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The force–velocity relation and intra-abdominal pressure during lifting activities

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An experiment was performed to test the static and dynamic lifting capabilities of the back. Twenty healthy male and female subjects exerted maximal force with the back under isometric and isokinetic lifting positions. Torque about the lumbosacral junction and intra-abdominal pressure (IAP) production were monitored under the experimental conditions. Torque production capability was found to increase as trunk angle increased and decreased as angular velocity increased. IAP was found to be primarily a funciton of angle and a weak indicator of torque. A significant IAP–torque onset delay was identified as was a physiological source of IAP.

1. Introduction

The notion that intra-abdominal pressure (IAP) may reduce the loading of the spine has existed for quite some time. When an object is lifted with the spine flexed, a flexor moment is produced about the spine. This moment is opposed by a counteracting extensor moment developed with the back and hip muscles. The IAP is believed to assist in the development of this extensor moment by producing a force anterior to the spine. Thus, the back muscle forces are reduced and this in turn reduces the compression forces upon the spinal column and discs. Regardless of the mechanism and consequences of IAP production, it is common for a materials handler to experience an increase in abdominal pressure when lifting an object.

Several investigations of IAP in relation to trunk load have been reported. Davis (1956) found that IAP increased when trunk moments increased, and this finding was confirmed by Bartelink (1957). Both studies concluded that IAP significantly reduced the load upon the spine. They also found that the IAP was proportional to the weight lifted. Davis (1956, 1959) studying a population of healthy males, identified patterns in the development of IAP during weight lifting. An abrupt rise in pressure during the lift was noted (snatch pressure) followed by a rapid fall to a level above the resting level which occurred when the weight was held. More recently Davis (1981) has also identified another later peak associated with the act of load placement. These peaks are believed to be associated with the increased torque required to overcome load and trunk accelerations at the beginning and end of a lifting manoeuvre. Davis also points out that the magnitude of the peaks, the mean pressure and the pressure–time quotient are all related to the torque on the lower lumbar spine.

Morris et al. (1961) later developed a mathematical model of the IAP and trun muscle forces acting upon the spine. They calculated that the IAP contribution reduce the load upon the spine by 30–50%. Their dynamic lifting experiments al demonstrated that IAP increased as more weight was lifted. Eie and Wehn (1962) als calculated the load relief effects of IAP and reported that maximum IAP in the subjects would have an 82–145 kg relieving effect on the spine. Later calculations by E (1966) have shown that the IAP was equivalent to approximately 40% of th contraction force of the erector spinae muscle.

Stubbs (1973), Davis and Stubbs (1976 a, b, 1977) and Davis (1981) attempted to use IAP to determine safe levels of work under actual on-the-job working conditions. Davis and Troup (1964) investigated the effects of pushing, pulling and lifting upon IAP. They found that IAP was proportional to both the weight magnitude and the speed of lifting. Their results showed that pressure changes were greater when pushing, less when lifting and least when pulling.

IAP investigators have also attempted to determine the best lifting position. Morris et al. (1961) have found greater IAP pressures in 'leg lift' as opposed to 'back lift' techniques. However, Davis and Troup (1964) and Eie (1966) have concluded, based upon IAP, that the trunk should be kept vertical when lifting. Eie (1966) has also documented the IAP under several other conditions. He found marked differences in the IAP of cross-country skiers depending upon whether they used one or two arms to pull. He also investigated IAP responses to jet flight.

Recently, efforts have been underway to quantitatively evaluate the relation between IAP and spine loading. Andersson et al. (1976, 1977) demonstrated that, under static conditions, the IAP increased linearly with both trunk flexion angle and an increase in load. Örtengren et al. (1981) also investigated the relation between IAP and measured disc pressure under static loading conditions. They found a significant correlation ($r = 0{\cdot}77$) between the two measures. Schultz et al. (1982), on the other hand, found very weak correlations ($r = 0{\cdot}36$) between the same measures and even weaker correlations ($r = 0{\cdot}24$) between IAP and computed spine compression.

Most of this previous research has evaluated IAP under static conditions or has not quantitatively measured or controlled the velocity of trunk motion under dynamic conditions. Yet, velocity of motion is definitely a physical factor which influences the ability to handle loads manually. Thorstensson et al. (1976) in studies of knee extension found that a significant amount of information regarding the force–velocity relation of the knee may be gained by investigating isokinetic and isometric force production capability. In the present experiment, the IAP was monitored as a function of the force–velocity relation of the back. Thus, we were able to evaluate the relation between velocity of motion and production of IAP under simulated lifting motion conditions.

2. Method

2.1. *Subjects*

Ten male and ten female college students between the ages of 18 and 26 years volunteered to participate in the study. Male height and weight (mean ± S.D.) dimensions were 179·0 ± 4·4 cm and 73·8 ± 8·4 kg, respectively. Female height and weight dimensions were 162·6 ± 5·5 cm and 56·1 ± 5·8 kg, respectively. All subjects reported that they were in good health and exercised regularly. Subjects were examined by a physician prior to participation in the study and only subjects free of back complaints and who had never experienced back pain or back disorders were eligible to participate in the experiment.

2.2. Design

Two independent variables, velocity and angle, were defined in this study. Unlike previous studies, the velocity (V) of spinal extension was controlled with an isokinetic dynamometer. After an initial acceleration phase, the dynamometer restricted the rate of movement to a pre-set maximum. This device was capable of monitoring the torque exerted during isometric and isokinetic exertions. Four levels of the velocity variable were defined relative to a subject's maximum velocity capability (threshold). Each subject's threshold was determined in a pre-test in which the subject was asked to exert maximum torque against the dynamometer while the velocity level was increased. This threshold pre-test was controlled by the apparatus and required no feedback to the subjects. The threshold was defined as the maximum isokinetic velocity one could attain while exerting 6·78 N m of torque upon the dynamometer. The velocity levels were then set at 75% (V100 condition), 50% (V66), 25% (V33), and 0% (V0) of the threshold velocity. The zero velocity level was an isometric exertion.

The angle variable (A) relates to the angles through which the back passes when extending the spine in a 'back lift' activity. The angle variable represents a sampling of angles through which the back moves when extending from a flexed position as is the case during a 'back lift' activity. These angles are defined by the spine's relation to the lumbro-sacral (L5/S1) junction of the back as shown in figure 1. Cailliet (1968) has shown that most back motion in the sagittal plane occurs at L5/S1. Pre-tests indicated that most healthy subjects could produce a trunk angle (with the pelvis stabilized) of at least 67·5°. The isokinetic experimental tasks required the subject to begin in this 67·5° position and continue exerting maximal force with the back until the trunk had passed through the 0° (upright) position. In order to compare performance under isokinetic as well as isometric conditions, three angle levels were defined as 0, 22·5 and 45°. These angles served as static testing positions. The 67·5° angle was not included in the analysis

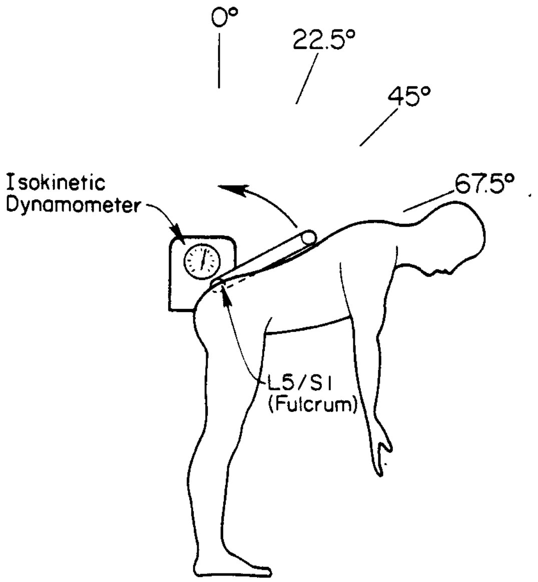

Figure 1. Orientation of subject and dynamometer. The starting position and experimental angles used to compare static and dynamic exertions are indicated.

since the first 20° of motion were an acceleration phase before constant velocity was attained. All subjects were tested under each V and A condition combination.

The dependent variables in this study consisted of the force production capability of the back (torque) and the IAP. Trunk torque production under static and dynamic condition was monitored with a Cybex II (Lumex Ins.) isokinetic dynamometer. The dynamometer lever arm was of fixed length and rested upon the back just below the scapula when the subject stood erect. The lever arm's axis of rotation (fulcrum) was aligned with the (L5/S1) junction of the subject so that sagittally symmetric exertions could be monitored. The dynamometer was fitted with a goniometer which indicated the angle of the back. A frame was constructed which secured the subject's hips and legs so that the subject–dynamometer relationship was maintained throughout all tests. Figure 1 also shows the subject and dynamometer orientation. The trunk muscles (latissimus dorsi, erector spinae, internal oblique, external oblique and rectus abdominus) contraction forces were also monitored via intramuscular electromyographic recording techniques and are reported elsewhere (Marras *et al.* 1984). IAP was measured with a 0·8 mm diameter Millar Mikro-Tip transducer catheter which was passed via the nostrils into the stomach. This catheter was attached to a control unit which amplified the signal.

All experimental data were recorded on an FM analog tape recorder, digitized on a PDP8/E minicomputer, and analysed on an Amdahl computer.

2.3. *Procedure*

A standardized testing procedure was used. After being instrumented, subjects were permitted a warm-up period. They were instructed in how to exert force against the dynamometer and were allowed to adjust hip and feet positions so they were comfortable yet stable.

Subjects were instructed to exert maximal torque with the back while the threshold of velocity was determined. After the threshold velocity had been determined, the experimental session began. Subjects were asked to produce maximal torque against the dynamometer arm with the back under all experimental conditions. Standard testing protocol was followed for static exertions (Caldwell *et al.* 1974). Subjects were asked to indicate if they felt each exertion was truly a maximum exertion and if not, the exertion was repeated. Otherwise, only one exertion was recorded under each experimental condition.

3. Results

The maximum velocity 'threshold' summary statistics are shown in table 1. Males demonstrated significantly greater thresholds than did the females ($t(18) = 9{\cdot}30$, $p \leqslant 0{\cdot}001$).

Table 1. Threshold velocities (deg/s) of subject group.

	Mean	S.D.	Maximum	Minimum
Males	230·4	20·24	264	192
Females	200·4	17·48	234	180
Both	215·4	23·99		

Table 2. Torque values (N m) associated with various trunk angle and velocity conditions*.

Angular velocity (V)	Angle (A) (degrees) 0	22·5	45
0	96·79 ± 25·33 (47–149)	131·06 ± 46·28 (61–231)	135·19 ± 47·36 (74–237)
33	43·19 ± 21·82 (7–81)	64·34 ± 20·79 (41–102)	84·07 ± 28·72 (41–163)
66	30·04 ± 18·78 (0–69)	51·05 ± 15·70 (30–81)	74·72 ± 36·04 (20–149)
100	13·22 ± 12·72 (0–39)	44·81 ± 29·41 (7–111)	40·00 ± 17·74 (7–68)

* Values are mean ± S.D. (range); $n = 20$.

Summary statistics describing the torque production capabilities of subjects are shown in table 2 and figure 2. The torque production capability of the back was greatest under isometric conditions (VO) and monotonically decreased as the velocity of motion increased. Torque production was also greatest at larger trunk angles and decreased as the trunk angle decreased.

The raw data were also converted into normalized values so that relative as well as absolute differences could be identified. Both the raw and normalized data were tested for statistical significance in response to the velocity and angle conditions. Table 3 shows the statistical significance summary for torque data. Raw torque exhibited statistically significant responses to all experimental conditions. However, when the data were normalized and tested, most sex differences were not found significant.

The raw IAP values varied from 5 to 145 mmHg. The magnitude of abdominal pressure was similar under isokinetic conditions (V33, V66 and V100) regardless of the velocity conditions. However, *post-hoc* analysis by a Newman–Keuls procedure indicated significant differences between static (V0) and isokinetic velocity conditions at all trunk angles ($p < 0.05$). Less variation and range in IAP was observed as the velocity condition increased.

Table 4 shows the statistically significant responses of IAP to the various experimental conditions. When raw data were considered, only angle was found to

Table 3. Statistical significance summary for raw and normalized torque response to velocity and angle. Values indicate F statistic.

Independent variable	d.f	Torque	Normalized torque
Velocity (V)	3, 16	115·64**	154·64**
$V \times$ sex	3, 16	6·87**	0·25
Angle (A)	2, 17	69·36**	49·99**
$A \times$ sex	2, 17	10·41**	2·18
$V \times A$	6, 13	3·85**	2·61*
$V \times A \times$ sex	6, 13	4·41**	3·77**

* Significance at 0·05 level, ** significance at 0·01 level.

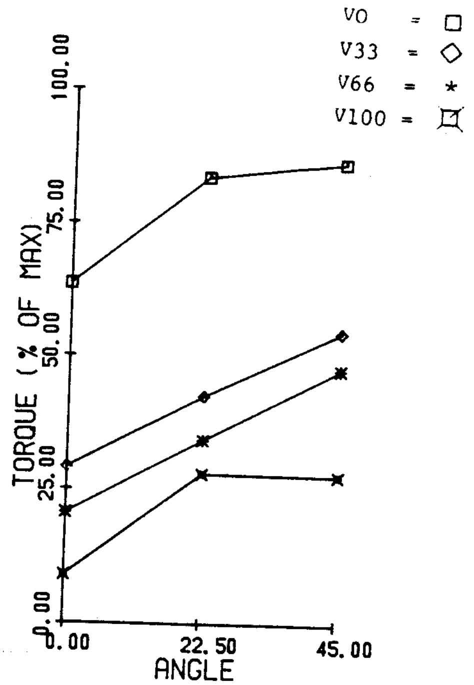

Figure 2. The torque–velocity relation as a function of trunk angle.

Table 4. Statistical significance summary for raw and normalized IAP response to velocity and angle. Values indicate F statistic.

Independent variable	d.f	IAP	Normalized IAP
Velocity (V)	3, 16	2·85*	3·93**
$V \times$ sex	3, 16	0·32	0·10
Angle (A)	2, 17	37·79**	46·75**
$A \times$ sex	2, 17	10·39**	8·25**
$V \times A$	6, 13	1·70	1·75
$V \times A \times$ sex	6, 13	1·55	1·40

* Significance at 0·05 level, ** significance at 0·01 level.

affect IAP significantly at the 0·01 level. However, when IAP was normalized, both angle and velocity exhibited a significant effect upon IAP. Angle also had a significant influence upon IAP when it was considered as a function of sex.

The nature of the relative IAP relation to the velocity and angle conditions for males and females is presented in figure 3. *Post-hoc* analyses indicated that there were significant differences between all velocity conditions except when the $V33$ and $V100$ conditions were contrasted ($p < 0·01$). The most dramatic differences are between the isometric and isokinetic conditions as shown in the figure.

A shift in time was identified between the onset of IAP and the onset of torque. The magnitude of the shift varied in direct proportion to the velocity of motion. Under very slow or isometric conditions the onset of IAP and torque was approximately simultaneous. However, as velocity increased IAP onset preceded the development of torque and the magnitude of the torque delay increased as velocity increased. The

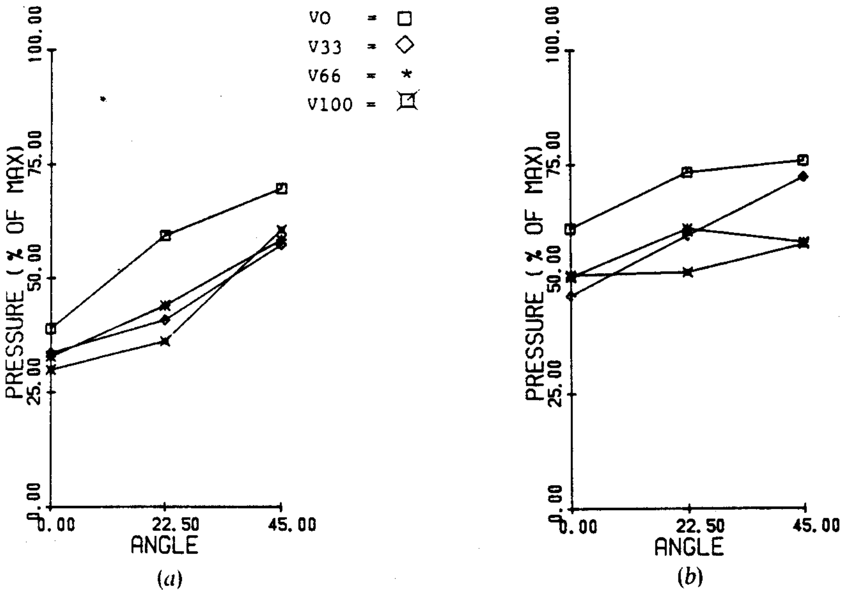

Figure 3. Intra-abdominal pressure activity of (*a*) males and (*b*) females.

magnitude of the delay under each velocity condition was statistically significant ($F = 25{\cdot}86$). Further investigations revealed a significant linear relation ($r = 0{\cdot}809$) between the IAP-torque onset delay and the actual velocity of the exertion. This correlation was slightly greater for females ($r = 0{\cdot}833$) than for males ($r = 0{\cdot}795$). When the IAP-torque onset delay was considered as a function of sex a shift in the regression relation was noted. The male data produced a regression line which was constantly greater than, yet nearly parallel to, the female regression line. Males generally exhibited greater IAP-torque onset delays even under isometric conditions. This relation is shown in figure 4.

Correlational analysis also revealed two other significant relations. First, a weak but significant linear correlation ($r = 0{\cdot}389$) was found between the IAP and the torque activity. Next, an unexpected linear correlation ($r = 0{\cdot}423$) was found between IAP and the activity of the latissimus dorsi muscles. Figure 5 shows the mean activity of the latissimus dorsi muscles compared with IAP.

4. Discussion

Many biomechanical representations of the human body are used to evaluate the strain experienced by the spine during lifting activities. These representations usually consist of a stick figure which is linked together at five or six points representing the major articulations of the body. This process permits the evaluations of moments acting at these major articulations. One of the most crucial links that is evaluated via these methods is that between the back and hips (L5/S1). This region is of interest because many of the lifting related injuries occur at this point. It is also the primary point of sagittal motion in the spine. In this experiment an isokinetic dynamometer was used to control the velocity of motion at L5/S1. The dynamometer did not induce a load on the subject, instead the subject used his back to push against the dynamometer lever arm. It was believed that this procedure would test the capabilities of the back link in certain lifting situations.

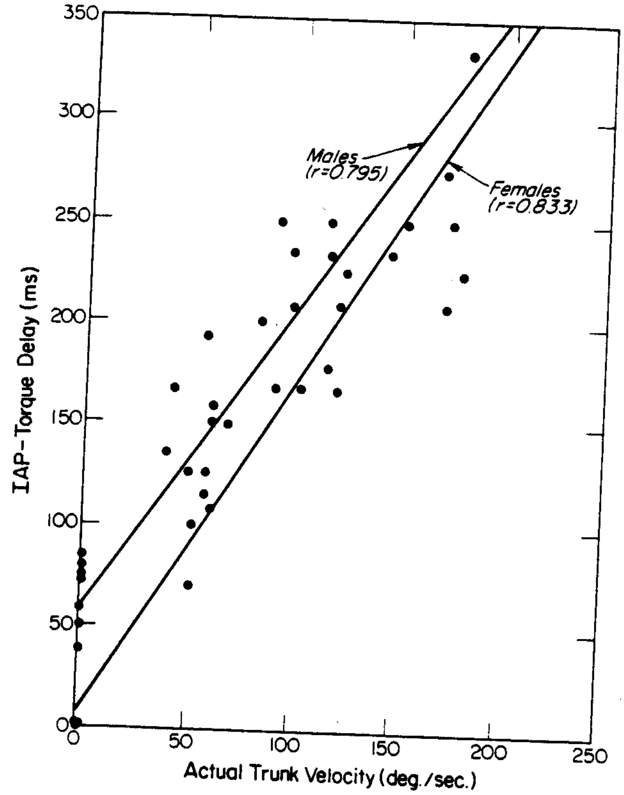

Figure 4. The IAP-torque delay as a function of the actual velocity of trunk motion. The differences in regression lines indicates the greater delay by males than females.

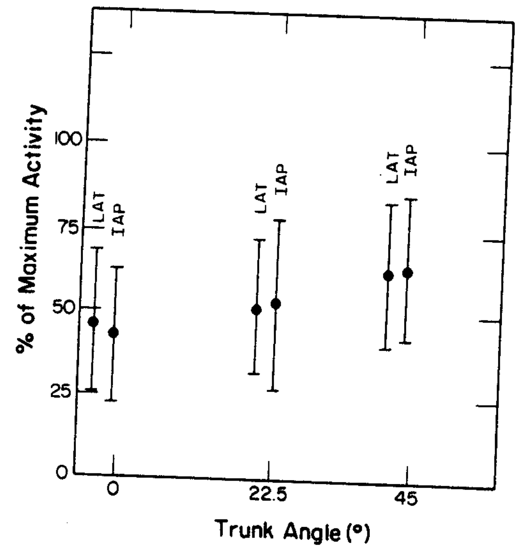

Figure 5. Mean and standard deviation of latissimus dorsi muscle and IAP activity as a function of trunk angle.

A review of the experimental results show similarities with other reported lifting data. First, the IAP signal characteristics were similar to those found by other researchers while investigating actual lifts. Snatch pressures followed by the typical rapid fall to pressures above the resting level can be seen when subjects exerted force upon the dynamometer. Next, the torque exerted by the back during this experiment throughout the angle range is similar to back loadings observed by others in unrestrained static positions (Andersson *et al.* 1976, 1977). There are also some obvious differences between this experiment and an actual lift. First, all motion in this experiment occurred at the back and not a combination of back and leg/hip motion as occurs during actual lifting from a low level. The experimental task would be similar to lifting from waist level at a distance. This situation would be similar to some industrial environments where workers must lift from an assembly line. Next, the use of isokinetic motion in this experiment has eliminated acceleration (except for an initial build-up period) which would be present during unrestrained lifts. However, this assumption of a smooth lift has been frequently used by many who have attempted to evaluate the workplace (i.e. lifting guides (NIOSH 1981)).

The experimental procedure employed here permitted the evaluation of the force–velocity characteristics about L5/S1 and the influence of IAP. The back extension force–velocity relation was similar to that described by Thorstensson *et al.* (1976) for knee extension. Substantial differences in the amoung of torque one is able to produce under static and dynamic conditions was observed. At any given angle of back flexion the torque produced was greater for isometric than for isokinetic efforts. However, as the angular velocity increased, the torque decreased. Figure 1 indicates a relatively large reduction in torque (over 35%) from the isometric condition occurs when even a small amount of motion is introduced into the experimental condition (*V*33). Thereafter, equal increases in angular velocities result in moderate decreases (8–12%) in torque. These findings suggest that the introduction of motion into a lifting task dramatically reduces the worker's ability to support the load. However, classical physics would suggest that in actual lifting situations motion (and thus acceleration) increases the moment experienced by the spine (since force is proportional to mass times acceleration). Therefore, existing lifting guidelines based solely upon static evaluation of the spine would greatly underestimate the stresses induced upon the vertebral column during lifting.

Figure 2 also indicates that the torque production capabilities of the back are greater at increased back angles. This is particularly true under the *V*33 and *V*66 experimental conditions. This finding may also have implications in manual materials-handling applications. It would appear that a person would be more able to lift a load if the back were at a slight angle while still keeping the load close to the body since there is more available torque. This is contrary to the findings of Davis and Troup (1964) and Eie (1966) who advocated keeping the back vertical.

The results indicate that IAP responded to changes in angle much more so than changes in velocity except when changes between the general categories of static and dynamic exertions were considered. However, the influence of IAP during lifting situations may not be obvious via the statistical analysis since a torque–IAP onset delay was noted. In many high-velocity test conditions, the IAP had terminated before the torque production began. Hence, the onset delay may indicate a preparatory response of the abdominal cavity which is involved in overcoming the trunk's inertia of rest. These facts suggest that the biomechanical significance of IAP may be related to the management of trunk acceleration. Davis and others have suggested that the peaks of IAP may be related to acceleration. However, the IAP–torque onset delay identifi here may also be an indicator of trunk acceleration. These facts clarify the role of IAP, the support of trunk load. Previous reports have suggested that IAP helps suppo trunk load. This study suggests that the support occurs in response to acceleratio during the motion phase of a lift. This acceleration support in turn reduces vertebr stress (since $F = m \times a$) and thus trunk load.

There also seems to be significant differences in the manner in which males and females used IAP. Females generated much greater IAP in erect postures. Fur thermore, females were found to have less of an IAP–torque delay which is particularly apparent under slower velocity conditions. This is seen via the differences in the regression lines for males and females in figure 4.

Previous studies have been unable to identify a source of IAP, however, many have speculated that it may be due to the activity of the abdominal musculature. This research has identified a statistically significant correlation between the IAP and the activity of the latissimus dorsi musculature. It appears that this muscle pulls the chest downwards, thereby applying pressure to the abdominal contents. This association may be even greater if the phase of onset of IAP and torque could be analysed more closely. No significant correlation was found between IAP and the contraction of the rectus abdominus, external oblique or internal oblique musculature in this study. This IAP–latissimus dorsi relation may help explain previous findings in the literature. Much of the activity influencing IAP described by Davis and Troup (1964) and Eie (1966) may be explained by considering the activity of the latissimus dorsi muscles.

5. Conclusion

In conclusion, use of an isokinetic dynamometer appears to be a valid and realistic method of investigating the force–velocity relation of the low back. Torque production decreased as velocity increased and trunk angle decreased. IAP was found to be primarily a function of trunk angle and a weak but significant indicator of the torque exerted by the back.

IAP–torque onset time discrepancies have been identified which is believed to be an indicator to the degree of acceleration needed to move the trunk. This suggests that the greatest biomechanical advantage of IAP may be in the management of trunk acceleration forces which occur prior to any exertion of torque with the back.

Une expérimentation a été effectuée pour tester les capacités statiques et dynamiques du dos lors du levage. Vingt sujets masculins et féminins ont exercé la force maximale avec le dos dans des positions de levage isométriques et isocinétiques. Le moment de torsion à la jonction sacrolombaire, ainsi que la pression intra-abdominale (IAP) ont été évalués au cours de l'expérience. On a trouvé que le moment de torsion augmentait avec l'angle du tronc et diminuait avec la vitesse angulaire. L'IAP était avant tout une fonction de l'angle, mais un faible indicateur du moment de torsion. Une augmentation significative dans le délai de réponse IAP-moment peut être considérée comme étant à l'origine de l'IAP.

Eine Untersuchung zur Ermittlung der statischen und dynamischen Fähigkeiten der Kraftausübung des Rückens beim Heben von Lasten wurde durchgeführt. Zwanzig gesunde männliche und weibliche Versuchspersonen übten maximale Rückendräfte unter isometrischen und isokinetischen Bedingungen beim Heben. Das auf den lumbosacralen Bereich wirkende Biegemoment und der intraabdominale Druck (IAP) wurden unter Versuchsbedingungen registriert. Die Fähigkeit zur Ausübung eines Biegemoments nahm mit dem Rumpfwinkel zu und fiel mit ansteigender Winkelgeschwindigkeit. Der IAP wurde vorwiegend als eine Funktion des Rumpfwinkels und als eine schwache Einflußgröße des Biegemomentes identifiziert. Eine signifikante Verzögerung der Anfangsbeziehung zwischen dem IAP und dem Biegemoment sowie die physiologischen Ursachen des IAP wurden ermittelt.

腰の静的及び動的持上げ能力を調べるために実験を行った。健康な男女被験者20名に対し，等尺性及び等運動性の持上げ状態で腰を用い最大力を発揮させた。腰仙連結のまわりのトルクと腹腔内圧（IAP）を実験条件下で測定した。トルクの発生能力は体幹の角度の増加とともに増し，角速度の増加とともに減少することがわかった。腹腔内圧は主として角度の関数となり，またトルクの弱い指標となることがわかった。腹腔内圧とトルクの発生の遅延は腹腔内圧の生理学的な原因にあると同定された。

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