

TRUNK MOTION DURING LIFTING: TEMPORAL RELATIONS AMONG LOADING FACTORS

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ABSTRACT

The time dependent aspects of trunk muscle activation are of utmost importance when evaluating the loading of the spine during lifting. If all spine supporting muscles reach peak force simultaneously during a lift, the effects upon the spine would be much different than if the forces activated sequentially. This research has studied the recruitment and peak activity pattern of the back musculature as well as their association with trunk supporting force production. Forty-five subjects were evaluated in this effort under static and controlled dynamic con-

ditions. Most recruitment delays between signals were similar except between the muscles and torque. However, significant peak delays were noted among all experimental conditions. Generally, when the trunk exerted lifting force under static conditions, the peak time delays were similar to a dynamic lift of 30 deg/s. Dynamic lifts of 15 deg/s resulted in much longer peak time delays between signals whereas dynamic lifts of 90 deg/s resulted in very short peak time delays. The biomechanical significance of these findings is discussed.

INTRODUCTION

Static analyses of trunk loading have been the primary tool used by ergonomists to evaluate back injury risks in the workplace. Often a job or lifting task is designed or re-evaluated based upon the limits described by static models. For example, the National Institute for Occupational Safety and Health has recently published a lifting guide (NIOSH, 1981) which is based exclusively upon static force exertion capabilities while in a sagittally symmetric posture. Schultz and Andersson (1981) have also produced a three-dimen-

sional model which may be used for lifting evaluations. This model has also been validated using static analysis techniques (Schultz et al., 1982).

These models are usually validated by observing lengthy static exertions of the muscles and then determining how these internal loading forces (muscle force) combine with external loading forces (forces due to the weight of the object lifted) to create compression upon the spine. These compression levels are usually compared with in-vitro vertebrae fracture data to determine the limits of spine loading due to the lifting task.

In most static models the load due to the internal and external forces is determined by monitoring the average force which is supplied from a muscle over a lengthy period of time (Caldwell et al., 1974; Schultz et al., 1982). The time exertion period usually ranges from 3 to 15 s. Kroemer and Marras (1981) developed an empirical model of muscle force generation and found that the best predictor of muscle loading is the time development history of the muscle force signal. They pointed out that the development of force changes significantly over time within the muscle. These changes may have profound effects in the development of total force within a biomechanical structure.

Dynamic actions of a body link may also result in significantly different force-time characteristics during an exertion compared with static exertions. When a body link moves during the exertion of force, the various internal loading structures may be recruited and produce maximum force at different points in time compared with static exertions. Thus, these temporal characteristics may not be well represented in a model by muscle force averages.

The temporal aspects of internal and external loading of the body must be investigated so that the characteristics of instantaneous loadings can be appreciated. This knowledge is needed so that more accurate models of trunk loading can be developed which represent the biomechanical risks of injury under dynamic lifting conditions. For example, if all the internal forces reach their maximum force simultaneously, the cumulative effects of such loading upon the spine would be significantly greater than would be predicted if only the average force of all the muscles were considered.

The objective of this research was to investigate the differences which occur in key internal and external trunk loading events during static and dynamic trunk lifting actions. Two events were defined for these pur-

poses. First, the signal onset time of the internal and external loading forces was observed. This signal onset time represents the point at which the signal increased its activity from the resting level. The onset event time shows the point at which each signal was recruited and began to contribute to the total force experienced by the trunk. Second, the point of maximum (peak) activity of each signal was investigated. This event represents the point at which the maximum loading of the muscle occurs. Both of these events were investigated in terms of the relative delay time between the various internal and external loading factors. Thus, when the delay time was short, the events occur more simultaneously and this situation represents a greater risk to the spine.

In order to evaluate the internal and external forces which load the trunk during a lift, the transverse plane technique of Schultz and Andersson (1981) was used to identify the appropriate internal structures. They assumed that if a transverse plane was passed through the trunk at the lumbar level of interest, the muscles which support the external load would be identifiable. The evaluations of Schultz et al. (1981) and Marras et al. (1984) have shown that in static and dynamic (isokinetic) sagittally symmetric lifting actions the latissimus dorsi and erector spinae muscle groups are responsible for most of the load support during the task. The temporal relationships among these internal structures and between these structures and external force generation capacity were evaluated in this study.

METHOD

Subjects

The subject population for this experiment consisted of normal healthy males between the ages of 17 and 61 years. The average age of the subjects was 31 years. Forty-five sub-

jects were tested in this experiment. A variety of occupations were represented in this experiment. Only subjects who had not experienced chronic low back disorders were used in the experiment.

Subjects were informed as to the nature of the experiment and were provided with an opportunity to become familiar with the experimental apparatus and the experimental task.

Anthropometric characteristics of the subject population were also recorded. A report of these characteristics may be found in Marras (1985).

Design

The independent variable in this experiment consisted of the trunk velocity. Trunk velocity was defined in terms of the angular velocity about the lumbro-sacral junction (L5/S1) of the spine. Velocity was investigated in terms of both isometric (static) and isokinetic (dynamic) exertions of the trunk. Isometric exertions were tested at three trunk angles consisting of 0 deg, 22.5 deg and 45 deg trunk angles. The 0 deg trunk angle refers to the upright standing posture of the trunk whereas the 22.5 deg and 45 deg trunk angles refer to the forward flexed angles of the trunk while the body is in a sagittally symmetric position. Dynamic velocities were evaluated at three levels. These consisted of 15 deg/s, 30 deg/s and 90 deg/s of trunk angular motion within the sagittal plane.

The dependent variables in this experiment consisted of the onset and peak time delays among the internal and external trunk loading variables. The internal trunk loading variables consisted of the right latissimus dorsi muscle (LATR), left latissimus dorsi muscle (LATL), the right erector spinae muscle (ERSR), and the left erector spinae muscle (ERSL). The muscle forces were evaluated via electromyographic (EMG) recording of the muscle activities. The EMG signals were in-

tegrated so that the relative muscle force development could be observed. The external loading variable consisted of the torque that was produced about the L5/S1 junction as the subject moved through the lifting postures. The trunk torque was measured by an isokinetic dynamometer which was capable of testing both static and isokinetic exertions.

The experimental task was intended to replicate the forces that were experienced by the trunk during a "back lift" effort. During such an effort, the trunk link between the sacrum and the shoulders must rotate about L5/S1. This motion begins with the trunk bent forward and the lifter extends this trunk link upward until the trunk is in an upward standing posture.

The experimental task in this experiment isolated the motion to that of the trunk. Subjects were placed in a reference frame which aligned the L5/S1 junction with the axis of rotation of the dynamometer. Subjects wore straps about the legs and hips so that the motion was isolated to that of the trunk.

The dynamic exertion began with the trunk bent forward to a 60 deg angle. Subjects were instructed to extend upward with the back and produce maximal voluntary force throughout the range of motion. Subjects were told to cease the exertion once they passed the 0 deg trunk angle. Static exertions were performed in a similar manner as dynamic exertions except the trunk angle was pre-selected and no trunk motion was permitted. Subjects were also asked to exert maximal force against the dynamometer in the static position. The static exertions were three seconds in duration.

All subjects were permitted a rest period of at least two minutes between exertions. This procedure minimized the fatigue that would be experienced by the subject.

Apparatus

The experimental apparatus used in this experiment is described in Marras et al. (1986).

This evaluation is a companion effort to that research.

RESULTS

Signal onset

Initially, the differences between the times of signal onset were evaluated. Signal onset refers to the point at which the signal began to change from its normal resting level. The differences between the onset points of the various signals was evaluated for statistical differences. Table 1 summarizes the results of Analysis of Variance (ANOVA) evaluations of these differences. These analyses indicate that the only significant differences between dependent variable onsets occurred between the LATR and torque, the LATL and ERSR, the LATL and torque, and between the ERSR and torque.

The signal pairs which yielded significant differences between onsets are shown in Fig. 1. Duncan Multiple Range tests were also performed to identify the significant differences and are shown in Table 2. The figures indicate that when the onset of the latissimus dorsi muscle activity is compared with the torque production onset the delay time

TABLE 1
ANOVA summary of onset delay time differences

LAG variables	df	ANOVA sum of square	F	pr > F
LATR-LATL	5	0.0138	0.74	0.5968
LATR-ERSR	5	0.2664	1.50	0.1879
LATR-ERSL	5	0.2731	1.46	0.2015
LATR-TORQ	5	1.4775	5.26	0.0002 *
LATL-ERSR	5	0.4795	2.47	0.0330 *
LATL-ERSL	5	0.2989	1.60	0.1583
LATL-TORQ	5	1.9632	6.56	0.0001 *
ERSR-ERSL	5	0.1578	1.14	0.3392
ERSR-TORQ	5	0.6906	2.31	0.0438 *
ERSL-TORQ	5	0.8221	1.59	0.1632

* Significance at the 0.05 level

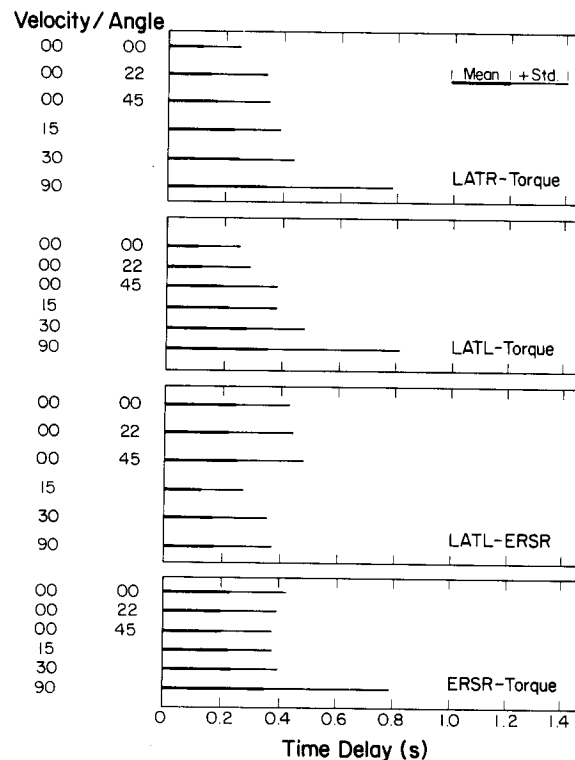


Fig. 1. The mean and standard deviation of the time delays between and among onsets of internal and external forces.

between these variables increases as the static angle increases. Under dynamic conditions, the delay times increase as the velocity condition increases and the dynamic delays are greater than those displayed under static conditions. Duncan evaluations indicated that for most significant differences the 90 deg/s conditions were often different from all other conditions and that the static exertions were often similar to slow dynamic conditions. This trend is particularly apparent when the significant muscle-torque delays were examined.

Significant differences between the muscle onset delays (LATL-ERSR) are more difficult to interpret. Detailed examinations of these delays indicated that all delays except the 0 and 45 deg angles were similar as were the delays between all conditions except the 15 deg/s velocity which was much shorter.

TABLE 2

Duncan range test significance summary for onset delays. Conditions with the same letter are not significantly different ($\alpha \leq 0.05$)

Condition	LATR-TORQ	LATL-TORQ	LATL-ERSR	ERSR-TORQ
STA 0	A	B	B	A
STA 22.5	A B	B	A B	A
STA 45	A B	A B	B	A
DYN 15	A B	A B	A	A
DYN 30	B	A	A B	A
DYN 90	C	C	A B	B

Peak loading

The difference in the time occurrence of the maximum (peak) muscle and torque forces was also investigated. This provides information as to the point of maximum loading of the trunk due to the synergistic action of the maximum internal and external loads. The peak delay times between the variables were tested for their significance of difference. Table 3 shows the results of ANOVA tests performed on these peak delays. This analysis indicated that significant differences existed among all possible peak delays.

Figure 2 graphically depicts the nature of these peak delay differences. The mean and

standard deviation of these delay differences are shown in this figure. Table 4 shows the results of a Duncan analysis of the peak delay times. This analysis indicates the conditions which are responsible for the ANOVA significances reported in Table 3. These analyses indicate that in every case the 15 deg/s exertion results in the greatest peak delay times and the 90 deg/s condition results in the shortest delay times. The 30 deg/s condition varies in its grouping according to the Duncan criteria. However, of particular significance is the fact that *the 30 deg/s condition is often indistinguishable from the static conditions in the generation of peak delay times.*

Temporal correlations

The correlation between the onset delay times, peak delay times and mean force levels for each variable were evaluated. Many significant correlations were observed among the variables. Due to the number of significant correlations observed, they will not be reported here, however, these correlations are available from the author upon request.

Some of the more interesting correlations involve the association among spine loading variables and the delay times. The amount of torque generated by the back was positively correlated with most peak delays among variables but negatively correlated with the onset

TABLE 3

ANOVA summary of peak lag time difference

Peak lag variable	df	ANOVA sum of square	F value	pr > F
LATR-LATL	5	4.7596	5.24	0.0002 *
LATR-ERSR	5	11.7912	8.79	0.0001 *
LATR-ERSL	5	21.4121	18.31	0.0001 *
LATR-TORQ	5	3.7915	3.51	0.0044 *
LATL-ERSR	5	8.9193	6.77	0.0001 *
LATL-ERSL	5	20.2214	15.99	0.0001 *
LATL-TORQ	5	8.1616	6.78	0.0001 *
ERSR-ERSL	5	7.3099	16.17	0.0001 *
ERSR-TORQ	5	20.0357	15.48	0.0001 *
ERSL-TORQ	5	31.0755	25.67	0.0001 *

* Significance at the 0.05 level

TABLE 4

Duncan range test significance summary for peak delays. Conditions with the same letter are not significantly different ($\alpha \leq 0.05$)

Condition	LATR-LATL	LATR-ERSR	LATR-ERSL	LATR-TORQ	LATL-ERSR	LATL-ERSL	LATL-TORQ	ERSR-ERSL	ERSR-TORQ	ERSL-TORQ
STA 0	A	A	A	A	A	A	A	A	A	A
STA 22.5	A	A	A	A	A	A	A	A B	A	A
STA 45	A B	A	A	A	A	A	A	A	A	A
DYN 15	B	B	B	A	B	B	B	B	B	B
DYN 30	A	A	A	A	A	A	A	C	A	A
DYN 90	C	C	C	B	C	C	C	C	C	C

delay times between the latissimus dorsi muscles and torque. Peak delay times also tend to be a much better indicator of muscle force level than do onset delay times. In particular, the peak delay between the erector spinae muscle and torque appear to provide a

good positive and significant indicator of the force level present in a particular muscle of interest.

Many positive correlations were also noted between the peak delay times. Thus, knowledge of the peak delay between any two vari-

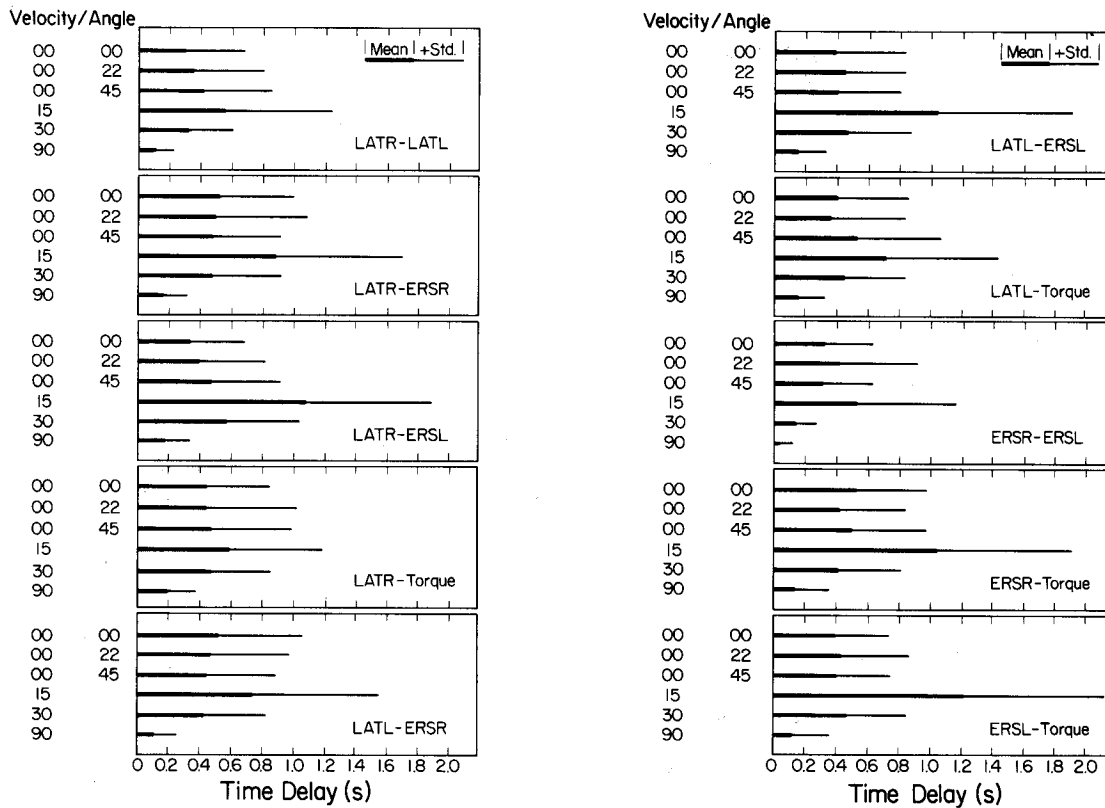


Fig. 2. The mean and standard deviation of the time delay between and among peak internal and external forces.

ables resulted in significant positive correlations among the other peak lag combinations.

DISCUSSION

When signal onset delay time characteristics were considered most of the significant differences were due to the delay time between the onset of the internal forces and the onset of the external forces (torque). The most apparent difference occurred in the 90 deg/s condition. This condition usually resulted in the greatest time delay between the onset of the muscle force and the onset of torque production. Under most conditions, as the velocity of the trunk increased, the delay time between the muscle and the torque also increased. This finding suggests that generally dynamic trunk exertions result in different time sequences of trunk loading than do static trunk exertions.

The advanced analyses of these results indicate that when the delay time between the latissimus dorsi muscles and torque are considered, the delay times under static conditions are similar to those produced under the 15 deg/s condition. Furthermore, the delay times produced at greater static flexion angles of the trunk were similar to those produced under the 15 deg/s and 30 deg/s dynamic conditions. The 90 deg/s condition always produced the greatest onset delay which was always distinguishable from other velocity conditions.

The onset delay time characteristics between the right erector spinae muscle and torque were different than those involving the latissimus dorsi muscles. Only the 90 deg/s condition resulted in significantly different and longer onset delays compared to the other velocity conditions.

The significance of these findings suggest that the synergistic effects of internal and external trunk loadings is similar to static loadings under slow dynamic conditions.

However, at faster velocities, there are significant increases in time between the trunk loading due to internal forces and those due to external forces. Hence, under static conditions, there is one loading phase of the spine whereas during more rapid dynamic conditions there are two distinct loading phases of the spine during lifting.

Even more significant differences were observed when the peak force delay times were considered. This criterion is even more significant than onset time delays since the loading of the spine due to the synergistic action of the internal and external loading forces can far exceed the loading predicted by average muscle force estimates.

The evaluation of the peak lag time delays indicated that significant differences were evident between all delays. Some consistent patterns were evident from advanced analyses. In every case the 15 deg/s exertion condition produced the greatest peak time delays, whereas, the 90 deg/s conditions produced significantly shorter delay times between peak activities. Furthermore, most peak delay time reactions did not produce significantly different patterns between static and 30 deg/s conditions.

These findings suggest several interesting interpretations in the use of static models to assess the effects of lifting upon the loading of the spine. First, it is apparent that the instantaneous peak maximum activity of the muscles should be used to assess the risk involved in lifting. The peak activities represent the loading characteristic which is most significant in the synergistic loading of the trunk. This research has shown that this parameter changes drastically as a function of trunk velocity.

Second, the associations between most internal and external loading factors indicate that if peak loading forces were evaluated in a static model, the results would yield similar temporal relationships among loading factors as those experienced during a 30 deg/s trunk

velocity lift. Thus, if the time events of the loading structure are of interest, static models are a reasonable assessment of the peak activities if the back motion occurs at 30 deg/s. When total trunk load is of interest, the relative magnitude of the muscle force during motion must also be considered.

Third, if the trunk motion during a lift is slow and of the order of 15 deg/s, the delay time between the loading variables increases significantly. This indicated that the occurrence of peak activities due to the various loading structures are being distributed throughout the lift time. This result would tend to reduce the total force experienced by the spine due to peak loading compared with static lifts.

Finally, during rapid dynamics lifting motions of the trunk, the time between the occurrence of the peak loading decrease significantly compared to static exertions. Trunk exertions of 90 deg/s resulted in peak time delays which were generally less than half those observed for static lifting actions. Thus, all peak loadings tend to occur more simultaneously and the resultant loading of the spine would far exceed those of static exertions. This situation is particularly hazardous when the internal loadings occur at the same time as the external loadings.

These findings indicate that if static lift models were used to evaluate the effects of temporal peak loadings it would not be valid for dynamic motions of the spine other than at velocities of 30 deg/s.

Marras and Wongsam (1986) have investigated the range of trunk velocities exhibited by normal healthy subjects under leg lift and back lift conditions. They found that the mean normal trunk velocity exhibited by these subjects under unloaded (external force) conditions was approximately 36 deg/s. This may indicate that static models may be appropriate for the evaluation of peak loading provided that a realistic assessment of muscle force magnitude during motion has been con-

sidered (see Marras et al., 1986). However, a large amount of variability was also observed. Future research should be involved with determining the range of trunk velocities which are used during industrial lifting situations. If this information were available, then the adequacy of static models to represent the range of actual lifting situations could be assessed.

Overall, the peak time delay patterns appear to be a more significant indicator of the changes that occur during dynamic trunk motion compared with onset delay times. This finding is reinforced when correlations between the peak signal time delays and the muscle and torque mean force levels are considered. It appears that knowledge of the peak delay times helps in determining the magnitude of force which will be generated. This finding is consistent with the empirical model reported by Kroemer and Marras (1981). This information may provide a necessary link in the development of trunk exertion models which will be useful in the evaluation of dynamic trunk motions.

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