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Measurements of Loads on the Lumbar Spine Under Isometric and Isokinetic Conditions

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Ten male and ten female subjects were tested for their ability to exert maximal force about the lumbo-sacral junction (as is done during lifting) under controlled isometric and isokinetic conditions. The myoelectric activity of ten trunk muscles, intra-abdominal pressure, and torque produced by the back were monitored. There are prominent differences in the manner in which subjects utilize the musculature of the trunk for the production of torque statically and dynamically. A significant lag was identified between the onset of intra-abdominal pressure and torque, and this lag increased with increasing trunk velocity. These differences between isometric and isokinetic exertions suggest that isokinetic trunk testing provides a means of controlled evaluation that is appropriate for manual materials handling situations. [Key words: isometric, isokenetic, lumbar spine]

AN IMPORTANT ASPECT in the understanding of low back pain (LBP) is the biomechanical analysis of loads upon the lumbar spine. Proper evaluation of loads upon the spine is important for several reasons. First, it is believed that the sensation of pain in the low back may be related to mechanical loading factors. At least it has been observed that the pain sensation of those already suffering from LBP increases with increased loads upon the lumbar spine. Second, an accurate biomechanical analysis is necessary for ergonomic purposes. If one is to evaluate workplaces and manual material handling (MMH) operations, the physical attributes of the worker and job demands must be considered. Finally, a thorough understanding of the biomechanical loads upon the spine is essential for employee selection and screening as well as for clinical, low back, morphologic assessment.

Most *in vivo* biomechanical analyses of loads upon the spine have been concerned with static (isometric) exertion conditions. However, most MMH tasks and conditions that may contribute to LBP are dynamic in nature, and the effects of the movement upon loads on the lumbar spine is unknown. Therefore, the objective of this study was to investigate the effects of controlled movement upon parameters that are indicators of loads on the lumbar spine.

MEASUREMENTS OF LOADS UPON THE SPINE

No direct means exist that measure loads upon the lumbar spine *in vivo.* Only indirect measurements or parameters are available that are believed to be related to the loads upon the spine. These indirect parameters include disc pressure, electromyographic activity of the trunk musculature, and intra-abdominal pressure. The state of knowledge of how these parameters relate to MMH tasks will be reviewed.

Intra-discal pressure measurements are considered a semi-direct method of evaluating spinal loads *in vivo.* Nachemson and Morris (1964) first measured such pressure by insertion of a fluid filled membrane-covered needle connected to a transducer into the lumbar disc. Subsequent investigations[10] refined measurement techniques using a transducer needle to monitor intra-discal pressure. Recent MMH related findings[3] have demonstrated that a linear relationship exists between the trunk moment and observed pressure in static trunk positions. Intra-discal pressure has also been correlated with myoelectric activities of back muscles and intra-abdominal pressure[1,2,4] during uncontrolled "back-lift" and "leg-lift" activities.

The disadvantage of intra-discal pressure measurement is that this is an invasive procedure and has the potential for injury to the subject, especially under movement conditions. This type of invasive measurement also has been observed[16] to inhibit subject performance. This inhibition most likely would be magnified under maximum exertion. Furthermore, disc pressure is only a partial indicator of spinal load. It does not reflect the load borne by the articular facets.

Electromyographic investigations of trunk muscle activity during lifting have been extensive. The myoelectric activity of the trunk muscles has been associated with the trunk moment, load lifted, body posture, and distance of the object from the lumbar spine.[1,2,5] Many of these studies have also revealed that the myographic activities of the back muscles under leg-lift and back-lift conditions were fairly similar or slightly greater under the latter condition. However, in all of these investigations, trunk movement was not controlled quantitively and consistently.

The final indirect measurement of loads upon the lumbar spine is that of intra-abdominal pressure (IAP), which it is believed to assist in the load relieving capability of the trunk. The early work of Davis[7] indicated that IAP increased when trunk moment increased. Later Andersson, Ortengen, and Nachemson[2] revealed a linear relationship between IAP and the trunk load and angle. Other studies[9] have investigated IAP activity during dynamic lifting. However, the trunk movement in these studies was not well documented or controlled.

All three parameters have been investigated synergistically by Ortengren et al[13,14] and Schultz and Andersson et al[16] who found significant correlations between disc pressure, electromyographic activity of back muscles, and IAP during spine loading and lifting activities. However, the correlation between disc pressure and IAP was rather weak.

The deficiency in all of these studies is the fact that the well-controlled experiments involved only static or isometric exertions. There have been no controlled experiments that have included dynamic effects or their relationship to static exertion upon these

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parameters. Therefore, inferring MMH ergonomic principles based solely upon static data may be misleading.

It is clear that an investigation regarding the biomechanical aspects of lifting should focus upon the L5-S1 junction (which has been identified as the weak link in the back), and the supporting mechanisms. Relevant to a study of the L5-S1 junction in relation to MMH are the factors of movement, trunk angle, maximum muscular exertion, age, and sex. These factors were included in the design of the present experiment. Hence, the objective of this study was to investigate the ability of male and female subjects to produce torque about the lumbar spine during a dynamic lift under controlled velocity conditions.

The biomechanical parameters that were monitored were EMG trunk muscle activity and IAP. Because of the risks involved, disc pressure was not measured.

MATERIALS AND METHODS

In order to maintain experimental control in a system as complicated as the human body, several assumptions were made. First, the load upon the spine was measured directly at the back rather than using the arms for lifting a weight. This situation was assumed to create loads upon the trunk that would be analogous to a lifting situation. Next, all internal mechanisms in the trunk were assumed to be in dynamic equilibrium at any instantaneous point of a lift. The final assumption is that a wholistic or multivariate investigation of muscle response can establish its relationship to the torques generated at the base of the spinal column.

The muscle selection criterion of Schultz and Andersson[15] was employed in this study to identify trunk muscles that would contribute to loads upon the lumbar spine. This criterion assumes that if a transverse plane was passed through the trunk, all muscles that keep the trunk in equilibrium (and thus support the load) should be identified. They are the latissimus dorsi muscles on the right (LATR) and left (LATL) sides, the erector spinae muscles on the right (ERSR) and left (ERSL), the internal oblique muscles on the right (INOR) and left (INOL), the external oblique on the right (EXOR) and left (EXOL), and the rectus abdominis muscles on the right (RCAR) and left (RCAL). Intra-abdominal pressure (IAP) also is assumed to act along such a transverse plane.

Subjects. Ten male and ten female volunteers were studied in this experiment. Ages of subjects ranged from 18 to 26 years. All subjects were considered normal in that they had never experienced back pain and were considered to be in good physical condition. These conditions were verified via interview and physical examination prior to participation in the experiment.

An attempt was made to control anthropometric variability by testing subjects within one standard deviation of mean height and weight dimensions (as defined by NASA, 1978).[12]

Experimental Design. Twelve dependent variables were chosen for this experiment. They are the "load supporting" internal mechanisms of the trunk that would be identifiable if one were to pass an imaginary transverse plane through the L5 level of the trunk (as suggested by Schultz and Andersson, 1981) plus the torque that was produced about L5. The integrated electromyographic* (I EMG) signal was used as a dependent measure that indicated the force-producing capability of each of the 10 trunk muscles. IAP was measured in terms of the millimeters of mercury generated within the abdominal cavity. The final dependent variable is the torque produced about the L5-S1 junction. This variable is measured with the dynamometer axis aligned with the L5-S1 junction. Hence, torque data are directly related to moments developed about L5-S1.

The independent variables are operationally defined as the physically controllable factors that can influence lifting performance. These variables have been identified as the velocity of the lifting activity and the angle of the trunk during the lifting activity. A blocking variable of sex was also included in the study.

There is presently no method of controlling the motion of an unrestricted lift. However, with the advent of isokinetic dynamometers, the velocity of motion could be controlled with the assumption that there is no appreciable acceleration present after the initial motion begins. Hence, isokinetic motion of the trunk was used as one of the independent variables in this study. This type of motion was particularly well suited for this study since isometric and isokinetic muscle electromyographic activity has been related to muscle force.

The velocity of lift was established uniformly for all subjects since a comparison was to be made over a large range of velocities. In order to define these levels for each subject, a pretest session was necessary. Each subject was asked to exert maximal force at a maximum velocity upon the dynamometer. The allowable dynamometer velocity was gradually increased for each trial in the pretest session until no appreciable torque could be applied to the dynamometer. That limiting level was reduced by 25% and the new velocity condition was operationally defined as the 100% or maximum voluntary velocity condition. Three other velocity levels were established, based upon this maximum level. These levels were defined as 66%, 33%, and 0% (isometric exertion) of the 100% velocity level (V0, V33, V66, V100).

The trunk angle factor in the experimental task was divided into an acceleration phase and a constant velocity phase. The latter was divided into three levels. The range of this factor was specified quantitatively in the experiment as being representative of the range of motion of the trunk during lifting, with the pelvis fixed. These angles defined in relation to the trunk are represented in Figure 1. Pretests showed that the greatest comfortable forward angle of the back from an upright standing position with the pelvis fixed was 67.5°. If a subject was to attempt a lift with the back, the trunk angle would start at 67.5° and end in an erect 0° (upright) position. It was desirable to keep the angle levels equally spaced. Therefore, the angle levels were defined at 22.5° increments (A0, A22.5, A45).

Pretests showed that much of the motion during the first 22.5° of the lift was acceleration. This violated the assumption of isokinetic motion, therefore, the 67.5° angle condition was excluded from the analysis of experimental data.

The experimental task required subjects to produce maximal voluntary force using the back to lift the arm of an isokinetic dynamometer, with the exertion starting from a 67.5° forward trunk angle, as shown in Figure 1. This task was analogous to a back-lifting effort with the pelvis fixed.

The combination of independent variables in the experimental design is shown in Table 1. The velocity and angle variables were completely crossed while the sex variable was blocked under these conditions. Thus, every subject was tested under each of the angles by velocity conditions. The experimental conditions were presented to the subjects in a controlled but randomized order. Many of the methods used to record the dependent variables are invasive and, therefore, uncomfortable. Consequently, only one observation per subject was recorded under each experimental condition.

Apparatus. The configuration of the experimental equipment used in this study is shown in Figure 2. The ten electromyographic signals, intra-abdominal pressure, torque, trunk angle, and Schmitt trigger were all recorded simultaneously on a 14-channel FM analog tape recorder. The FM modulator cards were aligned prior to each experimental session. Exertions were also videotaped.

Subjects were placed on a platform constructed from one-inch pipe to control the positions of the feet, legs, and pelvis and to limit the motion of the spine but not of the pelvis. The isokinetic

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*The RMS rectified value was used to represent I EMG.

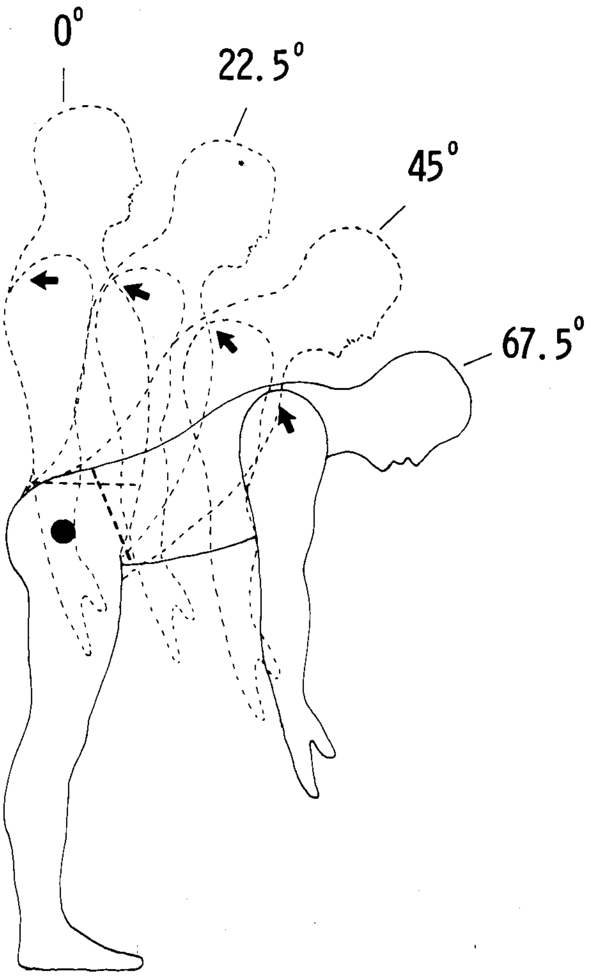

Fig 1. Definition of trunk flexion angles.

dynamometer was mounted on the reference frame so that it was aligned with the lumbo-sacral junction. The platform contained an adjustable floor that could accommodate a large anthropometric range of subjects. Ten electromyographic amplifiers were designed and fabricated for this experiment. These amplifiers were mounted in a single case that was alongside the test platform. These were differential amplifiers with a variable gain from 0 to 10,000. The output was filtered by second-order, active band pass filters with both low and high pass provisions. The filters and the differential amplification eliminated most of the noise. The latter feature was also desirable since it recorded only the difference in potential between electrodes, thus minimizing the possibility of crosstalk.

Table 1. Experimental Design

Velocity (% of max)	*Angle (°)*	*Men*	*Women*
0%	0° 22.5° 45°	S 1	S 2
		S 2	S 2
33.3%	0° 22.5° 45°	S 3	S 3
		S 4	S 4
66.6%	0° 22.5° 45°	S 5	S 5
		S 6	S 6
100%	0° 22.5° 45°	S 7	S 7
		S 8	S 8
		S 9	S 9
		S 10	S 10

Initial experiments revealed a noise problem when using intramuscular fine-wire electrodes. The fine-wire length from the muscle insertion site to the amplifier served as an antenna and picked up transient signals. The only way to eliminate this problem was to reduce significantly the length of fine wire used. This was accomplished by placing an EMG preamplifier at the muscle insertion site. Miniature EMG preamplifiers designed and fabricated in the EMG laboratory of McMaster University (Ontario, Canada) were used. These preamplifiers were small, lightweight, and attached to a Velcro belt so that they could be placed in close proximity to the muscle insertion site. They were differential in type, had a gain of 1000, and were sensitive to signals between 10 Hz and at least 7 kHz. These units also were equipped with a 220-k input resistor to protect the subject from shock. Guillotine-type connectors served as fine-wire terminal posts. The preamplifiers were interfaced with the main EMG amplifiers via small diameter shielded cables to eliminate the possibility of further noise pickup by the cable.

Quantification of EMG signals was done by comparison of a signal from a particular muscle site under one condition with the signal from the same muscle site under another experimental condition. If an electrode became dislodged from a muscle, exact comparison would not be possible. A means of monitoring the EMG signal from specific muscles therefore, was, needed during the course of the experiment. If an electrode became dislodged during the procedure, the electrode was replaced, and the experiment was repeated in its entirety. The EMG signal from each muscle was monitored visually on a dual beam oscilloscope before and after each exertion. To facilitate quick EMG signal verification, a switchbox was constructed to allow the experimenter to monitor visually any two EMG signals on the oscilloscope without interfering with the recording of the signal on analog tape.

Intra-abdominal pressure was measured with a Millar PC-380 catheter pressure transducer. This is an electromagnetic probe that is mounted at the end of a 0.8 mm-diameter catheter. The transducer signal was amplified, calibrated, and controlled by a Millar TCB-100 control unit. This signal was also recorded on the tape recorder.

A Cybex II isokinetic dynamometer was used to measure torque. A dynamometer control unit was fabricated to provide linear dynamometer output and a means of "zeroing" the transducer prior to each exertion. The control unit supplied by the manufacturer was not used.

Trunk angle was measured by two methods. First, a precision potentiometer was attached to the axis of rotation of the dynamometer arm. Next, this angle was verified with a series of Schmitt triggers at 22.5° intervals.

Electrode Selection. Several pilot tests were performed to determine whether surface or intramuscular electrodes should be used in the experiment. Surface electrodes have the advantage of being easy to use, noninvasive, and painless compared with intramuscular electrodes. However, surface electrodes have two major disadvantages. First, the electrode disc does not have a fixed orientation with respect to a muscle under movement conditions because skin and muscle are not moving in an identical manner. Second, these electrodes are not muscle specific, as they simply record the sum of all electrical activity under the electrode disc.

An experiment was conducted to compare the characteristics of surface and intramuscular electrodes of human muscle under isometric and dynamic (isokinetic) conditions. Silver-silver chloride surface electrodes were taped to a human latissimus dorsi muscle. Electrolyte gel was placed between the electrode discs and the skin to increase conductivity. A fine-wire intramuscular electrode also was implanted into the same muscle. The method of Basmajian[6] was used to prepare and insert the electrode.

The pilot subject was asked to perform maximal back extension exertions under both isometric and isokinetic conditions. EMG recordings of the muscles were monitored visually on a dual beam oscilloscope and recorded on a strip chart. The electrodes provided

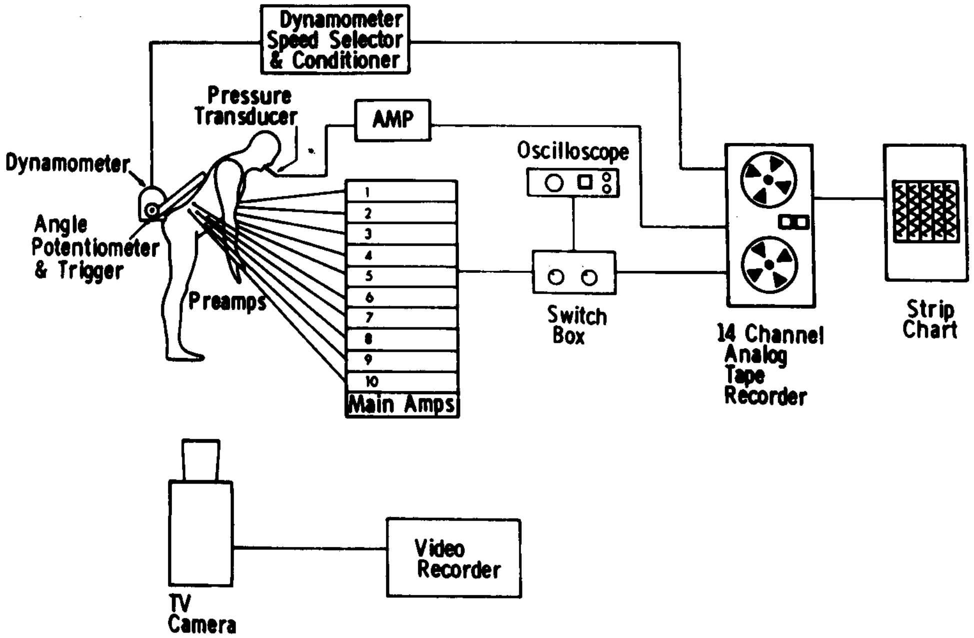

Fig 2. Schematic of experimental equipment used.

similar signals under isometric exertion conditions. However, under isokinetic conditions, there was a significant difference between these recording techniques. The surface electrode recordings "cut out" periodically as the disc orientation with the muscle changed. The signal amplitude and waveform of the surface electrode varied much more than those of the intramuscular electrode indicating a change in orientation between the electrode and the muscle. The intramuscular electrode on the other hand, produced a more stable, cleaner, and more reliable signal under a variety of conditions. Hence, intramuscular fine wire electrodes were used during the actual experiment.

Procedure. In the laboratory, the subjects were shown the use of the equipment and given instructions regarding test procedures. Just prior to a test session, the subjects were re-examined by the project physician to ensure that no significant changes in their physical condition had occurred.

The insertion of the electrode into the desired muscle was controlled by attaching fine-wire electrodes to an EMG recording unit with both visual and auditory signal amplification. As the electrode was inserted into the muscle, the physician listened for a "popping" sound that was present as the electrode punctured the muscle sheath. This event also was visible as spikes of motor unit action potentials in the visual signal trace.

The intra-abdominal pressure (IAP) transducer then was inserted by the physician. In order to minimize discomfort, a local anesthetic was made available to the subject. The catheter was fed into the nasal passage, down the throat, and into the abdominal cavity. The catheter was taped into position on the face and neck. This signal was immediately monitored to ensure proper placement. The subject was allowed approximately 10 to 15 minutes of rest to adjust to the catheter.

When the subject indicated that he had sufficiently adapted to the catheter, the practice session began. The purpose of this session was to allow the subject to become familiar with the apparatus so as to minimize variability due to learning effects. During exertions, subjects were asked to fold their arms in front of them to control arm position. They were allowed to practice both static (isometric) and dynamic (isokinetic) exertions. When their exertions demonstrated a consistency of performance, the practice session was terminated.

After a short rest period, a threshold pretest session was initiated. The purpose of this session was to determine a maximum (threshold) velocity capability. Each subject was asked to lift with the back with maximal exertion in terms of force and velocity as he/she passed through the experimental angles. The dynamometer velocity level was increased during each exertion until the subject could no longer exert appreciable torque while moving at a given velocity. The velocity threshold was defined as the velocity at which a subject could exert some torque but no more than 6.8 N.m (5 ft-lb) of torque during the maximum torque-producing portion of the exertion.

After another rest period, the actual experiment began. Subjects were tested once under each experimental condition (assuming no electrodes were dislodged) and were allowed at least two minutes of rest between exertions. Figure 3 shows a fully instrumented subject performing a test on the Cybex dynamometer.

Data Transformation. All EMG data were represented in terms of the electrical activity of the muscle in millivolts. EMG data from a muscle of a given subject could only be compared with the data from the same muscle under another exertion condition by the same subject. The activity of this muscle could not be compared with the activity of the other muscles of the same subject or the activity of the same muscle of other subjects[6] because of the site-specific nature of EMG recordings. Data was, therefore, normalized via a computer program that searched through the dependent variable data file of each subject and identified the maximum value of each dependent variable. All values of these variables were then divided by their respective maxima. Therefore, all data were transformed into a percentage of the maximum value attained by each dependent variable.

RESULTS

Analysis Overview

Results and data analysis will be reported in both the "Results" and "Discussion" sections. Since this study involved a series of extensive statistical analyses, significant results are presented in a series of summary tables. The text of the "Results" section is limited to an explanation of statistically significant results that can be extracted from each analysis rather than a discussion of statis-

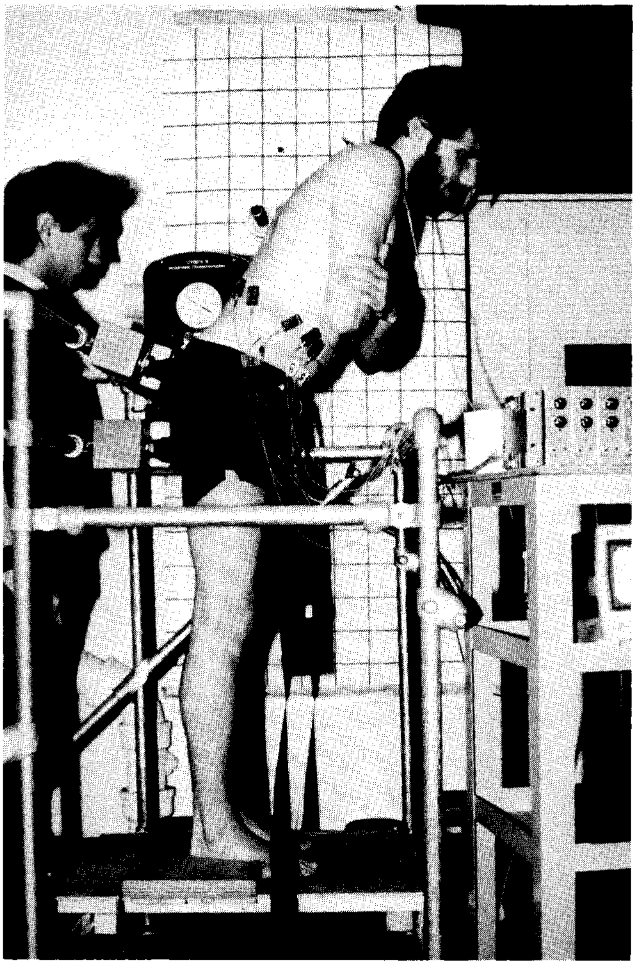

Fig 3. Photograph of a subject undergoing a test.

tical methodology.* A complete, quantitative analysis was performed by Marras.[8] The "Discussion" section is reserved for synergistic interpretation of experimental results.

The results of this experiment were subjected to several levels of statistical analysis. The sequence and relationship of the components of the analysis are depicted in the flow diagram shown in Figure 4. Level I of this analysis sequence consisted of general observations of the data. In advanced analysis, fundamental relationships, characteristics or problems within the data are often overlooked since statistical comparisons are based upon certain assumptions. Therefore, the objective of Level I analysis was to consider these factors. General observations consisted of examination of velocity factor thresholds, raw data, temporal delays between signals, and the torque-velocity relationship. Also, assumptions regarding data distribution and their impact upon subsequent statistical tests were considered.

After transformation, the data were subjected to Level II statistics. Here, multivariate analysis of variance (MANOVA) was employed to determine how the independent variables affected the results that were composed of a set of 12 dependent variables.

This analysis was followed by two Level III statistical techniques that performed collective as well as individual data interpretation of significant MANOVA findings from the previous level. Two

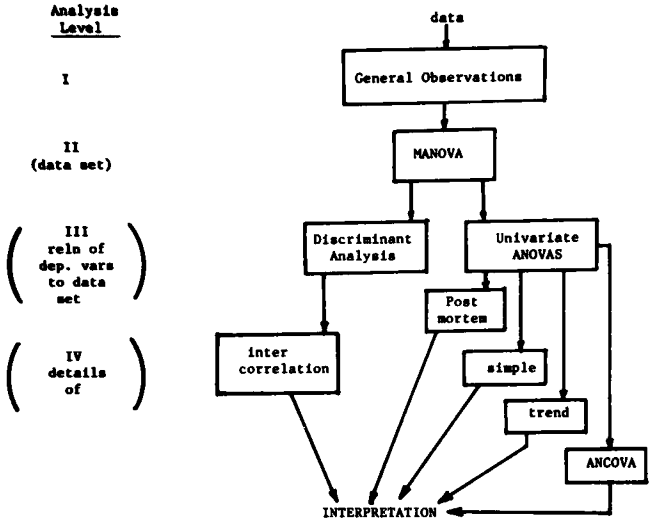

Fig 4. Flow diagram of levels of statistical analysis.

interpretive methods were employed. They were discriminant analysis and univariate analysis of variance (ANOVA). The basic difference between these methods is the manner in which interrelationships between the dependent variables were considered. In discriminant analysis, the intercorrelations between dependent variables were respected and response variables that were not sensitive to changes in experimental conditions were identified. ANOVA, on the other hand, considered each dependent variable as if it were the only dependent variable being measured. Here, it was possible to examine how each dependent variable responded to the experimental conditions (independent of the other dependent variables).

Variables that were found significant in the Level III analyses were subject to further analyses via Level IV statistics. The objectives of these methods were to determine which levels of the independent variables were responsible for dependent variables significance in Level III and also to describe the response characteristics of these dependent variables. Level IV methods consisted of a postmortem analysis (identifying significant velocity (V) and angle (A) levels), simple effects (identifying interaction effect of V and A), regression analysis (describing response components of dependent variables), and analysis of covariance (compensating for effects of body fat).

General Observations

Velocity thresholds are summarized in Table 2. The average velocity thresholds for all subjects was 35.9 revolutions/minute (rpm) with a standard deviation of 3.99 rpm. All thresholds were observed to fall within a 14-rpm range. When thresholds were considered as a function of subject gender, the male group exhibited greater velocity thresholds than did the female group. However, within each group, the relative variation was approximately equal.

Table 2. Velocity Threshold Statistics (in rpm)

Sex	*Mean*	*SD*	*t test*
Both	35.9	3.99	
Male	38.4	3.37	9.302*
Female	33.4	2.91	

*Indicates significance ($P < 0.001$).

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*All observed differences described in this paper were found to be statistically significant.

Table 3. Significance Summary (p 0.01) of Raw IAP (mm Hg) and Torque (ft. lb) as a Function of Velocity and Angle

Independent variable	*Dependent variable*	*F statistic*
Velocity (V)		
	IAP	2.86
	torque	115.64*
V X sex		
	IAP	0.32
	torque	6.87*
Angle (A)		
	IAP	37.79*
	torque	69.36*
A X sex		
	IAP	10.39*
	torque	10.41*
V X A		
	IAP	1.70
	torque	3.85*
V X A X sex		
	IAP	1.55
	torque	4.41*

*Indicates significance at $P < 0.01$.

Table 4. IAP—Torque Onset Delay (ms) Summary Statistics

	Condition			
	V0	*V33*	*V66*	*V100*
Mean	29.5	132.4	212.5	284.0
SD	36.2	33.5	114.8	87.3

Correlation of delay with velocity: $r = 0.799$.
Significance of difference: $F = 25.86$; ($P < 0.01$).

Raw (pretransformation) IAP and torque data were tested individually to determine whether these factors reacted differently in response to changes in velocity and/or angle conditions. The results of these tests are summarized in Table 3. These analyses indicate that changes in the velocity affected the amount of torque produced but did not influence the IAP. Changes in velocity also affected the torque-producing capability differently for men as opposed to women. Next, the amount of torque and IAP were seen to change with trunk angle. Differences in IAP and torque response to angle also were noted when male performance was compared with female performance. For example, IAP in men changed by a much greater amount between the A0 and A45 angles than it did for women. Finally, the unique combinations* of velocity and angle conditions were tested for their ability to influence the production of torque and IAP. It was found that these unique combinations influenced the ability to produce torque but not IAP. Furthermore, differences in the torque responses of men and women in reaction to these velocity and angle combination also were observed.

The relative time of onset of IAP and the onset of torque appeared to vary in direct proportion to the velocity of motion. Under very slow or isometric conditions, the onset of the IAP and torque was approximately simultaneous. However, as the velocity increased, IAP onset preceded the development of torque, and the magnitude of the delay of torque development increased as the velocity increased. Summary statistics regarding the nature of this relationship appear in Table 4. Substantial differences in delay were apparent between velocity conditions with the V100 condition demonstrating the greatest time difference and the V0 condition indicating the smallest time difference. This investigation also revealed a linear relationship between the IAP-torque onset delay and the actual velocity of the exertion.

Isometric-Isokinetic Torque Relationship

The ability of a subject to produce torque with the back under isometric and isokinetic conditions was a major concern of this study. Hence, it is reasonable to note some general observations regarding the relationship between isometric and isokinetic torque-producing capability. The nature of this relationship can best be described in terms of the graphic and contour representations of Figure 5. The contour plot represents the interactive nature of the angle and velocity factors. The numbers in this plot represent the percentile ranges of torque averaged for all subjects. These ranges have been divided into 25% increments. Thus, the plot should be interpreted as a topographical contour of the torque surface as a function of velocity and angle. Here, all torque values have been normalized in terms of the percentage of the maximum torque exerted by the subject. A rather clear relationship is evident here. Under all angle conditions, subjects were able to produce the greatest amount of torque with the back under isometric (V0) conditions. Of these isometric conditions, torque potential was substantially greater at angles of 22.5° and 45° than at 0°. As the

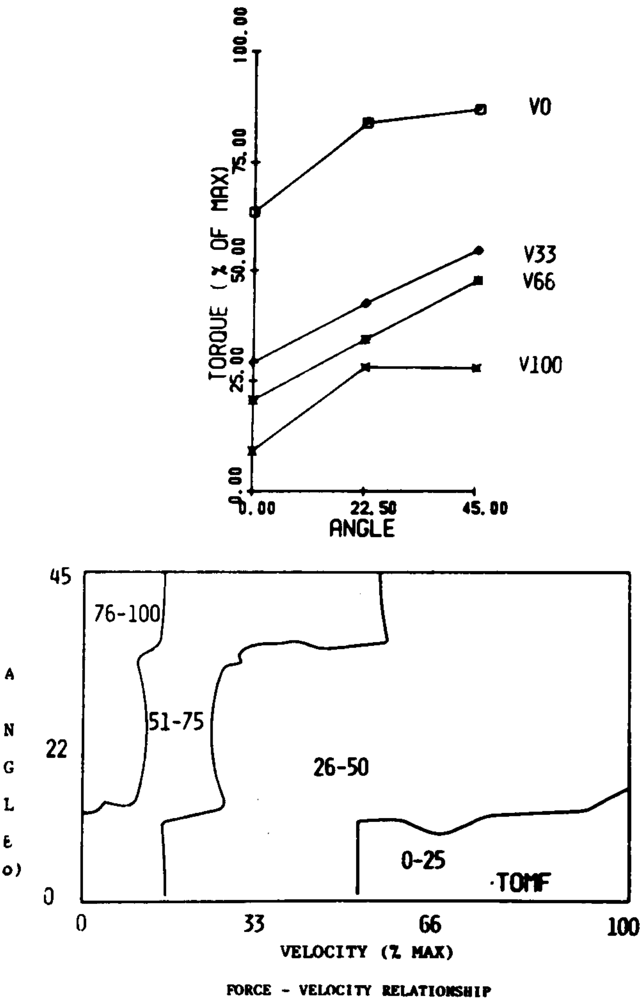

Fig 5. Torque as a function of velocity and angle.

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*Unique combinations are known as statistical interactions between independent variables.

velocity increased, torque-producing capability was reduced for all angle conditions. The largest reduction occurred between the V0 and V33 (changeover from isometric to isokinetic) velocity conditions, with the average reduction being 34%, 41%, and 31% under the A0, A22.5, and A45 angle conditions, respectively. The reduction in torque capability between the remaining velocity conditions was less dramatic. Reductions in torque from the V33 to the V66 conditions were 8–9% under all angle conditions, and reductions from the V66 to the V100 conditions were 12.5%, 5%, and 20% for the A0, A22.5, and A45 angle conditions, respectively.

Hence, an overall trend seems clear: the greater the flexion angle, the greater is the ability of the back to exert torque. Also, there is a significant decrease in torque generating capability between the isometric and isokinetic conditions, and this continues to decrease gradually as the velocity of the exertion increases.

Multivariate Effects

The purpose of this section is to investigate collectively and individually the activity of the 12 dependent variables in response to the various velocity and angle conditions. In order to facilitate quantitative comparisons, all dependent variables were transformed into a percentage of the maximum activity observed for each variable. Summary statistics for all independent variables after transformation appear in the Appendix. These statistics indicate that substantial activity was present in the internal oblique, external oblique, and rectus abdominis muscles under both isometric and isokinetic conditions. These findings are contrary to previous studies[16] that have employed surface electrodes.

Multivariate analysis techniques were applied to the data to determine whether the 12 dependent variables, as a set, responded differently to charges in velocity and/or angle. The results of this analysis are summarized in Table 5. These results indicate that the dependent variable set responded to changes in velocity, angle, and unique combinations of velocity and angle. The dependent variable set did not respond differently for men and women.

It has been established that the dependent variables, as a group, reacted differently to changes in experimental conditions. However, the individual characteristics of the variable set have not been established. This was the objective of the remaining statistical analyses.

In order to determine how each variable responded individually to changes in the experimental conditions, univariate analysis techniques were employed. The results are summarized in Table 6. Generally, these results indicate that the back muscles (latissimus dorsi and erector spinae), an abdominal muscle (RCAR), and torque are responsible for much of the multivariate significance of the velocity, angle, and unique combinations of velocity and angle factors. The other trunk muscles (internal and external oblique) also contributed to the multivariate velocity effect but not to the angle effect. Hence, this analysis helps to pinpoint which variables contribute individually to the multivariate effects that were found to be significant.

Table 5. Significance Summary of Multivariate Data Set

Independent variable	*Dependent variable*	*F statistic*
Velocity (V)	Data set	8.36*
V × sex	Data set	0.46
Angle (A)	Data set	7.84*
A × sex	Data set	1.03
V × A	Data set	2.21*
V × A × sex	Data set	1.19

*Indicates significant value; ($P < 0.01$).

The analysis also included discriminant function analysis techniques. They determine which combination of variables was most representative of the significant multivariate responses (Table 5) to velocity and/or angle found in earlier analyses. These analyses indicate that the significance of both the velocity and angle factors in the multivariate analysis can be characterized largely by the torque and IAP considered together. Most of the velocity condition discrimination predicted by the analysis was due to the difference between V0 (isometric) and the other velocity (isokinetic) conditions. No obvious discriminant differences were apparent for the angle effect discriminant analysis. The highest values of both IAP and torque were seen to occur in the V0 condition. This was the only condition for which the percentage of IAP employed was less than the percentage of torque.

Correlation coefficients were produced in the analysis to aid in interpretation of the linear relationship between variables. A summary of significant correlations between variables appears in Table 7. The correlation matrix revealed significant correlations between IAP and the latissimus dorsi muscles, torque and the latissimus dorsi muscles, torque and the erector spinae muscles, and IAP and torque. One would have expected a relationship between IAP and the abdominal musculature but this was not the case. Other anticipated significant correlations were found between the back muscles on the right and left, between the erector spinae and latissimus dorsi muscles, and between the right and left external oblique muscles.

The correlation between IAP and latissimus dorsi activity points to a possible source of IAP production, not previously reported in the literature. It is possible that the latissimus dorsi muscles, when active, tend to pull the upper torso down, thereby creating pressure within the abdomen. When this was considered in conjunction with the fact that there was a significant raw IAP effect in response to angle but not velocity, it is concluded that IAP can be a byproduct of trunk angle and may not possess any load relieving capabilities.

Table 6. Summary of Significant F Statistics for Univariate Analysis of Variance

Independent variable	*LATR*	*LATL*	*ERSR*	*ERSL*	*INOR*	*INOL*	*EXOR*	*EXOL*	*RCAR*	*RCAL*	*IAP*	*TORQ*
Velocity (V)	6.27	4.38	11.44	9.76		4.82		4.49	10.26		3.93	154.64
V × sex												
Angle (A)	25.30	13.89	3.70	7.41					6.13		62.59	66.88
A × sex											8.25	
VA	2.45	2.87	14.72	10.06			2.17		2.30			2.61
VA × sex												3.77

Table 7. Significant Dependent Variable Correlations (r)

	LATR	*LATL*	*ERSR*	*ERSL*	*EXOR*	*EXOL*	*IAP*	*TORQ*
LATR	1.000							
LATL	0.482	1.000						
ERSR	0.389	0.339	1.000					
ERSL	0.439	0.424	0.657	1.000				
EXOR					1.000			
EXOL					0.447	1.000		
IAP	0.374	0.423					1.000	
TORQ	0.291	0.345	0.366	0.350			0.389	1.000

The remaining analyses (Level IV) concern tests that were capable of determining which particular testing conditions were responsible for the significant effect of the velocity, angle, and unique combination of these factors on the individual variables. The results of these tests were considered synergistically in the interpretation of each dependent variable.

The activity of the latissimus dorsi muscles is shown in Figure 6 as a function of velocity under various angle conditions. There was a difference in response of these muscles between the isometric (V0) condition and the isokinetic conditions. Differences between the isokinetic conditions were not significant. This muscle group also responded differently for all combinations of angle conditions. Hence, it is clear that this muscle group exhibits greater myoelectric activity during isometric exertions than during isokinetic exertions. However, these muscles increase their activity as the back angle increases.

The erector spinae muscles exhibited a different response pattern that is shown in Figure 7. This muscle group acted differently during different velocity conditions, indicating that as velocity increased the activity of the muscle decreased. Unlike the latissimus dorsi, the response characteristic of this muscle was consistent with results found in the literature.[18] That is, power-producing and velocity-producing capability of muscle are mutually exclusive. The myoelectric activity of the erector spinae muscles was also unique in its reaction to angle conditions. The activity was different only between the upright (0°) and flexed positions but not between the flexed positions.

The remaining muscle groups (internal oblique, external oblique, and rectus abdominis) all exhibited substantial activity. However, the activity of these groups was only significantly dif-

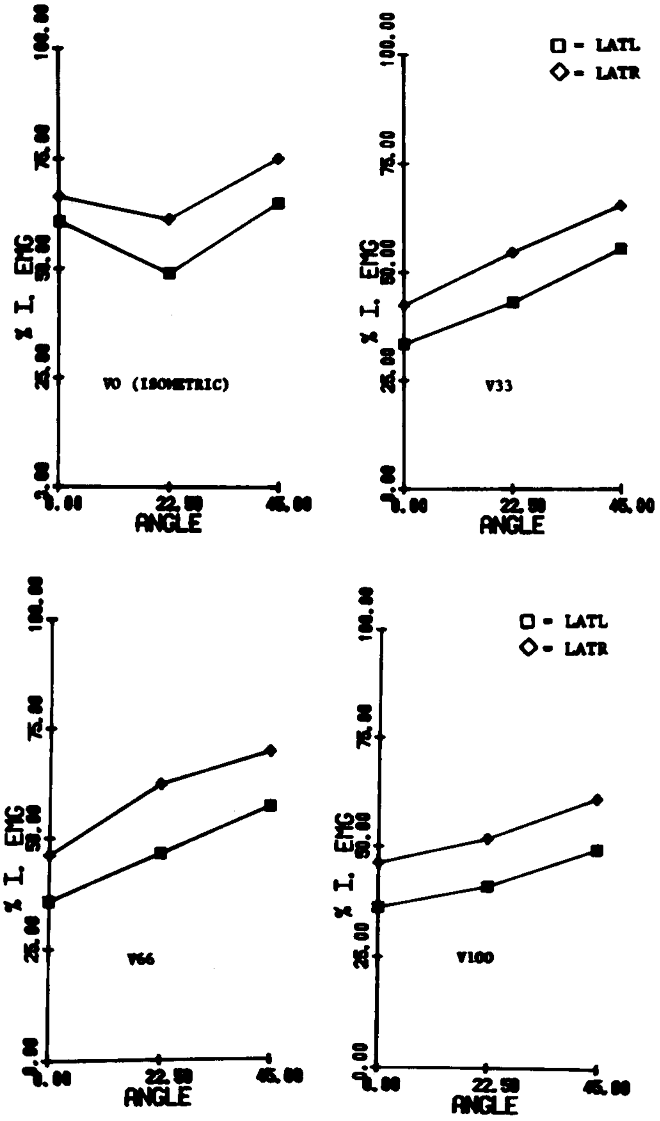

Fig 6. Activity of the latissimus dorsi as a function of velocity and angle.

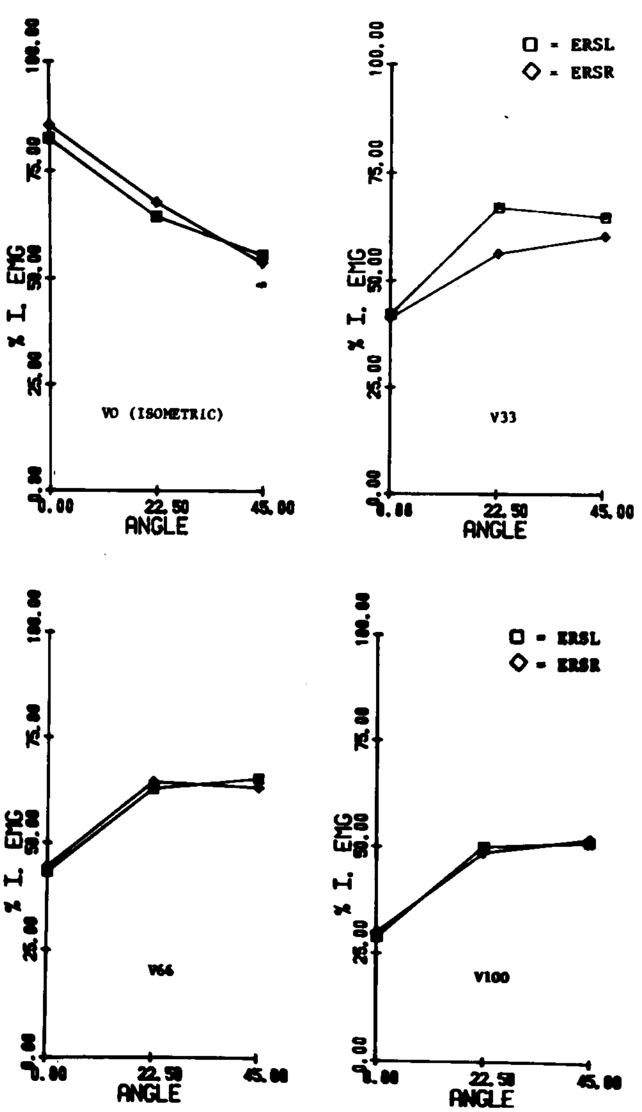

Fig 7. Activity of the erector spinae as a function of velocity and angle.

ferent under extreme differences in velocity conditions. For example, the EMG pattern of the rectus abdominis is shown in Figure 8. The significance of this variable was mainly attributable to differences between isometric and isokinetic conditions as the trunk passed through the 0° angle. Hence, it can be concluded that the function of this muscle was mainly in its braking action as the trunk approached the upright position.

The activity of IAP and torque as a function of angle and velocity conditions are shown in Figure 9. These two variables both exhibited different activity for all combinations of velocity and angle conditions indicating that their activity changed markedly in response to these effects. This fact also supports the discriminant analysis finding that these variables are most representative of the multivariate differences.

DISCUSSION

In this study, the contribution of the internal mechanisms were evaluated collectively and individually in response to the various experimental conditions. Since a variety of analysis techniques were employed, a discussion emphasizing the synergistic relevance of the analysis is warranted.

The velocity threshold analysis indicated that men exhibited significantly higher thresholds than women. The torque production capability of men was also greater than that of women. These findings, when considered in view of the work by Thorstensson et al,[17] indicate that there may be physiologic differences in muscle composition between sex groups. Thorstensson found high positive correlations between maximum speeds of contraction, peak torque capability, and the percentage as well as relative area of fast twitch muscle fibers in knee extension tasks. If this same relationship holds true for the back musculature, it would be possible to evaluate lifting capacity simply as a function of torque and velocity of motion. Thus invasive EMG techniques, IAP techniques, and muscle biopsy analyses would be unnecessary for employee screening.

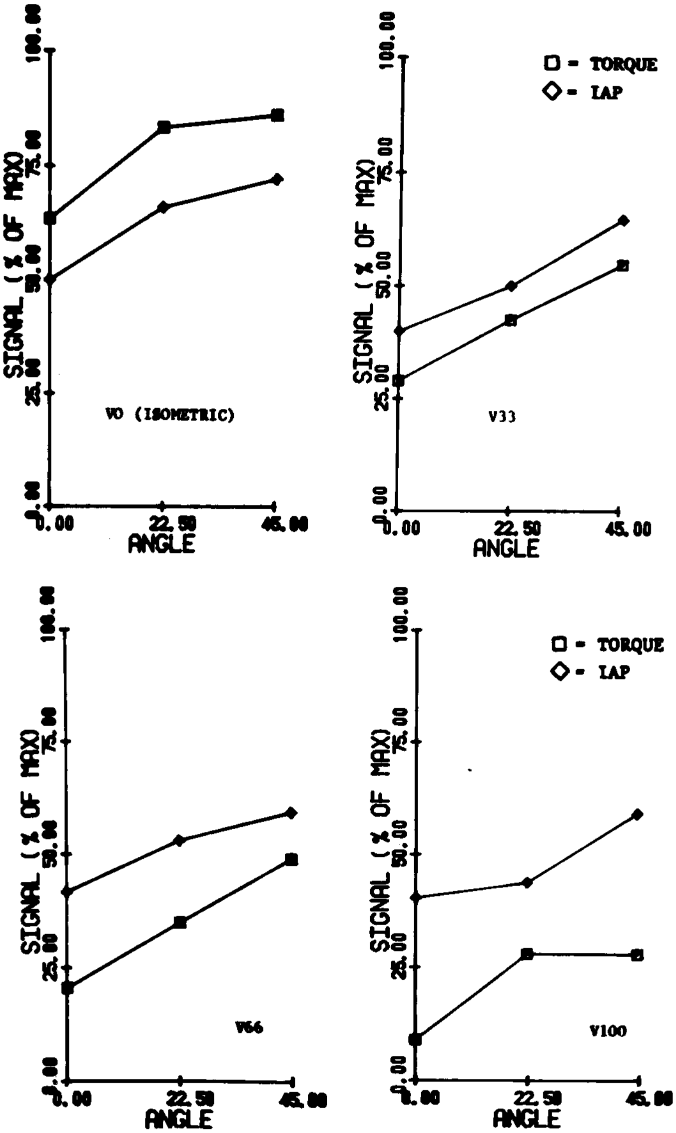

Fig 9. Intra-abdominal pressure and torque as a function of velocity and angle.

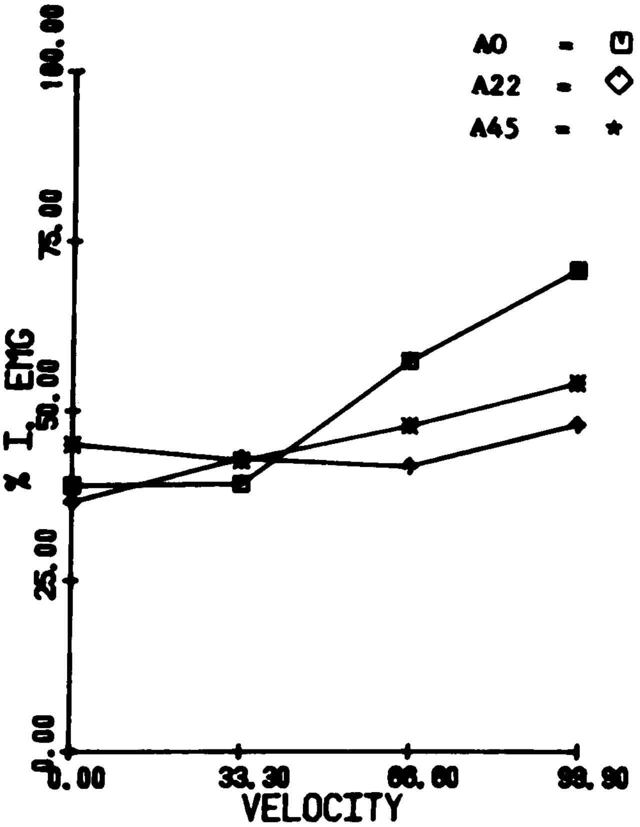

Fig 8. Activity of the rectus abdominis right as a function of velocity and angle.

Analysis of the raw IAP data revealed substantial pressures within the abdomen. However, the pressures were only significant for the angle factor and not for the velocity factor. Initial conclusions would lead one to believe that IAP is simply a byproduct of angle. However, onset delays also were noted between the production of IAP and the production of torque. In many high velocity tests, the IAP activity had terminated before the torque production began. Absence of a relationship between IAP and velocity should be interpreted with caution. The onset delay may indicate a preparatory response of the abdominal cavity that would be involved in overcoming the inertia of rest of the trunk. Future research efforts should consider this phenomenon as a significant biomechanical variable.

Torque production of the back was quite substantial. At any given angle of the back, the torque produced was higher for isometric than for isokinetic efforts. With increasing angular velocities, the magnitude of the torque decreased. This was true for all back angles throughout the arc of motion. The torque variable was also the most sensitive of the 12 dependent variables to changes in velocity and angle conditions. Discriminant analysis techniques consistently chose torque as the variable that characterized the differences between velocity and angle conditions. It was also found to be significant in all univariate tests and all experimental conditions. Torque regression analyses were also capable of predicting (ie, explaining) much of the experimental variation. These facts, considered collectively, indicate that torque capability was an extremely important variable in response to velocity and angle conditions. Perhaps, isokinetic strength testing should be incorporated into future pre-employment screening procedures. However, knowledge of the torque capability of abnormal subjects should reveal significant differences in biomechanical ability. Future research should investigate impaired subjects as a function of these same dependent variables. Thus, isokinetic torque production of the back could be used as a diagnostic tool to quantify the extent of impairment.

Knowledge of the torque-production capability of the back also leads one to question present manual material handling techniques. Presently, one is advised to lift objects with the back in an upright position. However, this study has demonstrated that torque potential increases as the trunk angle increases under all velocity conditions. If one accepts the premise that injuries are related to overexertions, it would be much wiser to lift an object with the trunk flexed, while still keeping the load close to the body to minimize the moment at the base of the spine.

Univariate analysis techniques aided in the evaluation of the contribution of the individual dependent variables to the experimental task. It was possible to piece together the contribution of the various measures even if the measure was not selected in the discriminant analysis. This analysis was particularly relevant to the biomechanical analysis of the various muscle involvements.

The univariate analysis of the latissimus dorsi muscles indicated that this muscle group, in particular, reacted differently under the various testing conditions. Overall, the activity of this muscle did not change greatly with changes in angle during isometric exertions, but did change significantly with angle changes during isokinetic exertions. However, under isometric conditions, these muscles were more active than under isokinetic conditions (where their activity was relatively insensitive to increases in isokinetic velocity). It is concluded that the activity of the latissimus dorsi muscles increased with increasing angle in isokinetic situations and also increased under isometric conditions. Therefore, the biomechanical contribution of this muscle is drastically different under movement conditions than under static conditions. It appears that it is primarily used to move the trunk and, thus, does not contribute much to torque production. Hence, biomechanical predictions, based upon static exertion data, would overestimate the force production capability of this muscle group under movement conditions. Also, the difference in sex usage of this muscle should be noted. This factor could be responsible for slower velocity thresholds in women and also may relate to a difference in muscle composition as stated earlier.

Another interesting characteristic of the latissimus dorsi muscle group is its correlation with IAP. This correlation may even have been greater if the IAP-torque time lag was considered. It appears that this muscle group pulls the chest down, thereby applying downward pressure upon the abdominal contents. This finding is in conflict with opinions in the literature. It was speculated that IAP was associated with abdominal muscle activity.

The erector spinae muscle group was the other group that responded differently to various experimental conditions under univariate scrutiny. This group was active under all velocity and angle conditions and did not exhibit any sex differences. It also reacted differently under isometric and isokinetic conditions. Under isometric conditions its activity decreased with increasing angle, whereas under isokinetic conditions the activity increased with increasing angle only between the A0 and A22.5 condition. It is the only muscle group with a force-producing capability which was greater under many isokinetic conditions than under isometric conditions at a trunk angle of 45°. (Figure 10). The activity of the latissimus dorsi group may compensate for the decline of activity of the erector spinae muscles at greater angles. This could be due to the greater mechanical advantage of the latissimus dorsi muscles. The difference in usage of the erector spinae muscles between static and dynamic conditions again emphasized the fact that static biomechanical analyses of dynamic work conditions should be interpreted with extreme caution.

The difference in utilization of the latissimus dorsi and erector

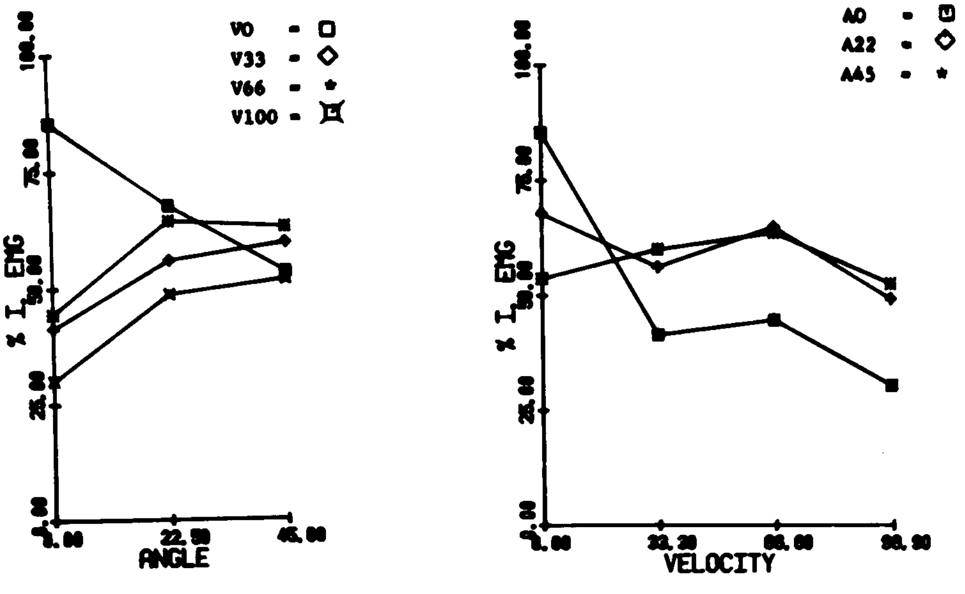

Fig 10. Activity of the erector spinae (*right*) as a function of velocity and angle.

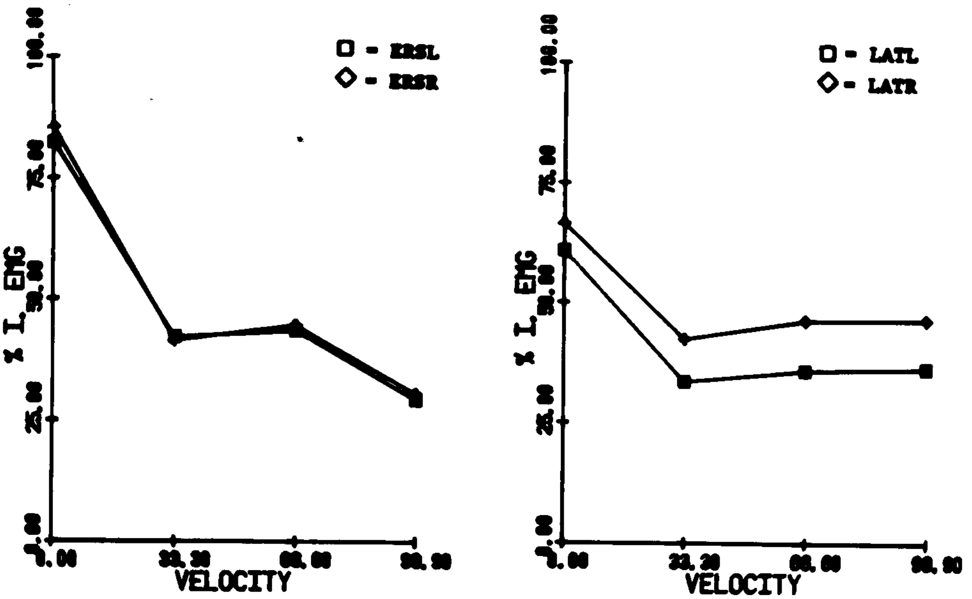

Fig 11. Comparison of activities of the erector spinae and latissimus dorsi under different velocity conditions.

spinae muscles is emphasized in Figure 11. The latissimus dorsi muscles responded at one level for isometric exertions and at a lower level for all other isokinetic exertions, whereas the erector spinae activity decreased progressively with increasing velocity. This fact points to the muscle specific significance of motion. Muscles seem to respond differently when in motion than when contracting against a fixed resistance; thus, these facts should be considered in biomechanical analyses of MMH situations.

Univariate analyses of the remaining trunk muscles indicate that they are active during most experimental conditions but are used as braking muscles as the trunk approaches an upright position at high velocity. There appear to be sex differences in the use of muscles as brakes. Men used the rectus abdominis and internal oblique muscles, whereas women used the rectus abdominis and external oblique muscles. This can be related to the IAP by sex interaction. Women exhibited significantly greater IAP than did men. These collective differences suggest physiologic and structural differences possibly related to childbearing.

In summary, this experiment has shown that there are marked differences between static dynamic utilization and recruitment of the internal mechanisms of the trunk. There are also sex-related differences in the use of these internal mechanisms. Therefore, future biomechanical research should attempt to investigate further these effects and incorporate them into the analysis of loads upon the spine.*

This study has demonstrated that there are significant internal changes that occur in response to velocity and angle changes of the spine. Isokinetic evaluation is a more realistic procedure for the evaluation of tasks related to MMH conditions. This research has focused exclusively on normal healthy subjects in a limited age range. Further research is needed to investigate the effects of age and the ability of abnormal subjects to perform is experimental task. Similar analyses would be in order to find a few key parameters (such as torque and IAP in this study) that characterize the ability to perform experimental tasks. Future research may also include mental states (such as pain thresholds) to help determine which variables are significant in LBP. The present study is a small step in the understanding of dynamic spine activity. Hopefully, this will eventually lead to a fuller understanding of the biomechanics of the spine and thus a minimization of back injuries.

CONCLUSIONS

The following points summarize the significant findings of this study: (1) Fine-wire, intramuscular electrodes provide a means of muscle-specific comparison under both static and dynamic conditions. (2) The torque-producing capability of the trunk is greater when it is flexed 22–45° than when it is erect (0°). (3) A time delay was identified between the onset of IAP and the onset of torque. It increased as the lift velocity increased. (4) Significant positive correlations were found between IAP and the activity of the latissimus dorsi muscles. (5) All trunk muscles were active under both isometric and isokinetic lifting conditions. (6) Both the latissimus dorsi and erector spinae muscles exhibited dramatically different response patterns between isometric and isokinetic exertions. (7) The results of this study suggest that ergonomic recommendations based entirely upon isometric lifting capabilities can be misleading.

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*Spinal loads were computed using a model developed by Schultz and Andersson.[15] To restrict the length of this paper, they are not reported here but can be found in Marras.[8]

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APPENDIX

Summary Statistics for Dependent Variables

Summary Statistics for Variate(s)

Variate	*Count*	*Mean*	*Variance*	*SD*	*WD Mean*	*Maximum*	*Min*
LATR	240	58.65	553.6	23.53	58.65	100.0	13.
LATL	240	47.85	546.8	23.38	47.85	100.0	6.0
ERSR	240	55.64	657.4	25.64	55.64	100.0	0.0
ERSL	240	56.47	775.3	27.84	56.47	100.0	5.0
INOR	240	56.35	672.9	25.94	56.35	100.0	6.0
INOL	240	65.07	525.3	22.92	65.07	100.0	8.0
EXOR	240	65.08	701.5	26.49	65.08	100.0	12.
EXOL	240	52.38	906.4	30.11	52.38	100.0	7.0
RCAR	240	47.37	1093.	33.06	47.37	100.0	6.0
RCAL	240	74.59	442.2	21.03	74.59	100.0	25.
IAP	240	53.16	561.4	23.69	53.16	100.0	4.0
TORQ	240	43.91	718.1	26.80	43.91	100.0	0.0

Factor	*Level*	*Variate*	*Count*	*Mean*	*Variance*	*SD*
Sex	Male	LATR	120	56.06	627.1	25.04
		LATL	120	45.68	537.5	23.18
		ERSR	120	53.52	696.8	26.40
		ERSL	120	56.56	772.1	27.79
		INOR	120	54.89	775.4	27.85
		INOL	120	55.62	553.8	23.53
		EXOR	120	64.22	693.5	26.34
		EXOL	120	49.04	866.7	29.44
		RCAR	120	53.17	1404.	37.47
		RCAL	120	71.47	499.1	22.34
		IAP	120	46.62	579.0	24.06
		TORQ	120	43.06	793.7	28.17
	Female	LATR	120	61.25	471.1	21.71
		LATL	120	50.01	551.2	23.48
		ERSR	120	57.76	614.3	24.79
		ERSL	120	56.37	784.9	28.02
		INOR	120	57.80	571.8	23.91
		INOL	120	74.52	321.0	17.92
		EXOR	120	65.94	713.8	26.72
		EXOL	120	55.72	931.2	30.52
		RCAR	120	41.58	724.3	26.91
		RCAL	120	77.71	369.5	19.22
		IAP	120	59.70	462.2	21.50
		TORQ	120	44.77	647.0	25.44
Veloc	V0	LATR	60	67.85	626.6	25.03
		LATL	60	58.47	682.3	26.12
		ERSR	60	68.98	693.0	26.32
		ERSL	60	67.45	698.1	26.42
		INOR	60	58.12	711.0	26.66
		INOL	60	59.53	448.4	21.18
		EXOR	60	67.40	739.3	27.19
		EXOL	60	60.10	984.9	31.38
		RCAR	60	40.15	1026.	32.03
		RCAL	60	73.27	433.1	20.81
		IAP	60	62.88	642.3	25.34
		TORQ	60	77.90	272.3	16.50
	V33	LATR	60	54.23	598.9	24.47
		LATL	60	44.13	555.0	23.56
		ERSR	60	52.47	659.5	25.68
		ERSL	60	57.73	786.6	28.05
		INOR	60	54.47	750.1	27.39
		INOL	60	61.28	575.6	23.99
		EXOR	60	61.00	557.4	23.61
		EXOL	60	45.23	824.6	28.72
		RCAR	60	41.82	1057.	32.52
		RCAL	60	76.30	418.3	20.45
		IAP	60	51.50	526.0	22.93
		TORQ	60	42.05	286.1	16.91
	V66	LATR	60	59.40	425.9	20.64
		LATL	60	46.47	435.4	20.87
		ERSR	60	57.45	479.7	21.90
		ERSL	60	57.25	713.4	26.71
		INOR	60	57.20	547.1	23.39
		INOL	60	69.03	518.0	22.76
		EXOR	60	64.37	694.0	26.34
		EXOL	60	47.30	783.9	28.00
		RCAR	60	49.40	1040.	32.25
		RCAL	60	73.65	486.4	22.05
		IAP	60	50.63	525.5	22.92
		TORQ	60	34.15	320.1	17.89
	V100	LATR	60	53.13	453.8	21.30
		LATL	60	42.32	380.5	19.51
		ERSR	60	43.65	489.8	22.13
		ERSL	60	43.43	644.8	25.39
		INOR	60	55.60	709.5	26.64
		INOL	60	70.43	494.9	22.25
		EXOR	60	67.55	821.7	28.67
		EXOL	60	56.90	918.7	30.31
		RCAR	60	58.13	1099.	33.15
		RCAL	60	75.15	447.5	21.15
		IAP	60	47.63	443.8	21.07
		TORQ	60	21.55	246.5	15.70
Angle	A0	LATR	80	50.26	587.5	24.24
		LATL	80	41.52	502.7	22.42
		ERSR	80	50.35	937.2	30.61
		ERSL	80	49.16	1066.	32.65
		INOR	80	54.95	678.6	26.05
		INOL	80	65.66	558.7	23.64
		EXOR	80	65.95	753.3	27.45
		EXOL	80	49.80	915.3	30.25
		RCAR	80	51.90	1216.	34.88
		RCAL	80	76.07	457.1	21.38
		IAP	80	42.96	422.1	20.55
		TORQ	80	30.51	561.4	23.69
	A22	LATR	80	57.59	453.0	21.28
		LATL	80	44.99	459.4	21.43
		ERSR	80	59.31	551.3	23.48
		ERSL	80	61.07	637.9	25.26
		INOR	80	56.39	646.8	25.43
		INOL	80	63.75	520.8	22.82
		EXOR	80	64.79	691.9	26.30
		EXOL	80	52.50	888.3	29.80
		RCAR	80	42.56	1039.	32.24
		RCAL	80	73.34	437.2	20.91
		IAP	80	53.05	563.2	23.73
		TORQ	80	47.09	639.8	25.29
	A45	LATR	80	68.11	471.3	21.71
		LATL	80	57.02	558.1	23.62
		ERSR	80	57.25	455.6	21.34
		ERSL	80	59.16	558.5	23.63
		INOR	80	57.70	706.6	26.58
		INOL	80	65.80	507.0	22.52
		EXOR	80	64.50	675.7	26.00
		EXOL	80	54.85	925.6	30.42
		RCAR	80	47.66	1007.	31.74
		RCAL	80	74.36	439.7	20.97
		IAP	80	63.47	500.0	22.36
		TORQ	80	54.14	673.3	25.95