hazardous as a fast lifting speed, and that risk evaluation considering peak value alone was probably not sufficient.

It is clear that the inconsistent results about the preferences of lifting speed exist depending on different aspects of view in the literature. The results basing on the biomechanical peak/average load tend to favor slow lift due to lower biomechanical costs. On the contrary, the results basing on subjective perceptions of human operators, work experiences, and the biomechanical cumulative load tend to support a fast lift.

In this study, it is hypothesized that one's maximum lifting capacity would occur when the task is performed at its optimal lifting speed for a particular task condition. If this is the case, as a result, one's preferred lifting speed should create one's maximum capacity in a particular task condition. Therefore, in this study, we evaluated preferences for lifting speeds performed at one's maximum capacity using the psychophysical method. It is expected that our psychophysical results can add additional knowledge to resolve the lifting speed recommendation inconsistency in the literature. The results may also provide an alternative perspective on the risk assessment and the design of lifting tasks.

Subjects and Methods

Participants

Ten male participants without low back pain and manual handling related work experience who were recruited from a college participated in this experiment. Participant demographics are summarized in Table 1. All the participants were asked to read and sign consent forms before participating in this study.

Experimental design and statistical analysis

A split-split-plot design (Table 2) was applied in this research. The independent variables applied were the lifting height as the whole plot, with two levels (floor to knuckle, set at 76 cm, FK; and floor to shoulder, set at 127 cm, FS); the lifting technique as the subplot, with two levels (stoop and squat); and the lifting speed as the sub-subplot, with five levels (Very Slow, Slow, Medium, Fast, and Very Fast). The lifting duration method similar to Fathallah *et al.*[14] was applied to manipulate the lifting speed. It was set to 5 seconds for very slow (VS), 4 seconds for slow (S), 3 seconds for medium (M), 2 seconds for fast (F), and 1 second for very fast (VF). It should be noted that the lifting speed was a categorical variable in this experimental design. The lifting speed variable has five levels categorized by VF, F, M, S, and VS. However, it is also noted that the actual lifting speed of VF is 76 cm/s (76 cm/1 second) for the FK lifting height and 127 cm/s (127 cm/1 second) for the FS lifting height. Other lifting speeds could be calculated by a similar way. The focus of the effect of lifting speed is on its categorical levels of speed, not on its numerical velocities. The analysis of variance (ANOVA) was performed to investigate the effects of lifting height, lifting technique, and lifting duration on the maximum lifting capacity. Results were evaluated with p values of less than 0.05 being considered statistically significant. The subjective preferred and disliked lifting duration in each session, and the favorite and the most disliked lifting duration were counted by their relative frequency individually. These relative frequencies were used to aid the analysis of ANOVA.

Table 1. Participant demographics. Ten male students recruited from university without low-back injury history and manual material handling work experience.

	Anthropometry		
	Stature (cm)	Weight (kg)	Age (years)
Mean	175.8	69.9	20.4
SD	7.7	10.9	0.8

Table 2. The split-split-plot design. The lifting height was the whole-plot factor, the lifting method was the subplot factor, and the lifting speed was the sub-subplot factor in this experiment.

	Lifting height (whole-plot)			
	FK		FS	
Lifting technique (subplot)	Squat	Stoop	Squat	Stoop
Lifting speed (random order)	VF	VF	VF	VF
	F	F	F	F
	M	M	M	M
	S	S	S	S
	VS	VS	VS	VS

Procedure

The psychophysical approach, maximum acceptable weight of lift (MAWL), developed by Ayoub *et al.*[28] was applied in this research to determine the maximum capacity. This approach can be used to find the maximum lifting capacities at different lifting frequencies[28]. In our study, we are interested in the capacity of lifting at a specific frequency, one time per 8 hour. This maximum capacity is approaching one's true maximum capacity and is also called one time maximum (OTM). Every participant lifted a box (64 × 31 × 30 cm, L × W × H) with handles at the center of the sagittal sides from the floor to the shelf in the sagittal plane. The participants could adjust the load by increasing/decreasing the amount of gravel in the box without any limitations until they felt the maximum capacity had been achieved in each lifting trial. The weight of the last successful lift with time difference within ±0.2 seconds from the preset duration in each trial was recorded as the maximum lifting capacity.

The experimental procedure was illustrated in Fig. 1. A practice session was implemented for the participants to become familiar with the trial before every formal session. The self-perception of lifting duration was the vital part of this practice. A metronome was employed to aid the self-perception of the preset lifting duration. All the participants continued the practice until they could execute the trial well at the required duration. A formal lifting session succeeded after the practice session. There was 3 minutes rest

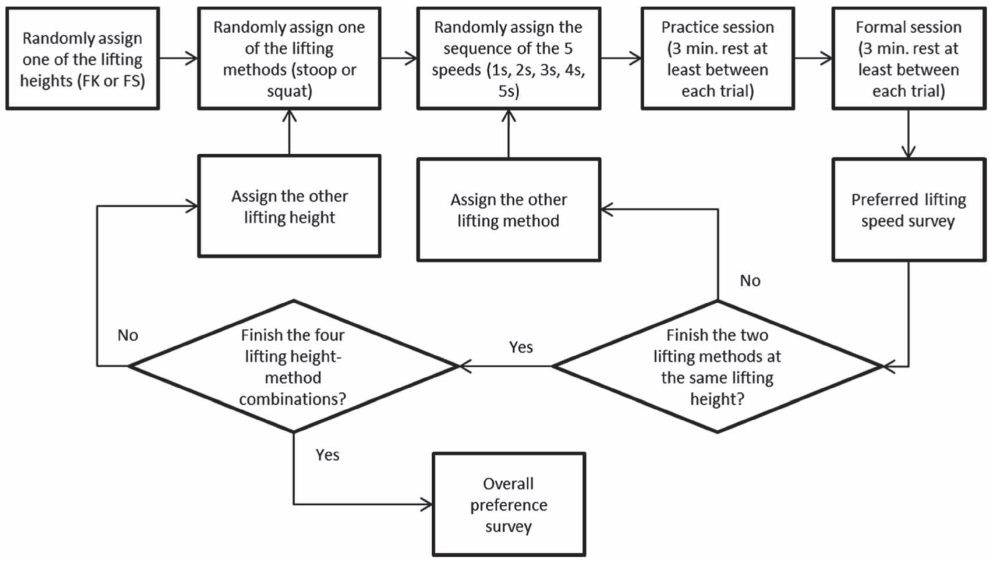

Fig. 1. The experimental procedure. The conditions in Table 2 were randomly assigned to each participant. Each participant had a practice session until he felt he was familiar with the condition before the formal session. After every formal session was completed, the participant answered the questionnaire about their preferred lifting speed in that session. Each participant repeated the above steps until he completed all four sessions. Finally, an overall preference survey was implemented.

at least between each lift; however, the participant could prolong the rest until feeling recovery from fatigue. This policy was necessary to protect the participants against any risk or jury during the experiment. One of the combinations of lifting height and lifting technique was randomly chosen in the first session. In the second session, the lifting height was the same as that in the first session, but the other lifting technique was used. In the third session, the other lifting height was set, and the lifting technique was randomly assigned. The remaining combination of lifting height and lifting technique was executed in the fourth session. The five levels of lifting duration were randomly executed in all four sessions. Each formal session was conducted at a different day. A questionnaire was employed to evaluate their preferred and disliked lifting durations (multiple options allowed) after the participants completed each session of the experiment. After each participant finished all of the four sessions, another preference questionnaire on the favorite and the most disliked lifting durations (multiple options allowed) was administered and comments about the selections were written down.

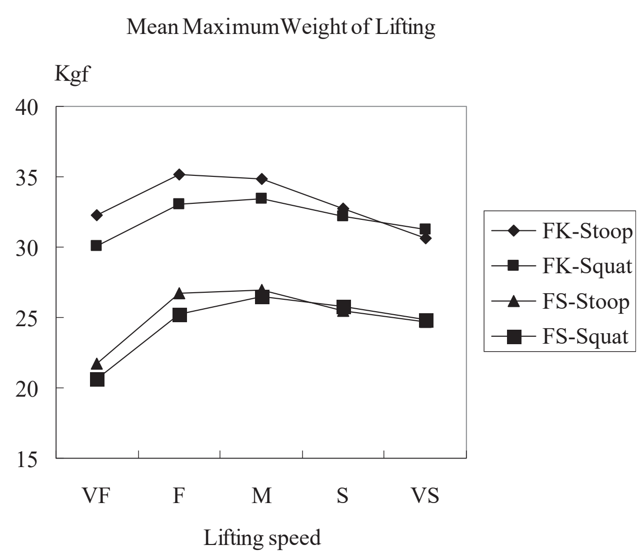

Fig. 2. Mean lifting capacity. The relationship between the mean maximum weight and the lifting speed shows the parabolic curve consistently under various combinations of the lifting technique and the lifting height. The optimal lifting speed with the maximum capacity occurred at fast or medium lifting speed depends on the lifting technique and the lifting height combination.

Results

One time maximum lifting capacity

The parabolic relationships among the mean lifting capacity and the five lifting speeds, and all four combinations of lifting height and technique, had the same patterns, as shown in Fig. 2. The effects of lifting height ($F_{1,9}$=135.71, p<0.001), lifting speed ($F_{4,36}$=15.18, p<0.001) and the interaction of lifting height and lifting speed ($F_{4,36}$=4.50, p=0.005) were significant. For the

Table 3. Relative frequencies of preferred lifting speed. In the FS and stoop lifting combination, the participants preferred the medium lifting speed. The fast lifting speed was preferred in other combinations of lifting height and lifting technique. None of the participants preferred the very slow lifting speed in the various combinations.

Lifting Speed	VF	F	M	S	VS
FK, Squat	2	6	1	1	0
FK, Stoop	1	6	3	0	0
FS, Squat	1	5	3	2	0
FS, Stoop	2	2	6	1	0

Table 4. Relative frequencies of disliked lifting duration. The participants disliked the extreme lifting speeds, and almost none of them chose medium in this option. Most of the participants greatly disliked the very slow at the FK lifting height. When the lifting height was FS, the two extreme lifting speeds were almost equivalently disliked.

Lifting Speed	VF	F	M	S	VS
FK, Squat	1	0	0	0	9
FK, Stoop	1	0	0	0	9
FS, Squat	4	0	1	0	7
FS, Stoop	5	0	0	1	6

Table 5. Relative frequencies of the favorite and the most disliked lifting speed. Almost all of the participants indicated that fast or medium lifting speeds were their favorites. For the most disliked lifting speed, only the extreme lifting speeds (very fast and very slow), were chosen by the participants.

Lifting Speed	VF	F	M	S	VS
Favorite	1	4	5	1	0
Disliked	3	0	0	0	9

effect of lifting height, no matter what the lifting speed was, the lifting capacity of FS was lower than that of FK.

Subjective evaluation

The relative frequencies of the preferred lifting duration for each height/method combination are presented in Table 3. In the FS and stoop lifting combination, the participants preferred the medium lifting speed. The fast lifting speed was preferred in other combinations of lifting height and lifting technique. None of the participants preferred the very slow lifting speed in the various combinations. Table 4 presents the relative frequencies of disliked lifting speed in each height/method combination. The participants disliked the extreme lifting speeds, and almost none of them chose the medium lifting speed in this option. Most of the participants greatly disliked the very slow lifting speed at the FK lifting height. When the lifting height was FS, the two extreme lifting speeds were almost equivalently disliked. Smaller variation in the disliked combinations demonstrated better consistency among participants' choices than was found for the preferred combinations.

Table 5 presents the relative frequencies of the favorite and the most disliked lifting speed. Almost all of the participants indicated that the fast or medium lifting speed was their favorites. For the most disliked lifting speed, only the extreme lifting speeds, the very fast and the very slow, were chosen by the participants.

Discussion

The lifting capacity

It is apparent that the lifting capacity at height FK is greater than that at height FS. A higher lifting height reduces the lifting capacity and increases the cumulative load. This finding is consistent with the literature[29].

The lifting speed is a significant factor in lifting capacity. Our results indicate that an optimal lifting speed exists consistently for the maximum lifting capacity on each combination of the lifting method and height, as shown in Fig. 2. This speed varies with the lifting height. Greenland *et al.*[27] reported a similar finding concerning the optimal lifting speed. They found that both the peak value of normalized BCF by percentage of body weight (% BW) and the cumulative value of normalized cumulative BCF (% BW × Time) were lowest at the medium lifting speed. In our study, the fast speed (2 seconds) was the optimal lifting speed at height FK, while the medium speed (3 seconds) turned out to be the optimal lifting speed at height FS.

Bernard *et al.*[25] employed a realistic lifting simulation and found that the optimal lifting speed did not occur because the range of lifting speeds was not sufficiently broad. However, the results of that study showed a tendency of the time integral of the dynamic moment to decrease with increases in lifting speed. In our study, the participants were asked to evaluate their OTM lifting capacity at various lifting speeds, and it was found that OTM lifting capacity varied with lifting speed. The parabolic curve in Fig. 2 shows the relationship between OTM lifting capacity and lifting speeds. That figure illustrates the existence of the optimal lifting speed when one attempts to lift one's maximum possible load.

The preference of lifting speeds

In the questionnaire survey, there is consistency between the responses from the participants' preferred lifting speed obtained at the end of each session (Table 3) and those from the favorite speeds obtained after all sessions (Table 5) were finished. Participants subjectively favored medium

Table 6. Comparison of OTM lifting capacity. The one time per 8 hour lifting frequency applied in the Ciriello and Snook (1983) and Snook and Ciriello (1991) is equivalent to the OTM in other researches. The mark "—" in the table indicates "Not applicable".

Tasks[a]	This study (Squat)	This study (Stoop)	Lee and Chen (1996)	Lee *et al.* (1995)	Ciriello and Snook (1983)	Snook and Ciriello (1991)
FK36M	—	—	41.27 (4.92)	40.48 (8.90)	61.0 (16.3)	44.0
FK48M	—	—	34.92 (3.83)	—	—	38.0
FK31MT1	30.4 (5.6)[b]	31.9 (7.7)	—	—	—	—
FK31MT2	34.3 (3.7)	34.9 (5.3)	—	—	—	—
FK31MT3	33.6 (4.6)	34.7 (6.5)	—	—	—	—
FK31MT4	32.2 (4.5)	32.7 (5.0)	—	—	—	—
FK31MT5	31.5 (4.9)	30.4 (4.8)	—	—	—	—
FS36M	—	—	32.63 (3.59)	31.96 (4.96)	—	—
FS48M	—	—	28.86 (3.98)	—	—	—
FS31MT1	21.0 (3.1)	21.3 (3.8)	—	—	—	—
FS31MT2	25.4 (3.7)	26.5 (4.7)	—	—	—	—
FS31MT3	26.5 (4.1)	27.0 (4.5)	—	—	—	—
FS31MT4	25.8 (4.3)	25.5 (4.2)	—	—	—	—
FS31MT5	24.7 (4.2)	24.8 (3.9)	—	—	—	—

a: There is 5 to 7 digits in the task code. The first two digits represent the lifting height, FK for floor to knuckle and FS for floor to shoulder. The third and fourth digits represent the box width in cm. The fifth digit, M, means the lifting frequency is OTM. And the last two digits represent the lifting duration in this study. T1 means the duration is one second. Similar notations are used for other durations.
b: Standard deviation.

to fast speeds from these results. Interestingly, those speeds are also consistent with the optimal lifting speed at which the psychophysically determined maximum lifting capacity occurred (Fig. 2). On the other hand, the data also show that the extreme lifting speeds, very fast (1 second) and very slow (5 seconds), with which low lifting capacities were associated (Fig. 2), were chosen as either disliked (Table 4) or the most disliked lifting speeds (Table 5). The participants indicated that they had to endure the load for a considerably longer period when they used the very slow speed. On the other hand, despite the lower amount of stress during very fast lifting, the participants disliked it because it was difficult to execute the lift successfully within one second. The participants also commented that this difficulty caused psychological stress during the experiment. Instead, they preferred the fast or medium speed due to the acceptable perceived workload and ease of success in lifting. This trade-off policy of the participants explains why the maximal lifting capacity occurred at the fast (FK) and the medium (FS) lifting speeds.

The comparison of values of one time maximum lifting capacity

The lifting capacities, measured by OTM-frequency, in the literature[29–32] and in this study are summarized in Table 6. The magnitudes in this study were much lower than those in the literature. A possible reason is the box length (64 cm) used in this study, which was much longer than that (48 cm) employed in the literature. Ciriello and Snook[33] and Garg and Saxena[34] indicated that the MAWL decreased slightly with increases in box length when the box width was fixed. However, the much longer box length in this research made it impossible for the load to be as close to the feet as in other studies. This difference could explain the smaller capacity results in our study. The extra attention on the lifting speed control required in the study may be another factor that influenced the lifting capacity. In past studies, the participants focused completely on the lifting. However, environmental conditions, machine pacing speed, the requirements of exact positioning of the load, and many other factors are common in practice. The influences of these conditions on lifting capacity are not clear, and further research into these influences is expected.

The risk evaluation of lifting speed

Jager and Luttmann[7] concluded that lumbar stress was related to not only posture but also kinetics during movement. Hall[13] suggested that the maximum (mean) compressive force, shear force, or moment was impacted by the lifting speed. A faster lifting speed increases the chances of lumbar spine injury. Biomechanical analysis has emphasized the importance of the peak or mean value of kinetics measurement. Very fast lifting requires strong muscle contractions, which instantly induce a considerable force and moment, and the musculoskeletal system is thus exposed to the risk conditions of injury. Consequently, it is suggested that a lifting task should be performed as smoothly and slowly as possible. Lin *et al.*[12] found that lifting neither too fast nor too slow minimized the work required to perform a lifting task. That finding means that, in terms of the cumulative load, a lifting speed should be neither too fast nor too slow.

Yoon *et al.* (2012) indicated that there was a biomechanical advantage of fast lifting. They suggested that workers be educated about the benefits of fast lifting pace. Our finding of an optimal lifting speed in this study is in line with and supports this argument. Accordingly, it is a reasonable tradeoff to treat peak/mean kinetics measurements as risk factors for instantaneous injury and cumulative kinetics measurements as risk factors for chronic disease in the risk evaluation of lifting. Synthesizing the results of our study and findings in the literature, we suggest that a suitable lifting speed be used to prevent instantaneous injury and/or chronic disease.

The existence of an optimal lifting speed was confirmed by the psychophysical method in this study. Since lifting conditions and workers vary, the optimal lifting speed will vary also. Principally, the lifting speed should be neither too fast nor too slow. The optimal lifting speed offers the maximum lifting capacity, an acceptable perceived workload, and ease of lifting skills.

A limitation of this study is that it is completely based on psychophysical approach with the focus on the maximum capacity. The low back load such as the moment, the shear force, or the compressive force occurred at the lumbar region was not applied in this research. Further study about the effect of the lifting speed on the lifting capacity under different lifting frequencies is also recommended.

Conclusions

Lifting is prevalent and inevitable in daily life and in industrial practice. It has been identified as the critical cause of low back pain. Low back pain is a frequently occurring chronic occupational disease. Lifting is a dynamic activity, and the most representative feature of this dynamic activity is the lifting speed. However, the risks related to lifting speed and its effects on lifting capacity have received little attention. This study found a parabolic relationship between lifting capacity and lifting speed, indicating that the maximum lifting capacity occurs at the optimal lifting speed. This could be advantageous if a heavy load is to be lifted, for the worker can generate a much larger capacity than the task requirement. It is suggested that another approach to safe lifting would be to incorporate training in how to determine an optimal lifting speed with lifting techniques.

References

1) Hales TR, Bernard BP (1996) Epidemiology of work-related musculoskeletal disorders. Orthop Clin North Am **27**, 679–709. [Medline]
2) Guo HR, Tanaka S, Cameron LL, Seligman PJ, Behrens VJ, Ger J, Wild DK, Putz-Anderson V (1995) Back pain among workers in the United States: national estimates and workers at high risk. Am J Ind Med **28**, 591–602. [Medline] [CrossRef]
3) Frank JW, Kerr MS, Brooker AS, DeMaio SE, Maetzel A, Shannon HS, Sullivan TJ, Norman RW, Wells RP (1996) Disability resulting from occupational low back pain. Part I: What do we know about primary prevention? A review of the scientific evidence on prevention before disability begins. Spine **21**, 2908–17. [Medline] [CrossRef]
4) Bergquist-Ullman M, Larsson U (1977) Acute low back pain in industry. A controlled prospective study with special reference to therapy and confounding factors. Acta Orthop Scand **48**, 1–117. [Medline] [CrossRef]
5) Kromodihardjo S, Mital A (1986) Kinetic analysis of manual lifting activities: Part I—Development of a three-dimensional computer model. Int J Ind Ergon **1**, 77–90. [CrossRef]
6) Garg A, "Lift Angle and its Effect on Stresses to the Low-Back," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1982. pp. 565–9. [CrossRef]
7) Jäger M, Luttmann A (1989) Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment human model. Ergonomics **32**, 93–112. [Medline] [CrossRef]
8) Yoon J, Shiekhzadeh A, Nordin M (2012) The effect of load weight vs. pace on muscle recruitment during lifting. Appl Ergon **43**, 1044–50. [Medline] [CrossRef]
9) Davis KG, Marras WS, Heaney CA, Waters TR, Gupta P (2002) The impact of mental processing and pacing on spine loading: 2002 Volvo Award in biomechanics. Spine **27**, 2645–53. [Medline] [CrossRef]
10) Cholewicki J, Silfies SP, Shah RA, Greene HS, Reeves NP, Alvi K, Goldberg B (2005) Delayed trunk muscle reflex responses increase the risk of low back injuries. Spine **30**, 2614–20. [Medline] [CrossRef]
11) NIOSH (1981) Work practices guide for manual lifting. National Institute for Occupational Safety and Health, Cincinnati. OH.
12) Lin CJ, Bernard TM, Ayoub MM (1999) A biomechanical evaluation of lifting speed using work- and moment-related measures. Ergonomics **42**, 1051–9. [Medline] [CrossRef]
13) Hall SJ (1985) Effect of attempted lifting speed on forces

and torque exerted on the lumbar spine. Med Sci Sports Exerc **17**, 440–4. [Medline] [CrossRef]
14) Fathallah FA, Marras WS, Parnianpour M (1998) An assessment of complex spinal loads during dynamic lifting tasks. Spine **23**, 706–16. [Medline] [CrossRef]
15) Lavender SA, Andersson GB, Schipplein OD, Fuentes HJ (2003) The effects of initial lifting height, load magnitude, and lifting speed on the peak dynamic L5/S1 moments. Int J Ind Ergon **31**, 51–9. [CrossRef]
16) Gagnon M (2005) Ergonomic identification and biomechanical evaluation of workers' strategies and their validation in a training situation: summary of research. Clin Biomech (Bristol, Avon) **20**, 569–80. [Medline] [CrossRef]
17) Lee J, Nussbaum MA (2012) Experienced workers exhibit distinct torso kinematics/kinetics and patterns of task dependency during repetitive lifts and lowers. Ergonomics **55**, 1535–47. [Medline] [CrossRef]
18) Lee J, Nussbaum MA (2013) Experienced workers may sacrifice peak torso kinematics/kinetics for enhanced balance/stability during repetitive lifting. J Biomech **46**, 1211–5. [Medline] [CrossRef]
19) Plamondon A, Denis D, Delisle A, Larivière C, Salazar E; IRSST MMH research group (2010) Biomechanical differences between expert and novice workers in a manual material handling task. Ergonomics **53**, 1239–53. [Medline] [CrossRef]
20) Valkenburg H, Haanen H (1982) The epidemiology of low back pain. Idiopathic Low Back Pain. Mosby. St. Louis.
21) Gagnon M, Plamondon A, Gravel D, Lortie M (1996) Knee movement strategies differentiate expert from novice workers in asymmetrical manual materials handling. J Biomech **29**, 1445–53. [Medline] [CrossRef]
22) Bigos SJ, Spengler DM, Martin NA, Zeh J, Fisher L, Nachemson A (1986) Back injuries in industry: a retrospective study. III. Employee-related factors. Spine **11**, 252–6. [Medline] [CrossRef]
23) Garg A, Beller D (1994) A comparison of isokinetic lifting strength with static strength and maximum acceptable weight with special reference to speed of lifting. Ergonomics **37**, 1363–74. [Medline] [CrossRef]
24) Konz SA, Johnson S, Work design: industrial ergonomics: Grid Pub., 1983.
25) Bernard TM, Ayoub MM, Lin CJ (1999) Effects of speed of lift on static and inertial moments at the joints. Int J Ind Ergon **24**, 39–47. [CrossRef]
26) Kroemer KH (1983) An isoinertial technique to assess individual lifting capability. Hum Factors **25**, 493–506. [Medline]
27) Greenland KO, Merryweather AS, Bloswick DS (2013) The effect of lifting speed on cumulative and peak biomechanical loading for symmetric lifting tasks. Saf Health Work **4**, 105–10. [Medline] [CrossRef]
28) Ayoub M, Bethea N, Deivanayagam S, Asfour S, Bakken G, Liles D, *et al.* (1978) Determination and modelling of lifting capacity. NIOSH, HEW Final Report for Grant No. 5 ROL OH 00545-02.
29) Ciriello VM, Snook SH (1983) A study of size, distance, height, and frequency effects on manual handling tasks. Hum Factors **25**, 473–83. [Medline]
30) Lee YH, Chen YL (1996) An isometric predictor for maximum acceptable weight of lift for Chinese men. Hum Factors **38**, 646–53. [Medline] [CrossRef]
31) Lee YH, Wu SP, Hsu SH (1995) The psychophysical lifting capacities of Chinese subjects. Ergonomics **38**, 671–83. [Medline] [CrossRef]
32) Snook SH, Ciriello VM (1991) The design of manual handling tasks: revised tables of maximum acceptable weights and forces. Ergonomics **34**, 1197–213. [Medline] [CrossRef]
33) Ciriello VM, Snook SH, "The effects of size, distance, height and frequency on manual handling performance," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1978. pp. 318–22.
34) Garg A, Saxena U (1980) Container Characteristics and Maximum Acceptable Weight of Lift1. Human Factors: The Journal of the Human Factors and Ergonomics Society **22**, 487–95.