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Intra-abdominal pressure during trunk extension motions

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Abstract

Objective. This study was designed to help interpret the biomechanical role of intra-abdominal pressure during lifting type motions of the trunk.
Design. An *in vivo* study was performed in which intra-abdominal pressure was observed as subject trunks were subjected to different dynamic trunk loading conditions common during industrial lifting.
Background. There is a little consensus as to the biomechanical role of intra-abdominal pressure during lifting. Previous studies have suggested that: it may assist in load relief when lifting, may be involved in trunk stability, and/or may be used as a measure fo spine loading. Thus, in general, our understanding of intra-abdominal pressure is rather poor.
Methods. In this study intra-abdominal pressure was monitored using a radio pill in 114 subjects over a series of four experiments. Subject's trunks were subjected to different dynamic trunk symmetric and asymmetric trunk loading conditions that are common during industrial lifting tasks.
Results. The results indicated that (1) intra-abdominal pressure increased to significant levels (above 10 mmHg) only when more than 54 Nm of trunk torque were supported; (2) intra-abdominal pressure increases monotonically (up to 150 mmHg) as a function of trunk velocity; and (3) under concentric conditions intra-abdominal pressure increases as a function of greater asymmetry, whereas, under eccentric conditions the response changes to a much lesser extent as asymmetry changes.
Conclusions. These findings suggest that intra-abdominal pressure appears to be more a by-product of trunk muscle coactivation. Any mechanical advantage gained from intra-abdominal pressure might be in the form of a preparatory action resulting from muscle coactivation that stiffens the trunk just prior to a rapid trunk extension exertion. This function may reinforce previous hypotheses regarding the stability role of intra-abdominal pressure.

Relevance

Intra-abdominal pressure has been observed during lifting for several decades, yet the biomechanical role of intra-abdominal pressure is poorly understood. This study has attempted to describe how intra-abdominal pressure behaves during lifting motions as the components of lifting are changed. The findings place in doubt biomechanical significance of intra-abdominal pressure. Thus, based upon this study, clinicians need not worry about interpreting intra-abdominal pressure, since it appears to be a by-product of muscle contraction and cocontraction. Copyright © 1996 Elsevier Science Ltd.

Key words: Intra-abdominal pressure, low back, biomechanics, back belts

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Introduction

Intra-abdominal pressure (IAP) has been well documented during lifting activities for nearly 40 years[1-10]. It has been observed that IAP is a naturally occurring pressure that increases when one holds one's breadth and performs a valsalva manoeuvre. IAP also increases when one performs a lifting task. IAP can be consciously controlled and can be increased through the use of lifting belts and abdominal corsets.

Studies have shown that IAP is associated with both load moment applied to the trunk[1,6-8,11-14] as well as with intradiscal pressure[15,16]. However, even though these studies have demonstrated an association

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between IAP and trunk loading, no studies have been able to prove causality.

IAP information has been applied in several ways. Davis[17] has considered IAP a means to assess loads on the lumbar spine. Davis and Stubbs[3–5] have used IAP to define safe levels of manual force exertions for young males. They have defined the acceptable forces that one could generate in various positions around the body before unacceptable IAP would be generated. On the other hand, lift belt manufacturers often cite the benefit of their products as increasing IAP. They assume that increasing IAP during a lift is a beneficial feature of belt wearing during lifting and contend that by wearing belts a reduction in back injuries would be expected[18]. This logic would hold only if IAP produces a counter-moment to the external load lifted, thereby helping to support the load. Hence there are conflicting opinions as to whether IAP is beneficial or detrimental during manual materials handling activities. The literature has yet to produce a definitive study that unequivocally establishes the role of IAP in trunk loading.

Several hypotheses exist that have attempted to explain how IAP occurs during lifting and what possible biomechanical role IAP may play. One of the most cited theories of IAP was articulated by Morris et al.[11]. He describes a cantilever model of the spine where the magnitude of the IAP was considered to be a mechanism to assist as an extensor moment and would result in lumbar spine compression relief. However, McGill et al.[10] questioned this hypothesis. They found that the benefit of IAP could easily be negated by the forces generated by the abdominal wall musculature. They concluded that the role of IAP was not well understood. However, Cresswell and Thorstensson[19] also found that IAP could be increased without the development of large forces in the trunk flexors. Thus, it is apparent that we do not fully understand the role of IAP in load relief during lifting.

Farfan[20] proposed that IAP may create hydrostatic pressure within the trunk cavity that has the effect of maintaining the hoop-like geometry of the abdominals. Yet, others[21] have pointed out that because of the increased lever arm between the abdominal musculature and the spine the effect of this hoop-like geometry would be to increase spinal compression.

Aspden[22] suggested a different model for the spine, where the spine was considered as an arch. He proposed that the role of IAP was to increase the pressure upon the convex surface of the spinal lumbar curve. He contends that an arch loaded in this manner would result in a system that is very strong and when the muscle and ligamentous support are considered the spine stiffness is greatly increased.

McGill and Norman[21] suggest that the role of IAP may be used to maintain alignment of the vertebral motion units, thereby minimizing or eliminating small movements in shearing modes at the facet joints. They also suggest that variations IAP may play a physiological role in that it may prevent venous blood pooling in the abdominal cavity through a 'pumping' action.

Stabilization of the trunk is a common theme of many of these hypotheses. Grillner et al.[23] and Maisson[24] point to the role of IAP in the support of sudden loading of the trunk. They note that since the trunk contains the largest mass in the human body and has a large moment of inertia, the maintenance of stability and equilibrium become extremely important in injury avoidance to the spine.

All of these previous studies have suggested interesting mechanisms and roles of IAP in the preservation and operation of the trunk. However, the role of IAP has not been explored quantitatively as a function of dynamic motion conditions typically observed in industry. Thus, the objective of this study was to provide insight to the possible mechanisms of IAP by describing its activity over a wide range of trunk flexion and extension controlled motions that would be similar to those involved in lifting or manual materials handling activities observed in industry. Typical observed[25] industrial lifting activities include both lifting and lowering in different lines of action and performed at different speeds of motion under various load conditions. Therefore, the specific hypotheses of this study endeavoured to determine whether specific patterns of IAP response occurred as a function of trunk moment, trunk velocity, and the direction of trunk velocity.

Methods

Approach

The objective of this study was to describe how actions of the trunk during typical manual materials handling conditions (trunk work position, concentric and eccentric motion, trunk velocity, acceleration, load moment) are associated with IAP. This study reports the outcome of four separate experiments that have been performed in order to elucidate the role of IAP during trunk extension moment production. This study focuses primarily on IAP activities. Muscle activities under these conditions have been previously reported[26–28]. Each of these four experiments involved highly controlled experimental conditions that required the subjects to exert a constant force with the back throughout a 45-deg range of motion while moving under specified asymmetry, velocity, and acceleration conditions. Experiments 1 and 2 explored the role of concentric and eccentric velocity relative to the other experimental conditions, whereas, experiments 3 and 4 attempted to assess the role of trunk acceleration. It was assumed that the point of bend about the spine was located at L_5S_1 and that this motion would relate to torques experienced about the spine during lifting.

Subjects

One hundred and fourteen volunteer subjects participated in the four experiments described in this paper. Of these subjects 94 were males and 20 were female. Their ages ranged from 17 to 40. None of the subjects

Table 1. Description of each of the four experiments

Experiment	*Male subjects (n)*	*Female subjects (n)*	*Subject wt avg (std) (kg)*	*Subject ht avg (std) (cm)*	*Asymmetry levels (deg)*	*Torque levels (Nm)*	*Sagittal angles (deg)*	*Sagittal velocities (deg s^{-1})*	*Sagittal accelerations (deg/s^{-2})*
1	34	10	75.6 (4.6)	178 (9.5)	0, 15, 30	27, 54	5, 22, 40	0, 10, 20, 30	N/A
2	9	2	86.4 (23.4)	182.9 (10.8)	0, 15, 30	27, 54, 81,... up to ability	5, 22, 40	0, 10, 20, 30... −10, −20, −30... up to ability	N/A
3	31	8	81.4 (4.3)	179 (3.1)	0, 15, 30	4.1	5, 22, 40	Variable	H, M, L
4	20	0	83 (14.9)	182 (10.34)	0, 15, 30	0, 54, 108	20, 40	0, 15, 30	0, 20, 40
Total	94	20							

− indicates eccentric velocity; H, high acceleration; M, medium acceleration; L, low acceleration.

had experienced a significant low back disorder and all were considered in good health. Subject occupations covered a wide range from professionals to those experienced in MMH. The mean (SD) stature and weight of the subjects involved in each of the individual experiments are reported in Table 1.

Experimental design

The experimental conditions associated with each of the four experiments are also reported in Table 1. The independent variables consisted of (1) the moment (torque) supported by the trunk and imposed by a trunk dynamometer, (2) trunk angle in the sagittal plane (0 deg indicating an upright posture and positive angles indicating forward flexed postures), (3) trunk asymmetry defined relative to the sagittal plane of motion as shown in Figure 1 (only deviations where the subject's trunk was rotated clockwise with respect to the pelvis were used as the asymmetric positions), (4) trunk concentric and eccentric isokinetic velocity, and (5) trunk angular acceleration. All independent variables were chosen to represent generally the range of conditions observed in the industrial environment[25], except for trunk acceleration, which in experiment 4 was limited by the capabilities of the dynamometer. Eccentric trunk velocity was included since it represents the underexplored area of lowering as opposed to lifting, which would be considered concentric velocity.

The dependent variables in this experiment consisted of IAP. Trunk muscle electromyography was also recorded during all experiments but was reported elsewhere[26–28].

Apparatus

All subjects in the four experiments were tested in a reference frame that assured the trunk would be aligned relative to the dynamometer. Concentric and eccentric velocity was controlled by a KIN/COM isokinetic dynamometer. This device was aligned with the L_5/S_1 junction of the back via an asymmetric reference frame (ARF) and is shown in Figure 2. This ARF positioned the subject relative to the dynamometer so that both symmetrical and asymmetrical back exertions could be tested.

Trunk moment about L_5/S_1 was controlled by the subject. The subjects viewed a computer monitor which graphically displayed their current level of torque production on-line. A target moment was shown on the computer screen, as was a tolerance about the target torque. Therefore the subjects were able to continuously monitor their torque production and use this feedback to maintain the specified torque level.

IAP was monitored with a pressure transducer radio pill inserted rectally. An antenna worn around the subject's trunk received the IAP signal. Rushmer[29] has demonstrated that pressures measured in this manner are very similar to pressures measured directly in the abdomen. The pill was sterilized before each subject was tested. The IAP transducer pill was calibrated before and after each data collection period. The calibration process required a small sealed calibration chamber and a sphygmomanometer. The IAP pill was placed in the chamber and an antenna (belt worn by subjects) was placed around the chamber. The chamber valve was opened and the container was pressurized by

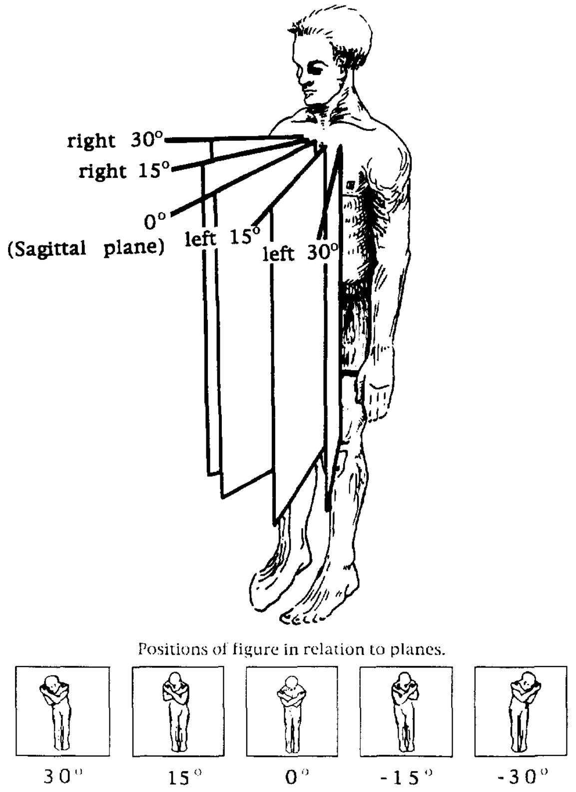

Figure 1. Asymmetric reference planes observed in this experiment.

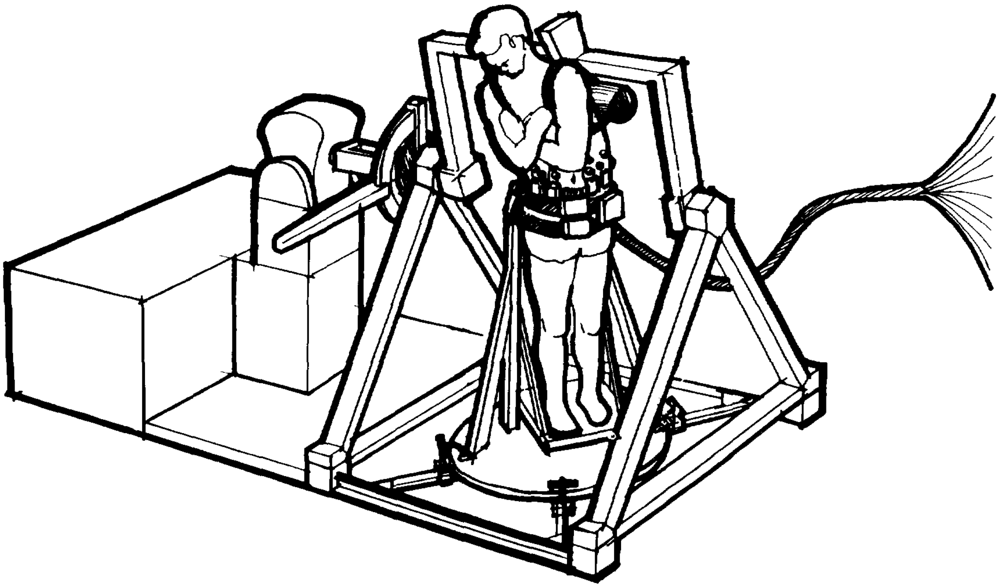

Figure 2. Asymmetric reference frame used to control subject planes of motion.

squeezing the sphygmomanometer pressure bulb. The valve was then closed and the mercury component of the sphygmomanometer was connected to the valve. Next the valve was opened and the mercury tube registered the pressure in the chamber. The voltage was monitored by the transducer's amplifier was then recorded along with the corresponding pressure. The range of calibration was from 0 mmHg to 150 mmHg (above atmospheric pressure). The process was repeated to make sure the pressure transducer pill was reporting stable readings.

The dynamometer signals, ARF position signals, and the IAP signal were all digitized with an A/Dconverter at 100 Hz. This multichannel A/D system interfaced with a 386-based microcomputer to collect, display, and store the data on-line. Further processing was performed on the University mainframe computer system.

Procedure

Subjects were interviewed to ensure that they had not experienced any significant back disorders. A practice session was permitted to familiarize the subject with the experimental task of controlling torque by interfacing with the computer feedback system. When the subjects became proficient at the task, an appointment was made for the experimental session on a different day.

In experiments 1, 2 and 3 the experimental task required subjects to extend their trunks, starting from a standing flexed position (with the thorax at a 45-deg forward angle from vertical relative to the pelvis) and ending in an upright standing position (thorax and pelvis angle of 0 deg). This task was performed with the trunk extending in the sagittal plane as well as with the trunk extending while twisted 15 and 30 deg in the transverse plane. The latter positions resemble asymmetrical industrial lifts.

In all four experiments the experimental task required the subjects to control their trunk moment between the tolerance limits of the exertion (defined on the computer screen) under each velocity and asymmetric position exertion. A target moment was displayed upon the computer screen as was a tolerance of ± 10% about the target moment. Therefore the subjects were able to continuously monitor their torque production and use this feedback to maintain the specified moment exertion level. If the subject failed to maintain exertions within the tolerance limits, the trial was rerun.

In experiments 3 and 4 the trunk acceleration was controlled by the subjects. In experiment 3 subjects were asked to accelerate the trunk at subjectively determined high, medium, and low constant accelerations while exerting a constant minimal torque of approximately 4.1 Nm (± 1.25 Nm) about L_5/S_1. As the subject performed the task he was asked to view a computer monitor that displayed his instantaneous trunk velocity and torque performance. The subject was asked to increase the velocity in a linear manner (± 0.8 deg s^{-1}) (constant acceleration) while maintaining a constant torque.

In experiment 4 low level accelerations were controlled by the dynamometer. In order to observe combinations of trunk angle, angular velocity and angular acceleration, the subject had to begin their exertion several degrees before the angle of interest. For example, if a given trial dictated that the subject was to be moving at 30 deg s^{-1} at the trunk angle of 20 degrees as they were accelerating at 20 deg s^{-2} then the subject had to begin this acceleration at a trunk angle of 43 degrees. In this way, all requirements of position, velocity, and acceleration were met.

Data analysis

Each dependent force value was evaluated as the trunk moved through a 'trunk posture window'. These windows consisted of the forward trunk angle (5, 22.5, and 40 deg) ± 1.25 deg of motion at the various asymmetric trunk positions. Each value represented the mean activity as the trunk passed through a 2.5-deg range of motion.

Statistical significance was determined by employing univariate analysis techniques. Univariate analysis of variance (ANOVA) procedures were used to determine how IAP responded to each experimental factor. Follow-up *post hoc* analyses were then used to identify the exact nature of these significant differences.

Results

The observed IAPs were evaluated for relative repeatability under each of the unique experimental conditions. The average coefficient of variation for each unique experimental condition was approximately 0.35, indicating good repeatability. The specific values of IAP varied up to about 150 mmHg. Specific values are discussed as a function of the independent variables via the figures.

The significant IAP changes associated with the various physical factors over the four independent experiments are summarized in Table 2. In general, significant changes in IAP were observed as a function of changes in trunk asymmetry, torque supported by the trunk, trunk velocity, and to a lesser extent sagittal plane trunk angle. In addition, unique combinations of asymmetry and trunk torque, velocity and trunk torque, and asymmetry and trunk velocity were observed once greater velocities were included as part of the experimental conditions. It is also notable that there are negligible effects of acceleration upon IAP. In addition, the fact that more significant effects appear in the second experiment (which included a much larger range of conditions) than the first experiment point to the fact that IAP appears to respond to the physical variables over a large range of variable values as opposed to simply responding strongly over a more narrow range. The specific nature of these various changes in IAP can be appreciated by examining the influence of each significant trend independently.

The influence of asymmetry on IAP can be appreciated by examining some of the results in detail. Figures 3, 4, and 5 (from experiment 2) illustrate the effect that torque and velocity have upon IAP at the various asymmetric angles. Several trends are apparent via these figures. First, increases in velocity (either concentric or eccentric) result in substantial increases in IAP, but only when trunk torque generation became substantial. Under all of these conditions IAP was always lowest under the isometric (0 velocity) condition compared to any of the dynamic conditions. For the most part IAP also increased monotonically as velocity increased, except during high-velocity sagittally symmetric exertion conditions, when very high levels of torque were supported by the trunk. The magnitude of the IAP increases, as a function of eccentric velocity increases, remained relatively constant (relative to the concentric increases) over the different trunk asymmetries. However, IAP magnitude increased substantially under the concentric velocity conditions as asymmetry increased. Thus asymmetry affected IAP under concentric velocity conditions to a much greater extent than under eccentric velocity conditions.

Second, the effects of torque upon IAP were only significant when greater levels of torque were supported by the trunk. As shown in Figures 3–5, torque influenced the level of IAP only at levels only above 54 Nm. These figures show that as the level of the supported torque increased, IAP increased rather dramatically. This trend was further intensified when dynamic trunk motion was present during the test. The finding that torque has a significant effect only above a given level is also confirmed by the lack of a significant effect for torque in experiment 1, which only considered torques up to 68 Nm.

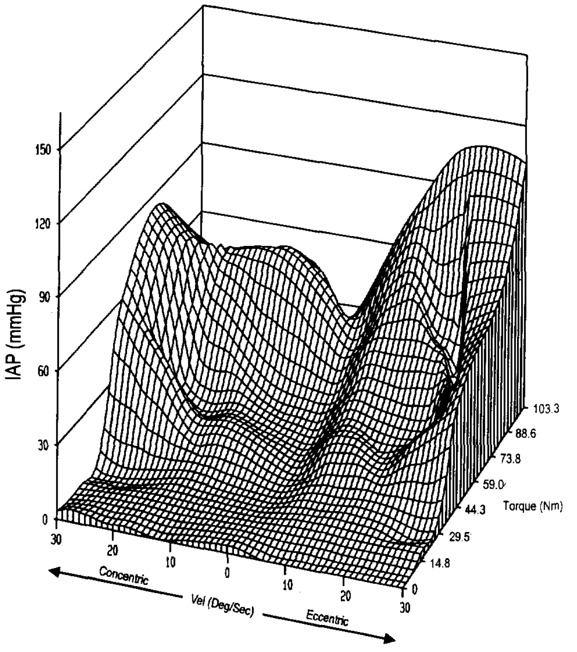

Figure 3. IAP activity as a function of velocity and torque at the 0° asymmetry condition. (From experiment 2.)

Table 2. Summary of ANOVA significance for the four IAP studies

Experiment	*Asym*	*Torq*	*Angle*	*Velocity*	*Accel*	*Asym*Torq*	*Torq*Velocity*	*Asym*Velocity*	*Asym*Torq*Velocity*
1	0.0005	0.0803	0.0001	NS	N/A	0.099	NS	NS	NS
2	0.0001	0.001	NS	0.0001	N/A	0.0001	0.0001	0.0007	N/A
3	NS	N/A	NS	N/A	NS	N/A	N/A	N/A	0.0001
4	0.0001	0.0001	NS	0.02	NS	0.0001	NS	NS	NS

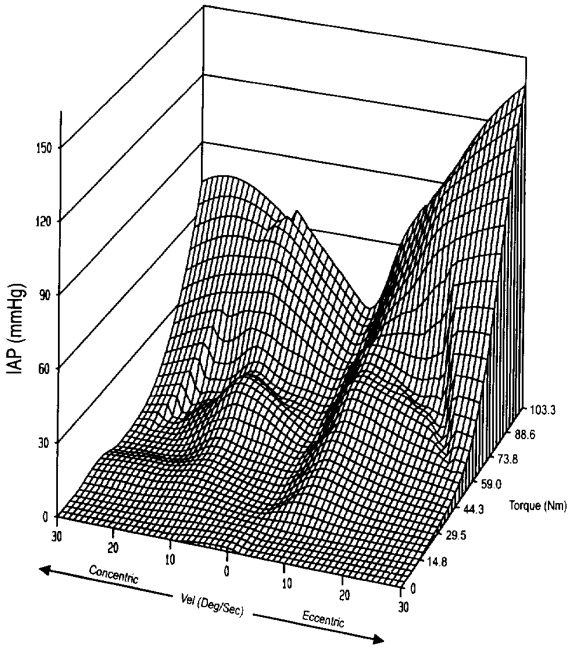

Figure 4. IAP activity as a function of velocity and torque at the 15° asymmetry condition. (From experiment 2.)

Third, by comparing Figures 3, 4, and 5 it is apparent that increased asymmetry tended to increase IAP. However, as mentioned earlier, this increase affected IAP to a much greater extent under high-torque, high-velocity, concentric conditions compared to high-torque, high-velocity eccentric conditions.

Finally, sagittal angle was found to have a significant affect on IAP in experiment 1 only. This trend is shown in Figure 6, where IAP is found to increase rather linearly as trunk angle becomes greater. However, it must be kept in mind that this experiment only considered a small range of trunk torque, and the increase in observed IAP is rather small (less than 10 mmHg). Thus even though this is a statistically significant increase in IAP, it probably holds no biomechanical meaning. This logic was validated by the lack of significance for this variable in experiment 2, where a much greater range of trunk torque was explored.

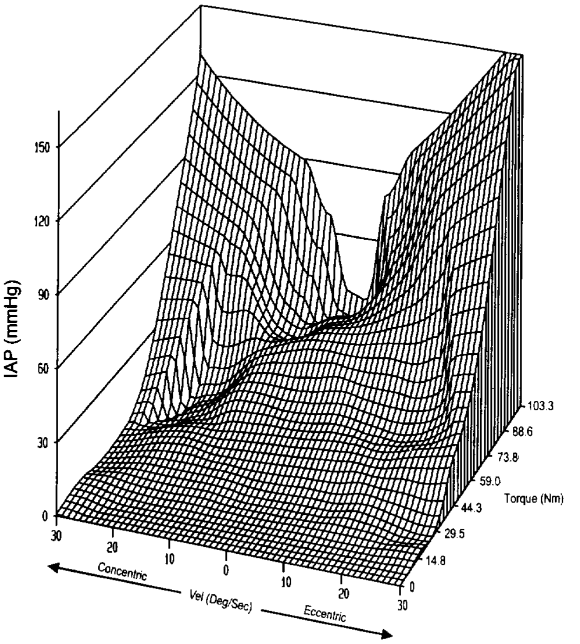

Figure 5. IAP activity as a function of velocity and torque at the 30° asymmetry condition. (From experiment 2.)

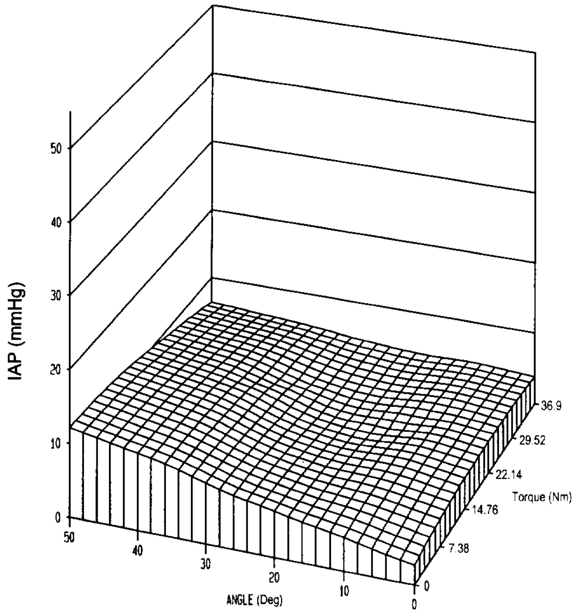

Figure 6. IAP activity as a function of angle and torque averaged over all asymmetry conditions. (From experiment 1.)

Discussion

The results of this study indicate that IAP levels changed in response to trunk asymmetry, trunk velocity, trunk torque, to a limited extent trunk sagittal angle, and to many of the unique combinations of these variables. One could generalize these finding in more functional terms by stating that: (1) IAP increases to significant levels only when more than 54 Nm of trunk torque are supported, (2) it increases monotonically as a function of trunk velocity, and (3) under concentric conditions it increases as a function of greater asymmetry, whereas under eccentric conditions the response changes to a much lesser extent as asymmetry changes.

This assessment has provided some clues as to the biomechanical significance of IAP. In order to appreciate the role of IAP, one could examine the possible contribution of IAP to spine loading or load relief as well as the possible role of IAP in altering the tolerance of the spine-to-load bearing.

It has been hypothesized that the role of IAP may be to provide a counter-moment to the load applied to the trunk. However, the results of this study indicate that there are several reasons that this might not be the primary role for IAP. First, the magnitude of the IAP response was rather small compared to the magnitude of the external load that was supported. Under the most extreme experimental loading conditions where the trunk supported 190 Nm of torque the IAP rose to only about 150 mm Hg. By applying Newton's force laws to a human trunk geometrically modelled as an ellipse with average trunk anthropometry, this would provide only 31 Nm of counter-moment to the trunk. Second, IAP did respond significantly to the torque supported by the trunk; however, a much stronger contributor to IAP was trunk velocity. In addition, if IAP's role was to respond to trunk force one would expect IAP to exhibit a strong response to trunk acceleration, since force is a function of mass and acceleration. However, experiments 3 and 4 resulted in no statistically significant responses to acceleration.

By considering the results of these experiments in conjunction with findings regarding muscle responses in previous studies, we may glean some insight as to how the trunk develops IAP. Our previous evaluations of trunk muscle activities have shown that as trunk velocity and asymmetry increase, muscle coactivation increases substantially[27,30]. During an exertion if an agonist muscle group is activated, compression is increased in the spinal column and the potential for pressure within the trunk's peritoneum exists if the trunk can be considered a closed and non-elastic system. However, at rest the trunk is elastic and only becomes rigid and less elastic if the antagonistic muscles and the subsequent trunk fascia become taught. Thus, it may be that IAP is simply a product of increased coactivation. Figure 7 shows how the external oblique muscles responded to the combination of torque and velocity conditions while the trunk was moving in sagittally symmetric lines of action (0 deg) during experiment 2. This figure indicates that the trunk muscle coactivation pattern closely follows that of IAP as shown in Figure 3. This finding suggests that IAP may play little role in load support throughout an exertion and may simply be a by-product of trunk muscle coactivation.

Further insight to the role of IAP can be gained by exploring the temporal sequence of events that occurs during an exertion. In a previous study Marras and associates[9] investigated the temporal relationship between IAP and the torque generated by the trunk. This work identified a significant delay between the onset of IAP and the onset of trunk torque production. Under isometric trunk extension conditions and slow trunk extension conditions, the onset of IAP and trunk torque occurred at approximately the same point in time. However, as the velocity of the trunk extension increased, the IAP onset preceded torque development and the magnitude of this delay increased as the trunk extension velocity increased. These findings suggest that the primary role of IAP may be one of a preparatory or trunk stiffening so that the trunk could overcome the inertia of rest and accelerate the mass of the trunk. Since experiments 1 and 2 focused upon IAP development during a constant velocity of the trunk (no acceleration), these tests would not be expected to observe this IAP torque onset delay.

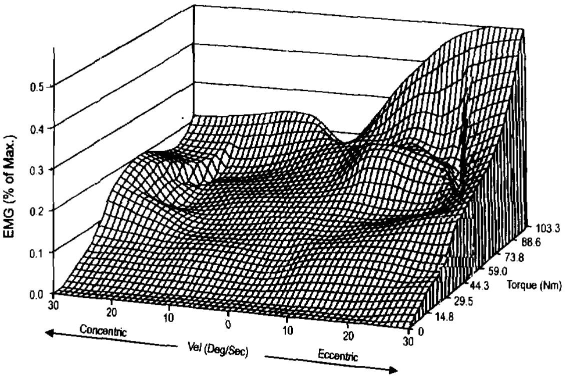

Figure 7. External oblique EMG activity as a function of velocity and torque averaged over all asymmetry conditions.

Considering both the results of the these four experiments in conjunction with the IAP torque onset delay information, we conclude that IAP appears to be more of a by-product of trunk muscle coactivation and does not provide a significant counter-moment to an applied trunk moment. The only mechanical advantage gained from IAP might be the preparatory action due to coactivation the trunk musculature just prior to an exertion in an attempt to stiffen the trunk just prior to a rapid trunk extension exertion. This function may also reinforce previous hypotheses regarding the stability role of IAP. It may be the case that IAP acts as a trunk stabilizer in a similar manner as it does when in a preparatory mode. In preparatory mode the trunk is stiffened so that it is rigid and can overcome the inertia of rest. In a similar manner in stability mode it may stiffen the trunk so that it can resist any perturbations to the system. However, from these results it appears that any stiffening contribution for either preparatory or stability purposes would be minimal at best.

It should also be considered that any benefits of IAP may not be related to the reduction of the biomechanically imposed loading of the trunk. It has been suggested that there may be a benefit of IAP that is related to tissue tolerance. Most studies of the disk and vertebral endplate tolerance to load have been performed while the spinal segment has been stressed under ambient air conditions. However, in the living trunk the IAP may also affect the tolerance of the tissues. This equalization of pressure may result in added strength of the disk structure.

Finally, some potential limitations of this study should also be acknowledged. First, even though the pressures measured at the rectum have been shown to be similar to IAP measurements[29], these validation studies are dated and need to replicated with more accurate modern instrumentation to assess the strength of this relationship. Second, all the subjects observed in this study were student volunteers. Experienced material handlers might produce a very different biomechanical response. However, it is doubtful that these limitations would significantly alter the conclusions of this study.

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