

Networks of Internal Trunk-Loading Activities under Controlled Trunk-Motion Conditions

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Many attempts have been made to describe the activity of the internal trunk-loading components (muscles and intra-abdominal pressure) in response to external forces acting on the trunk, as is often the case in the workplace. Most models that describe the activity of these internal components are static and do not consider the time series of events that occurs during performance of a task under dynamic conditions. This research has investigated the time sequence activity of ten trunk muscles and intra-abdominal pressure in ten males as they produced sagittally symmetric maximum trunk extension motions (lifting motions) at different velocities. These exertions include an isometric exertion and isokinetic exertions equal to 25, 50, 75 and 100% of a subject's maximum extension velocity. Several event times were noted for each internal trunk-loading component, and hypothesis tests were performed to determine which of these event times were statistically different from each other under the various motion conditions. This information was used to construct networks of internal trunk-loading activities under the various motion conditions. Time-series events that occur under all conditions, as well as those that changed as a function of velocity, have been identified. This information will be useful for the construction of dynamic internal trunk models, and will facilitate the assessment of dynamic loading of the lumbar spine in the workplace. [Key words: trunk musculature, intra-abdominal pressure, internal trunk loading, lifting motion, dynamic exertion]

BIOCHEMICAL EVALUATIONS of the lumbar spine have been recognized as an important effort for understanding how the spine is loaded under working conditions. Conventional models¹³ and analyses have recognized that both external and internal forces contribute to spine wear and tear. External forces are due to work performed outside the body (ie, lifting), whereas internal forces consist of muscle forces and intra-abdominal pressure, which serve as a counter moment to the external forces. Since the internal forces must act at a mechanical disadvantage due to their proximity to the spine compared with the external forces, these internal forces are often large and are the primary loading factors of the spine during work. Thus, it is extremely important to understand the activity of these internal forces during work.

Traditionally, most researchers^{2,13} have developed and validated biomechanical models that describe spine loading during static exertion of the trunk. These models are often validated under lengthy (10-15 seconds), static, steady-state conditions.

We believe that in occupational settings the loading conditions of the spine would be much different, in several respects, than those described by static models. First, during occupational lifting activities, motion is usually involved during the exertion. Second, the exertions are usually rapid and are not well represented by lengthy, static, steady-state exertions. Finally, under motion and maximal static-exertion conditions all muscles (agonist and antagonist), as well as intra-abdominal pressure (IAP), along the transverse plane are usually active and the internal forces change substantially and rapidly throughout the exertion.⁷ Collectively, these factors indicate that all internal support structures are activated at given instants throughout a lifting motion, and these instantaneous activations collectively result in exceedingly large loadings of the spine at certain points during the motions.

Thus, we believe that the chain of events that occurs within the trunk is of utmost importance in the determination of spine loadings. The objective of this research was to determine the sequence of loading events that occurs within the trunk under static and dynamic loading conditions. Furthermore, this effort has focused on identifying the significant differences that occur within the internal structures under simulated lifting conditions.

DATA SOURCE

Data used to study the sequence of events that occur during static and dynamic lifting motions was collected experimentally according to the procedures described by Marras et al.⁷ The data used in the present study consisted of the data obtained from the male subjects under all conditions in that study plus a supplemental maximum velocity condition. This study focuses on the time sequence of events that occurred during the exertions, and only that data will be reported. Analyses of the data related to internal force magnitudes can be found in Marras et al.^{7,8} and Reilly and Marras.¹² The experimental task required subjects to exert maximal force during extension from a stooped lifting position against an isokinetic dynamometer axis arm placed on the back of the subject. Since the exertion conditions were isokinetic, trunk acceleration was minimized. The point of rotation for the dynamometer corresponded to the lumbosacral junction (L5-S1) of the lumbar spine. The dynamometer permitted the subject to create both isometric and isokinetic sagittally symmetric trunk exertions.

In this study, velocity served as an independent variable. Five experimental conditions were observed. These consisted of an isometric exertion with the trunk bent forward at 67.5° from vertical, and four isokinetic exertions where the trunk exertion began at 67.5° and culminated with the trunk in an erect posture. Trunk velocities equal to 25, 50, 75, and 100% of each subject's maximum trunk velocity were controlled in the four isokinetic experimental conditions. In all exertions, subjects were asked to exert maximum trunk force.

The dependent variables in this study consisted of the internal trunk-loading components which influence the forces acting on the lumbar spine. The "transverse plane" technique of Schultz and Andersson¹³ was used to identify the internal trunk-supporting structures. These structures consisted of ten muscles and intra-abdominal pressure (IAP). The muscles investigated consisted of

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the right and left latissimus dorsi (LAT), right and left erector spinae (ERS), right and left internal oblique (INO), right and left external oblique (EXO), and the right and left rectus abdominus (RCA). Muscle activities were measured via integrated electromyography (EMG) using fine wire electrodes. The significance of these muscles to trunk loading was reported by Schultz et al.¹⁴⁻¹⁶ The literature reports mixed findings regarding IAP spine support.^{1,3-5,10,11} However, Marras et al.⁸ have reported a complex yet significant relationship between IAP and spine support. IAP was monitored with a catheter-transducer (natural frequency: 25-40 kHz) placed in the stomach via the nasal passage. Details regarding these measurement and recording techniques may be found in Marras et al.⁷

Subjects consisted of ten male college-age volunteers who were paid for their participation in the study. All subjects were in good health and had never experienced a low-back disorder. Subjects were selected so that gross anthropometry characteristics (height and weight) were within one standard deviation of the mean value described by Webb.¹⁷ Complete anthropometric characteristics were measured and reported in Marras.⁶ Subject testing procedures were the same as those reported by Marras et al.⁷

QUANTIFICATION OF INTERNAL-TRUNK ACTIVITIES

Event-Time Occurrence

In order to quantify several magnitude-time responses in signals as variable as EMG or IAP signals, the responses were summarized by indexing some key points in the signal. These key event times consisted of the time at which the signal increases from its initial resting level (t_1), the time at which the signal reaches its maximum or peak (t_2), and the time at which the signal returns to a resting level (t_3). These key points of an EMG signal are shown in Figure 1. The advantage of such a representation is that it permits one to model the continuous influence of a trunk-loading factor on the loading of the spine by considering only a finite number of key event times.

Initially, all event times were normalized relative to the time of the first occurrence of any signal and the last occurrence of any signal for all dependent variables throughout each exertion. The normalization process was performed by setting this maximum t_3

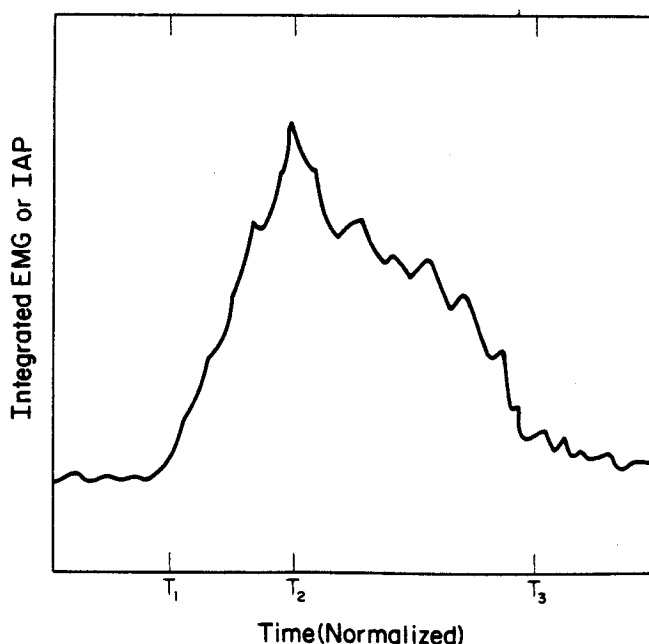


Fig 1. Key event times of an EMG or IAP signal

time within each exertion to one and setting the minimum t_1 time in each exertion to 0 (relative to all signals collectively). This process permitted all signals to be represented on a common time scale throughout all exertions. Events on this time scale represent the percentage of the total exertion time expired at the time the particular event occurred.

The mean t_1 , t_2 , and t_3 event times and their variability characteristics observed under all experimental conditions for each muscle group (right and left sides combined) and IAP are shown in Figures 2, 3, and 4, respectively. We assumed that the trunk motions of our subjects were sagittally symmetric and combined our observations for the right and left sides of the body. However, examinations of the data revealed that the exertions were not perfectly sagittally symmetric. Some interesting trends can be observed in these figures. Figure 2 shows that, under static conditions, the start time of the various signals is fairly homogeneous compared with the other conditions. This figure also shows that the RCA signal starts later as the velocity condition increases. This is probably indicative of the braking action of this muscle in response to trunk motion. Also apparent from this investigation is the fact that the ERS, LAT, and IAP signals tend to activate at similar times and follow similar patterns as the velocity conditions change. The INO and EXO signals also start at approximately the same time. Compared to the ERS, LAT, and IAP signals, however, the INO and EXO event times occur at a later time.

The behavior of the peak (t_2) event times was different. Figure 3 indicates that the peak signal times occurred at different times throughout all exertions and that the variability in event times between muscle groups appeared to decrease as the velocity condition increased. The IAP and LAT peak times occurred much later in the exertion under static conditions as opposed to the dynamic condition. The ERS signal peak occurred at approximately the same time during most exertions except under the 100% velocity condition. Other differences occur in the RCA and EXO muscles. Under the static conditions, these peaks occurred fairly early in the exertions. As the velocity condition increased, however, these peak times occurred later and acted as brakes for the trunk motion. Of particular significance is the fact that these muscles and ERS peak at approximately the same time during the 50% velocity conditions. The INO response occurred at fairly consistent points throughout the conditions.

The signal-termination point (t_3) also reveals some interesting findings (Figure 4). First, IAP is the last signal to return to a resting level under all conditions. Next, the ERS-termination time decreases as the velocity condition increases. Third, the EXO signal-termination time generally increases as a function of velocity. Fourth, IAP and RCA are relatively unchanged over all conditions. The LAT signal is also very constant at 25, 50 and 75% velocity, but changes under static and 100% conditions. Finally, extrapolation leads us to think there is a crossover point for the EXO, INO, and ERS muscles at about 33% velocity.

It should be pointed out that these findings represent the mean activity of all event times. These data also displayed a large amount of variability. Therefore, it is possible that individual subjects behaved in very different ways than are reported by these figures. This variability is the focus of an ongoing investigation.

Event Time Significance

Once the event times were normalized, they were treated as observed values of random variables. Since significant variability in event times was evident, hypothesis tests were performed to determine whether the differences between event times were statistically significant for all subjects combined under each condition ($\alpha =$

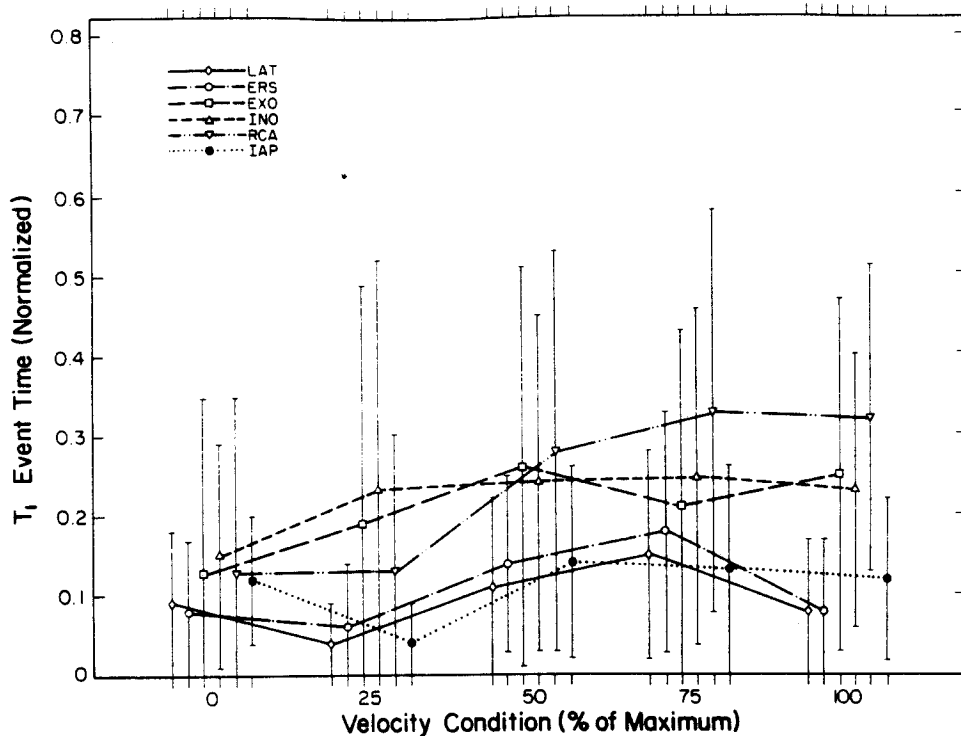


Fig 2. Mean and standard deviation of signal initiation event times (t_1).

0.10). Figure 5 summarizes the results of these hypothesis tests. Since all exertions were sagittally symmetric, these tests represent the combined data for the right and left sides of the body. These tests also were directional in they they determined whether a given event preceded or succeeded an event for another signal. The margins of the figure show the internal components (muscle or IAP) and the event times (t_1 , t_2 , or t_3) that are compared. In this figure, if a "1" appears in a cell, the row event preceded the column event and

the difference was statistically significant. If a "0" appears in a cell, there was no statistically significant difference in occurrence times between the row and column events. When a "1" appears in a cell, the column event preceded the row event and the difference was statistically significant. The conditions which are considered in each comparison are shown in the legend. As shown in the figure, many significant changes occurred as the velocity condition changed. Of particular interest are the occurrences where the event status

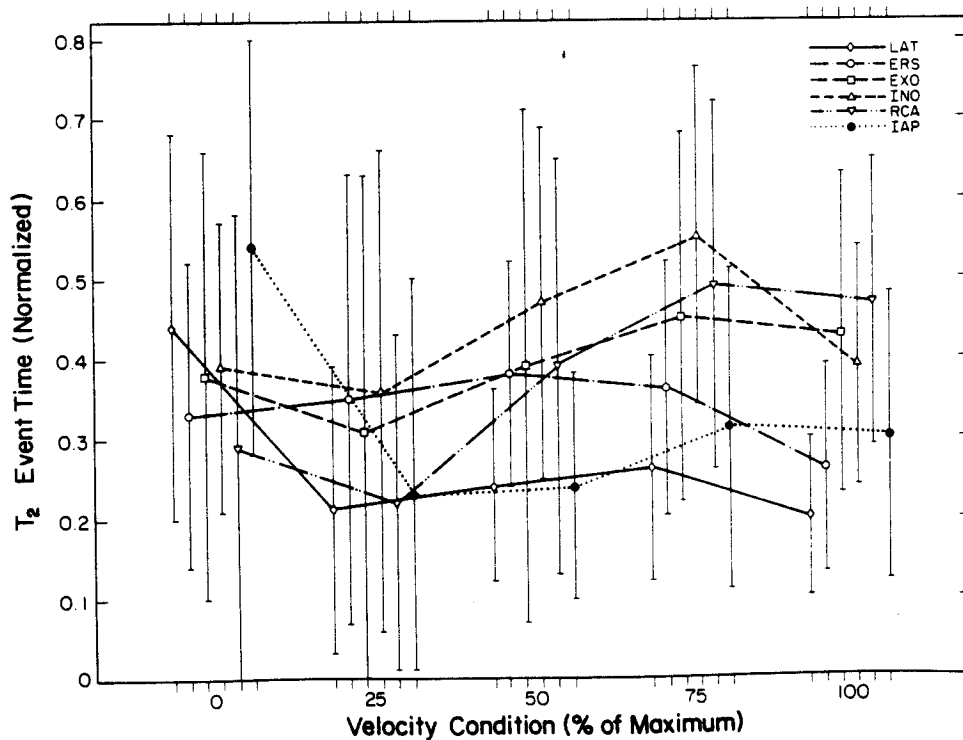


Fig 3. Mean and standard deviation of signal peak event times (t_2).

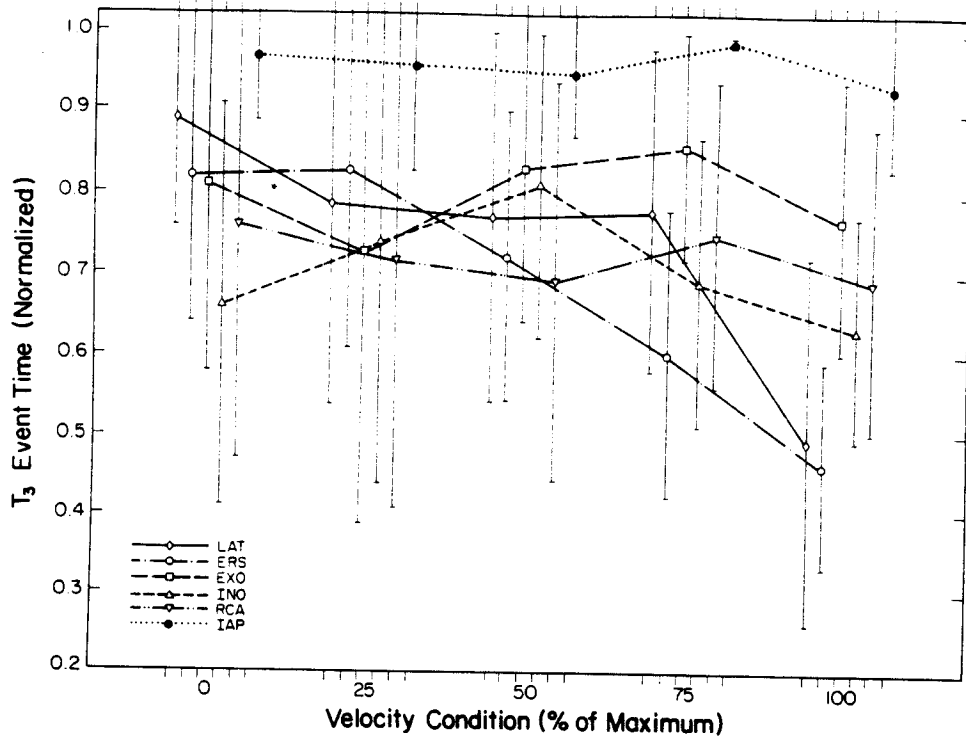


Fig 4. Mean and standard deviation of signal termination event times (t₃).

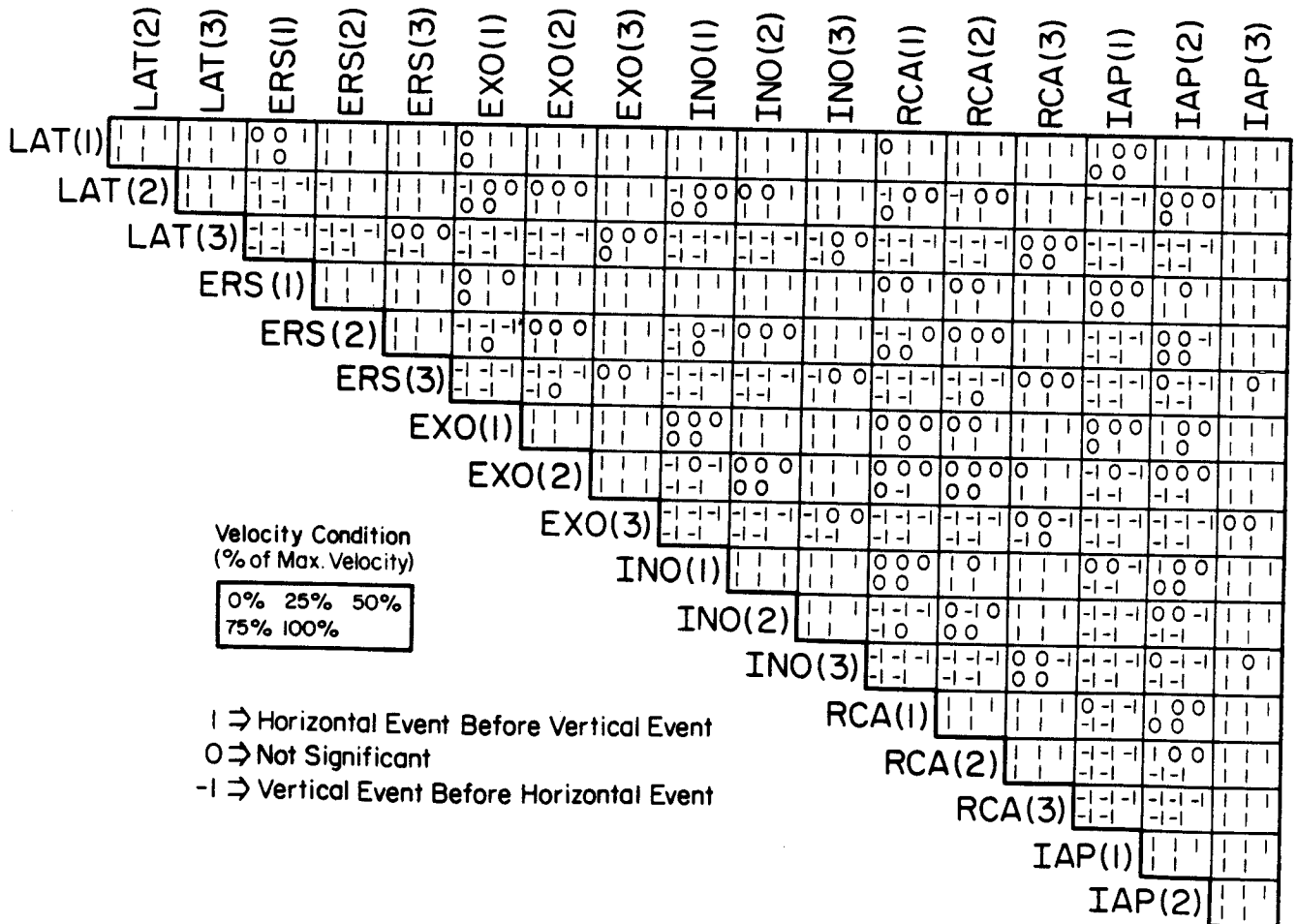


Fig 5. Summary of significant differences between event times under different conditions.

changes from one condition to the next. For example, INO(3) (end of internal oblique activity) occurs before ERS(3) (end of erector spine activity) under the static condition. Under 25% and 50% velocity conditions, the end times occur at about the same time throughout the exertion. Finally, under 75% and 100% velocity conditions, the pattern is reversed from the static condition, the ERS(3) event precedes the INO(3) event. Changes such as this could have profound effects upon the loading of the spine when the activity is considered in concert with the other event changes under the various experimental conditions.

Event Time Networks

A method was needed to describe the significant sequence of events that occurred under each velocity condition. Network representations of the events were chosen as a means to represent the interrelationships between the various internal force events. Such a representation would facilitate an appreciation for the order of events that occur under the various conditions. Once the significant differences between event times were determined through hypothesis testing (Figure 5), event networks were created to "map out" the sequence of events that occur under each velocity condition. These networks indicate the significant events that must precede or succeed other significant events under each condition.

In order to assist in interpretation of these networks, Figure 6 has been constructed to summarize the event sequences which are common to all velocity conditions. As shown in this figure, all signal initiation events (t_1) begin at about the same time under all velocity conditions, except for INO(1). This activity follows the onset of activity of the latissimus dorsi and erector spinae muscles. The peak activities of the signals also follow a given sequence. For example, the onset (t_1) of LAT, ERS, and IAP always precedes the onset of the ERS peak activity (t_2). Branches can be followed throughout the network to the "end," where the termination of LAT and RCA activity signals the end of IAP and the end of the exertion. These sequences occur under all conditions.

This figure, although derived from Figure 5, represents a simplification of the vast amount of data that was observed. However, a

means to concisely describe the differences between conditions was also required. Figure 7 has been constructed to represent the differences in event time activities throughout the networks. As this figure indicates, many changes in network structure occur throughout the velocity conditions. There are far too many changes to discuss each in detail. Of particular interest are the differences in network structure between isometric and isokinetic conditions. For example, under isometric conditions the LAT initiation (LAT(1)) precedes IAP initiation. However, under isokinetic conditions the LAT(1) activity precedes the RCA(1) activity, which does not happen under isometric condition. Numerous similar changes are shown in this figure.

When the source of variation is considered in Figure 7, it can be seen that most variations are due to a few velocity conditions or combinations of velocity conditions. For example, about 16% of the variations occur under the static condition. Approximately another 16% occur with both the 75 and 100% velocity condition networks. Since these conditions represent the extremes for velocity, this fact emphasizes the importance of considering the dynamic nature of a trunk exertion. About 11% of the variation occurs in only the dynamic conditions and about 11% of the variation occurs in the 50, 75, and 100% conditions. These findings also emphasize the importance of trunk motion.

DISCUSSION

This study has demonstrated how the sequence of trunk-loading events changes during controlled motion of the trunk. It should be pointed out that isokinetic testing is significantly different from true dynamic industrial lifting tasks since motion was controlled and only one link in the body was permitted to move. Since isokinetic motion control was employed in this study, angular trunk acceleration and thus moments-of-inertia effects are not theoretically possible. No system is truly isokinetic, hence, a small amount of acceleration does occur at the start and end of the exertion. However, these effects are minimized via the testing procedure. Hence, even though there are significant differences between this testing procedure and true dynamic lifting, this method permits us to begin to study the

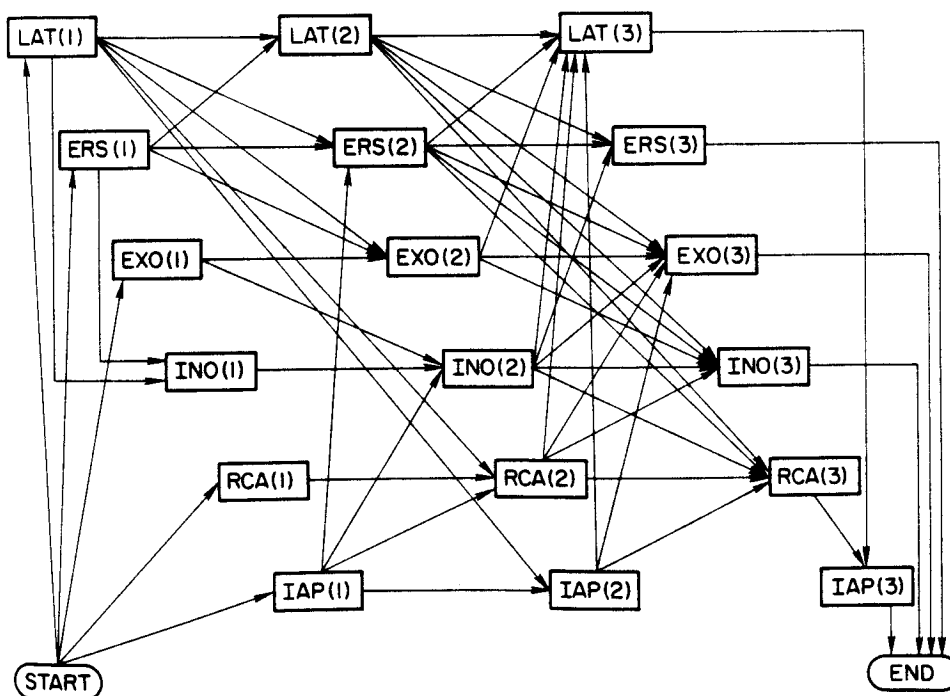


Fig 6. Network of event occurrence sequences which are common to all velocity conditions.

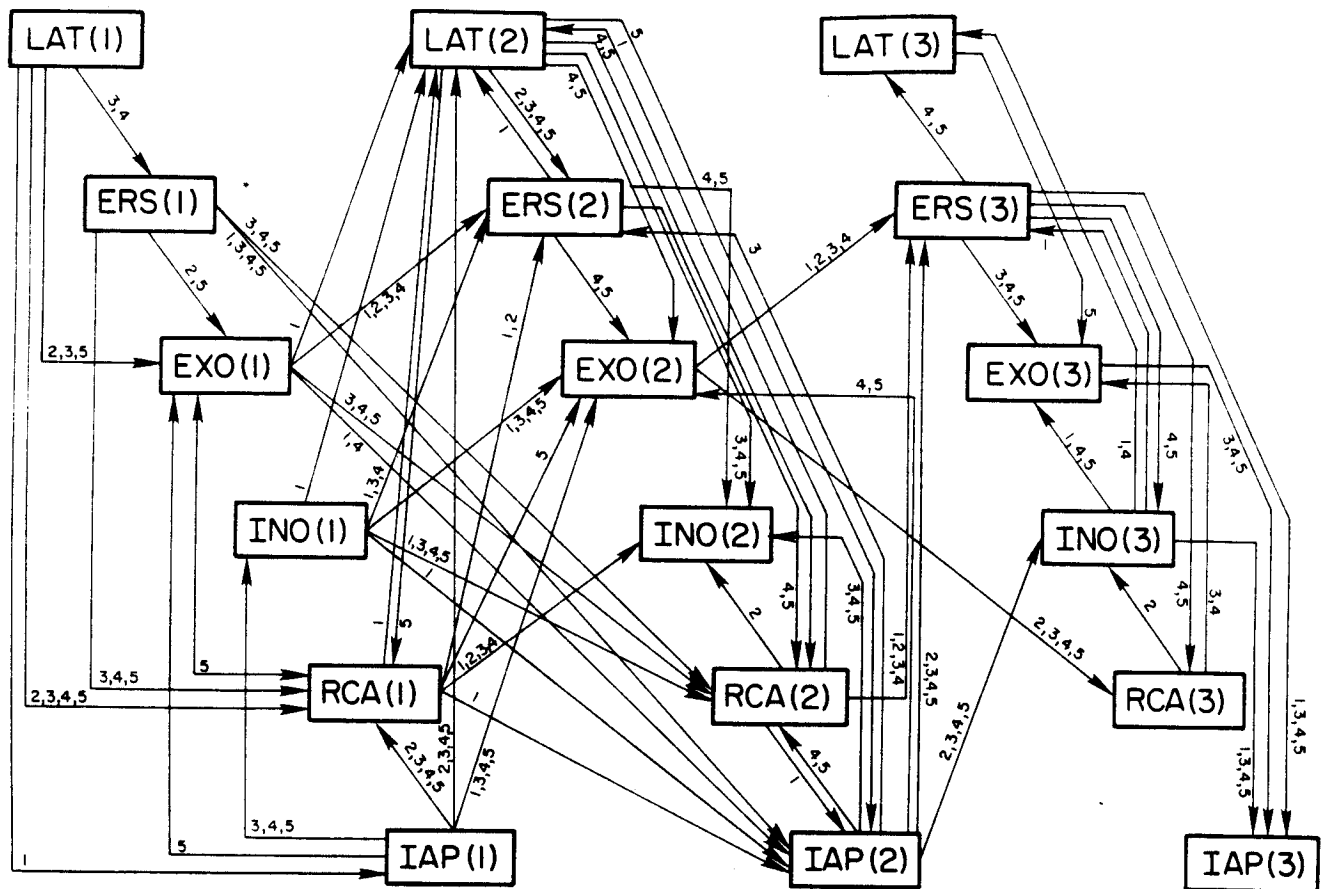


Fig 7. Differences in networks of event sequences between velocity conditions. (1 = isometric, 2 = 25% isokinetic, 3 = 50% isokinetic, 4 = 75% isokinetic, 5 = 100% isokinetic.)

effect of motion upon muscle recruitment patterns. Furthermore, since motion was controlled, this study permitted the quantitative evaluation of trunk muscle activity magnitude via EMG. These results are reported in a companion paper¹² that describes computed spine forces due to isokinetic motion.

The event occurrence times and event time networks have shown, in detail, the changes that occur in the times of occurrence of key events during static and various velocity conditions. For example, Figure 3 has shown that under the 50% velocity condition the peak RCA, EXO, and ERS signals occur almost simultaneously. This situation could have a profound influence on the loading of the spine and could represent a greater risk of a back disorder than other conditions. These issues are addressed in the companion paper.¹² The significance of these changes to spine loading can be appreciated by noting the network links that change or remain the same as a function of velocity conditions. Of particular interest are the sequences of events which precede other events. The events common to all velocity conditions will be discussed first.

This study has shown that there is a significant amount of interaction between events within the trunk. It appears that under all conditions all signals, except INO, start at about the same time. INO is activated following the onset of the LAT and ERS signals. The interaction appears to become more complicated as events further into the exertion are considered. When peak event times are considered, IAP(1) precedes the peak activity of all signals except LAT and EXO. LAT(1) and ERS(1) also precede each other's peak activities as well as other peak behaviors. Neither of these muscles, however, precedes INO. When the signal termination is considered,

many more interactions occur. For example, all peak signals precede LAT and EXO termination, whereas RCA(3) is preceded by all signal peaks except EXO(2). Even fewer signals occur prior to INO and ERS termination. Finally, RCA and LAT terminations precede the termination of IAP.

Patterns between velocity conditions are even more difficult to comprehend. It appears that the LAT onset occurs first and precedes other changes among the networks depending upon velocity. However, links which represent most of the differences between velocity conditions involve relations with peak IAP. Of particular interest is the fact that under the static condition ERS, EXO, INO, and RCA onset signals the peak of the IAP signal, whereas under dynamic conditions other sequences occur. It is also interesting to note that under the static condition, RCA(2) precedes IAP(2), whereas under many dynamic conditions the peak IAP signal precedes many other peak signals. These differences indicate that IAP signal pattern can change dramatically as velocity components change in an exertion. These differences between static and dynamic IAP may explain the inconsistencies in the IAP literature.

Another event which changes dramatically over velocity conditions is the peak RCA signal. Most changes in this signal suggest that the loading due to this muscle varies according to the braking function of the muscle. Other differences in the onset of this signal occur as a function of velocity and static conditions. For example, LAT(1) precedes ERS(1) and RCA(1) under the dynamic conditions, but not under the static condition. Instead, LAT(1) precedes IAP(1).

Many of the changes that involve differences at the higher veloc-

ity conditions may represent a reaction to acceleration. Even though, the study described involved isokinetic conditions, it is possible that, under extremely high velocity conditions, part of the initial and final motions involved accelerations and decelerations, respectively. These effects may be represented in the network of the greater velocity conditions.

This study has shown that the times of key events related to trunk loading change when static conditions are compared with dynamic conditions. Furthermore, substantial changes were also observed when dynamic conditions were compared with each other. This study has established two important findings. First, it has identified the sequence of events that occurs regardless of trunk velocity. Second, it has identified the changes that characterize the different velocity capabilities of the trunk. As previously mentioned, many of these changes involve the signal patterns of IAP and RCA, as well as numerous changes depicted in Figure 7.

It is obvious that many other significant events occur when velocity is included in the experimental conditions. There are far too many differences to point out. Most are obvious through examination of the networks. Figures 6 and 7 may serve as a guide to map out these differences. These figures also emphasize the importance of antagonistic muscle activity during force exertions. Previous studies did not report such activity, presumably due to the steady-state, static testing conditions.

It is obvious also from the plethora of data that dynamic conditions cannot be represented as simply quasi-static conditions, as suggested by many authors. Even when just the static and 25% velocity condition are compared, significant changes in event times occur. In fact, in many links of the networks a change in link direction occurs when the static condition is compared with any dynamic condition. These findings are also consistent with those of Marras et al.⁹ These facts indicate a change in muscle and/or IAP utilization as a function of motion, and this change must be considered when assessing spine loading.

It should also be noted that Figures 2 through 4 indicate substantial variation among the subjects in the event time occurrences. This study has described the significant group behavior of the subjects so that we may begin to understand the effects of trunk motion. Differences in sequence patterns between individual subjects is a topic of ongoing investigation. These results will be reported at a later time.

The time series networks which have been developed in this effort should serve several purposes. First, these networks should serve as a basis for the development of new biomechanical models that describe the three-dimensional motion and loading of the trunk during dynamic activities. Such a model is reported by Reilly and Marras.¹² These models can enhance the understanding of the manner in which the spine is loaded during the performance of dynamic tasks.

Second, these networks can be used in conjunction with models to serve as a basis for workplace design guidelines. The true muscular involvement and the resultant spine forces can be optimized so that the workplace can be arranged to minimize lumbar spine forces.

Finally, the networks which have been developed can be used as a basis of comparison for those who have suffered low-back disorders. If the pattern of muscle recruitment and activation is understood, then low-back-disorder patients' recruitment and activation patterns can be compared with those of normal subjects. In this way, a gauge of rehabilitation can be established. Furthermore, this same information can be used to determine when potential workers or patients are able to perform a task.

To appreciate the effects of these event time changes upon the loading of the spine, these event times and their associated magnitudes must be evaluated for their potential to load the spine. In order to understand the effects of such loadings as a function of velocity, these events were used as input into a simulation model that observed computed spine loading characteristics as the function of time. The results and implications of such a model are reported in a companion paper to this effort.¹²

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