A BIOMECHANICAL ANALYSIS OF LIFTING SPEED

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Keywords: Biomechanical model; Manual lifting; Speed of lift; Static moment; Dynamic moment.

ABSTRACT

When an individual lifts a load, reactive moments resulting from the effects of the external and internal forces act on the body joints. The moments consist of two components: a static element due to gravitational forces and a dynamic element due to inertial resistance to the movement. Although it is commonly advised that when a person lifts a load, the speed should neither be too fast nor too slow, the static and dynamic effects of lifting with different speeds on the musculoskeletal system have not been evaluated. Furthermore, a hypothesis which postulates that individuals move in such a manner as to reduce their total muscular effort to a minimum in accordance with the task's constraints, was applied by numerous researchers in the design of lifting tasks without being verified experimentally. This study was designed to test the hypothesis that for an individual performing a specific lifting task, there is a speed at which the sum of the static and dynamic moment components affecting the body joints is a minimum. Moreover, it was postulated that a person will most likely select that speed at which the sum of the moments is minimum. To test the hypothesis, a biomechanical model was used which computes the static and dynamic moment components to which a person is subjected while lifting at a particular speed. Eight subjects lifted 18.15 and 27.22 kg loads from floor to overhead reach height. Although no statistical analysis was used to verify the hypothesis, the results suggested that there is an optimal speed of lift for every person at which the musculoskeletal system is least stressed. The results also indicated that the person will most likely select a speed equal to or slightly slower than the optimal speed.

1. INTRODUCTION

It has been recommended that a person lifting a load should do so in a smooth, deliberate, and well-planned manner (NIOSH 1981). The lifting motion, it is advised, should not be fast or jerky in order to avoid the increase of inertial forces on the body due to acceleration. NIOSH (1981) cautioned that dynamic forces imparted by rapid or jerking motions can multiply a load's effect greatly. On the other hand, researchers (e.g., Konz 1983) concede that acceleration during the lift should be fast enough to get the benefit from the body's weight and momentum but not too fast. Konz (1983) recommends that the lift should not be too fast or too slow. In other words, some form of compromise should be reached between fast and slow lifts.

Jager and Luttman (1989) analyzed simulated lifting tasks using a dynamic biomechanical model. They contrasted the curves for the dynamic model calculations of the lumbo-sacral compressive force with the curves resulting for the static analysis where the influence of inertia was omitted. They attributed the discrepancies between the dynamic and static load analyses during the initial phase of the movement to the additional dynamic forces and torques produced in order to accelerate the body parts and the load out of the rest position. As for the retardation phase of the movement, the authors speculated that smaller forces are required from the muscles since the momentum can be utilized, which explained the lower values of the lumbar stress that occur in this phase than for the static calculations. Although idealistically presented, the authors succeeded in demonstrating that regardless of the speed of the lift, the peak value of the lumbar stress using the static analysis is the same for all identical lifting tasks. In fact, not only the peak value but also the lumbar stress throughout the movement is identical between lifts of varying speeds. The difference, however, is that the faster the lift, the shorter the time over which the stresses occur.

The pattern of the lumbar stress at different lifting speeds using the dynamic analysis, on the other hand, demonstrated a different trend. Unlike the static lumbar stress, the stress calculated from the dynamic analysis had a peak value approximately 12 and 42% larger when the speed was increased by 25 and 50%, respectively, due to the additional dynamic stresses produced as a result of the increased acceleration. Jager and Luttman (1989) concluded that the lumbar stress is not only dependent on the change in postures during the movement, but also on 'how quickly' the lift is executed.

Similar findings were presented by Kromodihardjo and Mital (1986). Based on current literature, the authors concluded that static models underestimate spinal stresses anywhere from 40 to 50% to nearly as much as 100%. Other researchers (e.g., Garg et al. 1982) reported that the compressive force at the low back and peak task moments at various body joints were approximately two to three times greater than those based on a static biomechanical simulation. The inertial forces, if not taken into account, will result in such discrepancies. This implies that dynamic stresses may be as high as 300% of the static stresses.

Nubar and Contini (1961) postulated that an individual will move (or adjust his posture) in such a manner as to reduce his total muscular effort to a minimum consistent with imposed task and workplace constraints. They called this the Minimal Principle in Biomechanics. Nubar and Contini (1961) defined muscular effort as a function of the product of a joint moment and its duration. In order to mathematically formulate their principle, they represented the effort function by the product of the sum of squares of the moments at all the body joints and the duration of the effort. Nubar and Contini (1961) further restated their minimal principle in mathematical terms proposing that *the most likely motion of the individual is one in which* the joint movements minimize the effort function or its time integral.

Based on the Minimal Principle in Biomechanics, several researchers used a variety of optimizing techniques for the design and evaluation of lifting and other tasks (e.g., Ayoub 1971, Petruno 1972, Muth et al. 1976, Ayoub and Chen 1986, Chen 1988, and Lee 1988). The fundamental assumption motivating all these models is that individuals will optimize their lifting performance in accordance with the task's constraints in such a manner so as to minimize the muscular effort expended throughout the duration of the lift. In order to formulate the models, the researchers considered that this optimum performance is proportional to a function of the net moments induced during a task. Specifically, Muth et al. (1976) expressed muscular effort as the time integral of the square of the moment at the ankle joint.

Although decades have passed since Nubar and Contini (1961) formulated their principle, and although it has been applied by numerous researchers in performance optimization problems, their hypothesis still awaits to be verified experimentally as it relates to lifting.

This study was conducted to test the hypothesis that the sum of the static and dynamic components of the reactive moments at the joints of an individual throughout the execution of a lift vary at the different lifting speeds in such a manner that there is a minimum value at a specific lifting speed. Furthermore, it is postulated that if free to determine his own lifting speed, the individual will more likely select that speed at which the minimum occurs.

2. METHODS

2.1. Subjects

Eight male volunteer college students served as subjects. Their ages were 21-29 years, heights 1.70-1.88 m, weights 60.34-100.27 kg. All subjects were in good health with no previous musculoskeletal problems and who had little or no experience in the area of manual materials handling. Throughout the experimental session, the subjects wore shorts and shoes, but no shirt.

2.2. Experiment

An isoinertial incremental lifting apparatus, described in Kroemer (1983), was used. The apparatus consists of a *vertical frame along which a carriage with handles slides* on guide rails. The minimum mass of the carriage is 18.15 kg. By adding loads of 4.54 kg each, the mass may be increased incrementally. The apparatus was selected in order to provide smooth vertical lifting movement of the load resulting in fairly similar motion patterns within and across subjects and therefore limiting variability of lifting time due to different motion paths of the load. In addition, the length of the motion path could be accurately measured and, therefore, it was possible to calculate the average speed of the load which was further used as an indicator of the speed of the lift.

A computer-based cinematographical motion analysis system, ExpertVision, was used to record motion paths of specified body joints while the subject executed the lift. Three video cameras operating at 60 fps captured the movement throughout the duration of each lift. The captured video images were then digitized into coordinates of the joint centers. The coordinates of each joint were then linked from frame to frame to form trajectories of the movement of the joints.

2.3. Task

The task consisted of a two-handed sagittal-plane lifting task from floor to overhead reach height. Two carriage masses were used: 18.15 and 27.22 kg. Each lift was executed once.

2.4. Procedure

At the onset of each experimental session, the subjects' anthropometric measurements were taken. Weight, stature, hand- forearm length, upper arm length, trunk length, upper leg length and lower leg length were measured. Segment lengths were measured according to the definitions in Winter (1979).

The subjects then received instructions regarding the lifting procedure. Basically they were instructed not to jerk the load and to keep the motion as smooth as possible. The subjects were free to select any lifting technique they felt comfortable with. They were then allowed to warm up and become familiar with the lifting apparatus. With the carriage set at the minimum mass of 18.15 kg, they lifted the load while grasping both handles from the bottom position to overhead reach. Each subject was allowed approximately 10 min to warm up.

Following the familiarization period, the subject's wrist, elbow, shoulder, hip, knee and ankle were identified using adhesive reflective markers. The subject was then instructed to lift the lighter load (18.15 kg) at different speeds, both fast and slow. He was also asked to lift at a speed that he preferred and which he would use if left to his own free will. Although the instructions given to the subject were to lift fast or to lift slowly, there was no objective method to control the speed. The subject subjectively determined what he perceived was fast or slow. Approximately 3 min of rest were allowed between trials. When it was felt that an adequate number of trials with varying speeds were executed and recorded (from 6-9 trials), the subject was given approximately 10 min to rest. Two incremental masses were then attached to the carriage and the same procedure was repeated for the resulting mass of 27.22 kg. Each subject was tested separately in one experimental session which lasted approximately 2.5 hours.

2.5. Biomechanical Model

The body was considered to consist of five segments: forearm, upper arm, trunk including the neck and head, upper leg and lower leg. Anthropometric data derived from Dempster (1955) were used to determine the masses, centers of gravity and moments of inertia of the segments (Winter 1979). In addition to the computed anthropometric data, other input to the model consisted of measured anthropometric data, load data, frame by frame movement data supplied by the motion analysis system and the time interval between frames.

Realizing the fact that when an individual lifts a load, the reactive moments on the joints consist of two components: a static element due to gravitational forces and a dynamic element resulting from the inertial resistance to the movement, a dynamic two-dimensional biomechanical model was used to evaluate the static and dynamic components of the reactive moments on the elbow, shoulder, hip, knee and ankle. Furthermore, the model calculates the time integral of the sum of the absolute value of the static components as well as the sum of the absolute value of the dynamic components of the moments on all the body joints throughout the execution of the lift. For the purpose of the analysis, the time integral of the sum of each of the absolute static and absolute dynamic components of the moments on the elbow, shoulders, hip, knee and ankle were combined for every lift.

3. RESULTS

In so far as the lifting speed was not monitored directly in each trial, nor was there a specific number of trials required from each subject while lifting each load, the resulting number of trials ranged between 5 to 9 trials per task (task = subject x load combination). The average lifting speed within each trial was computed by dividing the distance traveled by the load by the time of the lift. Each subject performed one or two trials at his preferred speed. The remaining trials ranged between fast and slow lifts based on the subjects' own perception. Two sets of

Table 1. Lifting speed and moment data summary (18.15 kg) (for 5 subjects)

	Numerical Values Range			
	Min	Max	Mean	S.D.
Optimal lifting speed (m/s)	0.98	1.70	1.38	0.23
Minimum moment integral (Nm.s)	758	1148	990	129
Preferred lifting speed (m/s)	0.95	1.44	1.14	0.19
Moment integral at preferred speed (Nm.s)	758	1245	1085	174

Table 2. Lifting speed and moment data summary (27.22 kg) (for 5 subjects)

	Numerical Values Range			
	Min	Max	Mean	S.D.
Optimal lifting speed (m/s)	1.08	1.23	1.18	0.05
Minimum moment integral (Nm.s)	940	1538	1274	199
Preferred lifting speed (m/s)	0.84	1.20	. 0.99	0.14
Moment integral at preferred speed (Nm.s)	1014	1546	1348	205

27.22 kg loads, respectively, with an average overall mean variation of 17 and 16% for each of the 18.15 and 27.22 kg loads, respectively.

The remaining two subjects did not provide a set of data along a wide enough range of speeds such that an optimal value might be reached. Because of the inadequate speed ranges and, thus, the absence of the familiar U-shaped curve, the subjects were excluded from the analysis.

4. DISCUSSION

The overall moments affecting the joints due to gravitational and inertial forces were separated into static and dynamic components. The model was designed to evaluate the time integral of the absolute value of each of the static and dynamic components of the moments acting on the body joints. The reason behind using the absolute values is that whether positive or negative, a joint reaction moment is produced as a result of concentric or eccentric muscular contractions. Both types of contractions result in mechanical work done by the muscles (positive work) or on the muscles (negative work) which both represent a form of loading on the musculoskeletal system. Marras et al. (1986) realized the significance of the absolute moment concept. They did not use, however, the cumulative value of the moment. Instead, they utilized the average absolute moment produced by the trunk throughout an experimental trial to evaluate the average torque production capability of the trunk.

The optimal lifting speed, represented by the velocity of the load, ranged between 0.98 and 1.7 m/s over all trials (for both the 18.15 and 27.22 kg) with an average value of 1.28 m/s. In a study by Leskinen et al. (1983), twenty test subjects determined their lifting speed while lifting a 15 kg box from a shelf 0.10 m above the floor to knuckle height. The resultant vertical load velocity ranged between 0.86 and 1.60 m/s with a mean value of 1.27 m/s. The authors did not refer to the extent of experience of their subjects in manual lifting. They did mention, however, that their subjects underwent training in the lifting techniques used in their study. The close similarity between the optimal lifting speeds resulting from the present study and the subjectively determined lifting speeds from Leskinen et al. (1983) may involve the training received by the subjects in the latter study. With training, subjects are more likely to better judge the most comfortable lifting speed, i.e., the speed that will result in the least exertion.

The subjects' preferred lifting speed ranged between 0.84 and 1.44 m/s over all trials (for both the 18.15 and 27.22 kg) with a mean value of 1.06 m/s which on the average was 16.5% slower than the optimal speed evaluated by the biomechanical model. Marras et al. (1986) found that as the velocity increases, the cost to the trunk muscle of producing a unit torque increases dramatically, i.e., the torque capability of the trunk muscle decreases. Hence, the deviation between optimal and preferred speeds may be a result of a compromise made by the subjects to achieve a low enough overall moment on their musculoskeletal system and at the same time operate at a velocity where their strength capabilities are not greatly reduced. Other researchers (e.g., Hafez et al. 1982) also found that the maximum voluntary strength of the different body joints decreases with the increase in the velocity of movement.

The optimal lifting speed differed when handling each load. Computed from the five-subject data (Tables 1 and 2), the optimal lifting speed at the 27.22 kg load was on the average 14% slower than that at 18.15 kg. A noticeable 29% increase of the corresponding moment integral at 27.22 kg accompanied the reduced speed.

A similar behavior was exhibited by each of the preferred speed and the corresponding moment. Preferred speed was 13% lower and corresponding moment integral was 24% higher at the 27.22 kg load.

The reduction in optimal and preferred lifting speeds when the subjects were lifting the heavier load by 14 and 13%, respectively, indicates that the heavier the load, the slower it should be lifted. It also indicates that intuitively the subjects perceived that effect, and although their preferred speed did not match the optimal speed, they nevertheless reduced their preferred lifting speed accordingly.

The increase in the moment integral corresponding to the optimal and preferred speeds by 29 and 24%, respectively, reveals that although the lifting speeds were reduced, the loading of the musculoskeletal system was more stressful at the heavier load.

The variation in moments between subjects may be attributed to differences in posture as well as body anthropometry and method of lift.

The two subjects whose data were eliminated from this study did not provide a set of data along a wide range of speeds such that an optimal value might be reached.

5. CONCLUSION

The results of this study indicate that for an individual with specific anthropometric characteristics lifting a specific weight using a certain posture, there is an optimal speed of lift which is the least stressful to the musculoskeletal system of that individual. Furthermore, if the individual is sufficiently trained and has adequate experience in the area of manual lifting, he will most likely select a velocity equal to or slightly slower than that optimal speed to execute his lifts.

6. SUGGESTIONS FOR FUTURE RESEARCH

This present work was basically a small scale study. The results are encouraging enough, however, to merit a larger scale study in order to further verify the hypothesis. Therefore, a study is recommended in which the test subjects are recruited from experienced industrial weight lifters or if unavailable, subjects need to be trained in performing the lifting task before participation. Such training may result in their speeds of lift approaching the optimal lifting speed determined by the model. Selecting another method for combining the moments of the different joints other than simply adding them in order to reflect their relative sensitivity may also provide further insight. It may also be interesting to investigate the relationship between the strength capabilities of the subjects at the different speeds and how this relates to the observation that subjects tended to select a slower lifting speed than the optimal.

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