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INTRA-ABDOMINAL PRESSURE AND TRUNK MUSCLE ACTIVITY DURING LIFTING

IV. *The Causal Factors of the Intra-abdominal Pressure Rise*

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ABSTRACT. The intra-abdominal pressure (IAP) has been regarded as important for stabilization and relief of the lumbar spine when exposed to heavy loads, such as when lifting. Previous trials, however, have failed to increase the IAP by abdominal muscle training. Twenty healthy subjects, 20 low-back patients and 10 weight-lifters, were tested with various breathing techniques in order to elucidate the causal factors of the IAP rise during lifting and the effects respiration. Those with high IAP and low IAP as well as those with great variations in IAP underwent an extended program. The intra-abdominal and intrathoracic pressures and the EMG of the oblique abdominal, the erector spinae and—in some cases—the puborectalis muscles, were recorded. The transdiaphragmatic pressure was calculated both during lifting and during the Mueller manoeuvre. The IAP rise during lifting seems to be correlated to a good coordination between the muscles surrounding the abdominal cavity. Of these, the diaphragm seems to be the most important for the IAP level. Closure of the glottis seems to help the diaphragm to maintain the IAP rise, otherwise the respiration type seems to be less important for the IAP during lifting.

Key words: low back pain, intra-abdominal pressure, electromyography, respiration, prevention

The intra-abdominal pressure (IAP) has been regarded as important for the function of the lumbar spine. It is believed to stabilize the trunk and relieve the lumbar spine when carrying out heavy tasks, such as lifting (2, 4, 6, 7, 9, 10, 15, 16, 25, 26, 31, 36). As regards the building up of the IAP, interest has been focused on the anterior abdominal muscles which are thought to initiate the pressure rise, except for the rectus abdominis which remains inactive during lifting of small or moderate weights. Recent investigations (18, 20, 29) showed, however, that strenghening of the abdominal muscles did not generally affect the IAP during lifting. Moreover, the oblique abdominal muscles seemed to be of minor importance for the IAP in those situations (18, 20). Thus it seemed desirable to elucidate the factors responsible for the IAP during lifting, in order to find possible ways of preventing low-back pain.

The abdominal cavity, containing mainly liquid and semisolid material, is surrounded by muscles, anteriorly by the rectus abdominis, laterally by the external and internal oblique abdominal muscles and the transversus abdominis, above by the diaphragm and below by the muscles of the pelvic floor. The dome-shaped diaphragm divides the abdomen from the air-containing thorax. The transdiaphragmatic pressure difference (P_{di}) reflects the tension and the position of the diaphragm and may be used to estimate the part played by the diaphragm in the building up and maintenance of the IAP.

When lifting heavy burdens, most people, even weightlifters, breathe in and hold their breath. There are, however, no systematic studies on the effects of different breathing techniques on the intrathoracic (ITP) and intra-abdominal (IAP) pressures and hence on the stability of the trunk during lifting.

The aim of this study was to analyse first the effects of respiration on the IAP during lifting, and secondly, the activation pattern of muscles possibly involved in the initiation and maintaining of the increased IAP during lifting.

MATERIAL

Fifty male volunteers took part in different sections of this study. Twenty subjects had no history of low-back pain, as previously described (18). Twenty subjects with chronic low-back pain were described in part II. The last 10 subjects were very skilled weightlifters, who had been training for 2–12 years (median value 6.5 years). Three of them were national champions in their own weight classes. Three weightlifters reported previous minor low-back complaints of short duration and 2 had intermittent low-back pain for 1–3 years, but not during the year before the examination. All the weightlifters generally

Table I. *Characteristics of the subjects*

	Healthy subjects	Low back patients	Weight-lifters
Number	20	20	10
Age (years)			
mean	28	32	23
range	23–33	22–37	18–28
Height (m)			
mean	1.80	1.80	1.74
range	1.71–1.87	1.74–1.88	1.61–1.88
Weight (kg)			
mean	75	76	80
range	65–85	57–89	58–123
Trunk flexion strength (N)			
mean	721	549	850
range	136	114	269
Trunk extension strength (N)			
mean	859	821	1 091
range	130	166	277
Duration of low-back pain (years)			
median	–	5.5	(*)
range	–	2–18	
Duration of weight lifting (years)			
median	–	–	6.5
range	–	–	2–12

* See text.

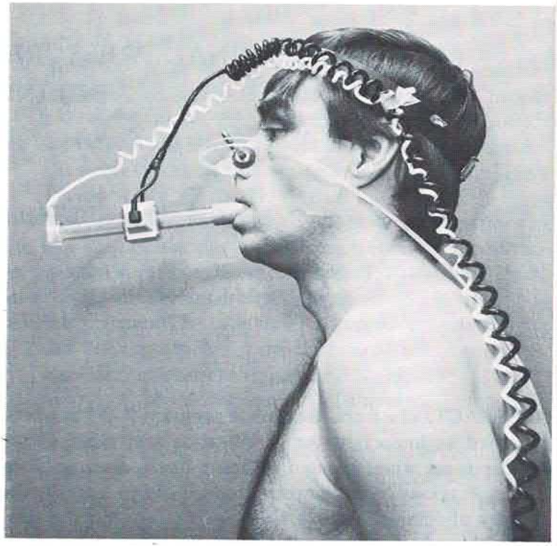

Fig. 1. The respiration recording system. The ultrasound unit is located on the middle of the tube and the thermistor in the distal opening. Note the spring-holder on the nose and the catheters for the pressure recordings.

used a leather belt for the heaviest training and at competitions.

Table I states the age, height and weight of all the subjects and also the strength of the trunk flexors and of the trunk extensors recorded by strain-gauge in the upright position as previously described (19).

METHODS

Electromyographic recordings

For the oblique abdominal muscles and the erector spinae muscle the myo-electrical activity was recorded by surface electrodes (for details, see part II).

In addition, 3 healthy subjects were supplied with wire electrodes for the puborectalis muscle, that is insulated bipolar fine-wire electrodes (Nikrotal LX, 0.05 mm in diameter) from which about 3 mm of the insulation was burnt off in a flame. They were prepared according to Basmajian (3), with the modification that the two electrodes were inserted with two separate carrier needles. Guided by an index finger in the ampulla recti the two needles, dorsolaterally from the anus, were pushed through the ischiorectal fossa to, but not into, the puborectalis muscle, the most prominent part of the levator ani muscle. After withdrawal of the needles, the two hooked and bared wire ends were located close to the lower margin of the muscle, about 1 cm apart. By spring-wire coil connectors (3) and screened cables, the electrodes were connected to preamplifiers fastened to the subject's waist.

Intra-abdominal and intrathoracic pressure recordings

The intra-abdominal (i.e. intra-gastric) pressure was recorded in all cases, and the intrathoracic (i.e. intra-oesophageal) pressure in the patients, the weightlifters and the 3 healthy subjects, mentioned above.

The pressures were recorded via an open polyethylene catheter filled with saline and without a balloon, as previously described (18, 19). The three fine polyethylene catheters (Portex 100, internal diameter of 0.86 mm), fused distally, were passed through the nose to the upper part of the stomach. The pressure changes during respiration indicated when the opening at the lower end rested in the stomach, and the second opening 25 cm proximally rested in the eosophagus. The third catheter contained air and served only as a guide. The pressure curves were recorded simultaneously with the myoelectrical signals on the mingograph and the tape, and the catheter was flushed with saline when necessary.

The pressure recording system was tested according to Asmussen, Lindström & Ulmsten (1). The rise time was found to be 0.015 s, the settling time 0.1 s and the overshoot 26% in repeated recordings, which was considered adequate for analysis of the frequencies occurring.

From X-ray films taken during pressure recordings we calculated the source of error due to the external location of the transducer and corrected the pressure values accordingly.

Table II. *Types of breathing technique studied and different modes of analysing the IAP during lifting; figures to the left refer to the text*

	Healthy subjects		Low-back patients		Weightlifters	
	No. of subjects	No. of lifts	No. of subjects	No. of lifts	No. of subjects	No. of lifts
1 Lifts after max. inhalation	20	80				
2 Lifts after max. exhalation	20	80				
3 Lifts during exhalation without facilitation			20	160	10	40
4 Lifts after exhalation with facilitation	20	160				
5 Lifts with natural respiration technique	20	160	20	160	10	40
6 Lifts with recording of respiration			20	80	10	80
7 Lifts with recording of respiration and EMG from the puborectalis muscle	3	54				
8 Lifts with great IAP variations within or between subjects			3	36	5	69
9 Peak IAP during lifting in relation to $P_{\mathrm{di\,max}}$ during the Mueller manoeuvre			20	120	10	60

Respiration recording (Fig. 1)

A new flow-meter was constructed for recording the respiratory flow without motion artefacts (Bengt Månsson, BN Elektronik, Åhus, Sweden). It is based on the vortex principle and consists of a tube, a mouthpiece, an ultrasound unit and a thermistor. Inside the tube, on either side of the unit, is a triangular shaped pole that converts the straight air flow into a turbulent one. The turbulence is detected by ultrasound across the tube, and the result will be a pulse frequency proportional to the air flow. The thermistor tells whether the air is passing in or out, and the signals from the ultrasound unit give the volume passed per time unit by integration.

The lifts

Lifts were done with 'leg lifting' as well as 'back lifting'. 'Leg lifting' means symmetric lifts with flexed knees and the back as straight as possible. 'Back lifting' is used when lifting with knees straight and back flexed. The lifts were carefully standardized and checked by a physiotherapist and with an accelerometer, an electrogoniometer, two switches, and with Super-8-film or videotape, as previously described (18, 19).

The examination procedure

Table II lists the different lifts included in this study.

One part of this investigation dealt with the effect of different breathing techniques. These lifts are compared to the corresponding lifts performed without any instruction about respiration.

1. After inhaling maximally the healthy subjects held their breath and lifted 25 kg with leg lifting and with back lifting.
2. After a maximal exhalation the healthy subjects held their breath and lifted 25 kg with leg lifting and with back lifting.
3. During exhalation the patients lifted 10 kg and 25 kg and the weightlifters 40 kg, all loads with leg lifting as well as back lifting.
4. The healthy subjects lifted 25 kg and 40 kg with back lifting as well as leg lifting using a special technique, suggested by Lewit (30) to facilitate the abdominal muscles. The subjects started with a maximal inspiration. They then rose on to their soles, and sank down on to the soles again at the same time as, during expiration, they bent forward to take the box. The lift itself was then performed with their natural breathing technique.
5. All the lifts above were done by the same subjects with the same lifting technique, except for the breathing instructions or facilitation movements.

The second part of this investigation was intended to analyse the various causal factors of the IAP rise during lifting.

6. The patients lifted 25 kg and the weightlifters 40 kg with leg lifting as well as back lifting, while we recorded their natural breathing techniques.
7. Three healthy subjects, who were found to be 'high pressurizers' or 'low pressurizers' in a previous study, were asked to lift 25 and 40 kg with leg lifting and back lifting, and while actively trying to contract the pelvic floor muscles.
8. In a simultaneous study of the effect of abdominal muscle training, previously described (20), we found 3 low-back patients who showed great differences of IAP after training, in contrast to the average effect. They offered a possibility to study variations in patterns of muscular activation and their leg lifts of 25 and 40 kg and their back lifts of 40 kg were included in this study. The same holds true for 5 of the weightlifters who showed interesting variations in leg lifts with 40 and 55 kg and in back lifts with 40 kg.
9. The patients and the weightlifters performed the Mueller manoeuvre (12, 34), before and after the ab-

dominal muscle training mentioned above. On each occasion, three consecutive tests were performed. After an ordinary expiration, when the subject was supposed to be roughly at the position of functional residual capacity (FRC), he was asked to perform a maximum diaphragmatic inspiratory effort with the mouth and nose closed. Before this, the subjects had, during attempted inspiration, practised pushing the abdominal wall outwards and avoiding rib cage expansion. The maximum transdiaphragmatic pressure ($P_{\mathrm{di\,max}}$) during the Mueller manoeuvre was then compared with the peak IAP during lifting.

Fig. 2 summarizes the methodology used in this study. With the healthy subjects in moments 1, 2, 4, and 5 the computer was omitted. Table II shows when the respiration system and the EMG of the puborectalis muscle were used.

Evaluation procedure, including statistical methods

Throughout the study all lifts were performed twice and the calculations were made from the mean values of these two lifts.

For the healthy subjects during moments 1, 2, 4, and 5 the signals were recorded with the Mingograph. From these curves we calculated manually the peak IAP and the values of the integrated EMG during 0.3 s coincidentally with the peak.

For the rest of the lifts, the analogue signals from the EMG of the oblique abdominal and the erector spinae muscles, from the IAP and ITP, from the electrogoniometer and from the accelerometer were simultaneously recorded on magnetic tape. The same applied to the EMG of the puborectalis muscle and the respiration recording, whenever applicable. All information was then fed into a computer where the myoelectrical signals were full-wave rectified and integrated over preset periods of 0.1 s, each containing 400 readings. The other signals were all averaged over the same periods of 0.1 s and converted digitally. The registrations comprise the periods from 0.5 s before the lift-off to the end of the lifting and from the start of the lowering to 0.5 s after the touch-down.

During the Mueller manoeuvre we recorded the maximum transdiaphragmatic pressure ($P_{\mathrm{di\,max}}$ = [IAP–ITP]$_{\mathrm{max}}$).

Concerning moments 1, 2, 4, and 5, the design of the study was chosen to get a matching situation where each subject could be compared with himself while performing a certain lift with and without modification. Here the analysis of significance was performed with the IAP and EMG values according to Student's *t*-test, and the strength of covariance was determined by Pearson's correlation coefficient, *r*. This also applies to moments 6 and 9 as regards the calculations.

Concerning moments 3 and 5, the analysis of significance was extended and carried out throughout the whole lifting procedure by calculating the 95% confidence limits of the mean difference between values with and without modification of the lifts. As the time varied between lifts, the time was then normalized and expressed as a percentage of the whole time, and for lifting and lowering separately, it runs from 0 to 100%.

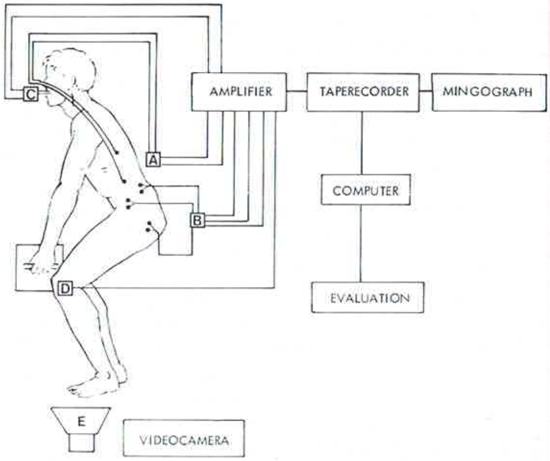

Fig. 2. Schematic view of the methods used in this study. For details, see text. *A*, Pressure recording system; *B*, EMG recording system; *C*, respiration recording unit; *D*, electrogoniometer; *E*, video camera.

Concerning moments 7 and 8, each separate lift was plotted to determine the mutual relationship between the parameters in case. The time was normalized here too, as described above.

RESULTS

Effects of breath holding after maximal inspiration

Maximal inspiration before, followed by breath holding during lifting, did not affect any of the three parameters, either the peak IAP or the myoelectrical activities of the oblique abdominal muscles and the erector spinae muscle during 0.3 s coincidentally with the peak (Fig. 3).

The average lifting times varied very little, 0.06 s out of the average lifting times of 1.78–1.94 s. The same applied to the times when the IAP and the myoelectrical activities of the oblique abdominal, and the erector spinae reached their highest values during the lifts.

Effects of breath holding after maximal expiration

Fig. 3 shows that this type of breath holding did not affect any of the three parameters significantly. Neither the total lifting times, nor the times of peak values were influenced materially.

Effects of breathing out during lifting

The intra-abdominal pressure decreased significantly during 30% of the lift time with leg lifting of 25

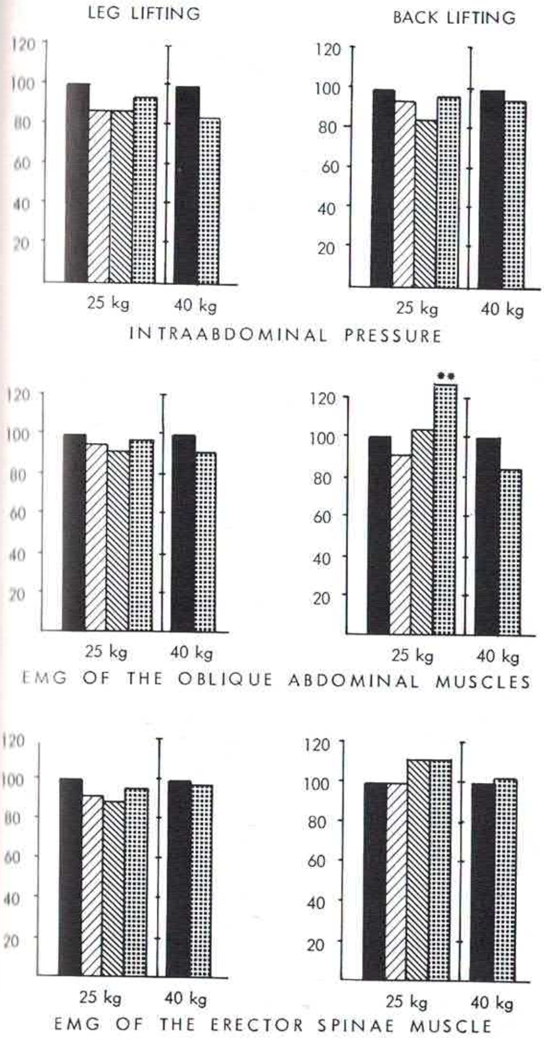

Fig. 3. Effect of different breathing techniques on the peak IAP (*upper graphs*), the EMG of the oblique abdominal muscles (*middle*), and the EMG of the erector spinae muscle (*lower*). The myoelectrical activities refer to the period of 0.3 s around the peak IAP. The average values are expressed in percentages of the corresponding average values when the subjects lift with their own natural breathing technique. ■, lifting with natural breathing technique; ▨, lifting during breath holding after maximum inhalation; ■, lifting during breath holding after maximum exhalation; ▦, lifting after exhalation with facilitation. ** $p<0.01$. All other differences: NS.

kg. In all other instances with 10, 25, and 40 kg, lifting as well as lowering, there were no significant changes vis-à-vis lifting with natural breathing.

The intrathoracic pressure decreased significantly during lifting and lowering with 40 kg, both leg lifting and back lifting. The average differences were 3–4 kPa. For the lifts of 10 and 25 kg there were no significant changes, but a tendency towards lower values in some instances.

The myoelectrical activity of the oblique abdominal muscles increased significantly during the last phase of lifting with 25 kg (leg lifts and back lifts), but otherwise there was no change in any instance.

The myoelectrical activity of the erector spinae muscle was quite unaffected in all instances, lifting or lowering, leg lifting or back lifting, irrespective of the weight of the burden. The patterns of activation, as reflected by the average curves, were quite unaffected by expiration.

Effects of facilitation

The next question is whether the proposed facilitation manoeuvre adds anything to the above. These lifts were examined by the same methods as moments 1 and 2.

Fig. 3 shows that the peak IAP was quite unaffected in all instances. The average activity of the oblique abdominal muscles was significantly increased with back lifting 25 kg, but in all other instances the muscular activity around the peak IAP was not significantly affected.

The average lifting times were not significantly changed by the facilitation technique, which was easy to learn and use. Nor did the times for the maximum IAP and myoelectrical activity alter markedly.

Natural breathing during lifting

In 160 lifts by both patients and weightlifters we recorded the subjects' natural breathing. After familiarizing themselves with the apparatus, that forced them to breathe through the mouth but offered no noticeable resistance, they were asked to lift in their usual manner.

Table III shows how the two groups breathed naturally. For 20–45% of the cycles they held their breath. For the rest of the cycles they seemed most commonly to exhale when lifting and inhale when lowering. Some started by holding their breath and then changed to breathing in or out during movements; others began to inhale or exhale before lifting or lowering. The weightlifters often seemed to take deeper breaths than patients.

It seems clear from all curves that breathing during lifting is inconsistent with a positive intrathoracic pressure.

Table III. *Natural breathing during lifting and lowering, expressed as volume of air passed trough the respiration tube from the lift-off to the end of lifting and from the start of lowering to the touch-down; number of lifts within parentheses*

	Low-back patients 25 kg		Weightlifters 40 kg	
Volume of air	Lifting (%)	Lowering (%)	Lifting (%)	Lowering (%)
<0.1 litres	45	36	27	20
Inhalation				
0.1–0.8 l*	17	50	0	47
>0.8 l	0	0	2	13
Exhalation				
0.1–0.8 l*	38	14	62	20
>0.8 l	0	0	9	0
Total	100 (69)	100 (50)	100 (56)	100 (40)

* In a few isolated cases the subjects breathed in and out a little during the lifting or lowering. The table then shows the net volume of air passing the tube.

For both patients and weightlifters who breathed during lifting, there was no definite correlation between the breathing volumes and the intrathoracic pressure. Nor was there any significant correlation between the breathing volumes and the peak intra-abdominal pressures, either for the patients or for the weightlifters.

The Mueller manoeuvre

The patients could produce an average maximal transdiaphragmatic pressure of 10.4 kPa (SD=4.23) and the weightlifters 8.3 kPa (SD=4.09). The test showed fairly good reproducibility in repeated trials with the same subject (SD=1.88 and 2.27 kPa respectively for the patients and the weightlifters).

The Mueller manoeuvre is regarded as a test of the strength of the diaphragm (12, 34), and it was therefore interesting to try the correlation between the $P_{\mathrm{di\,max}}$ and the peak IAP during different lifts. Table IV shows that for the patients there was a positive correlation, significant in nine out of twelve instances. For the weightlifters we could find no correlation in any of the lifts with 25 and 40 kg.

Building up of intra-abdominal pressure during lifting

From the lifts noted under moments 7 and 8 in Table II we tried to analyse the possible effects on

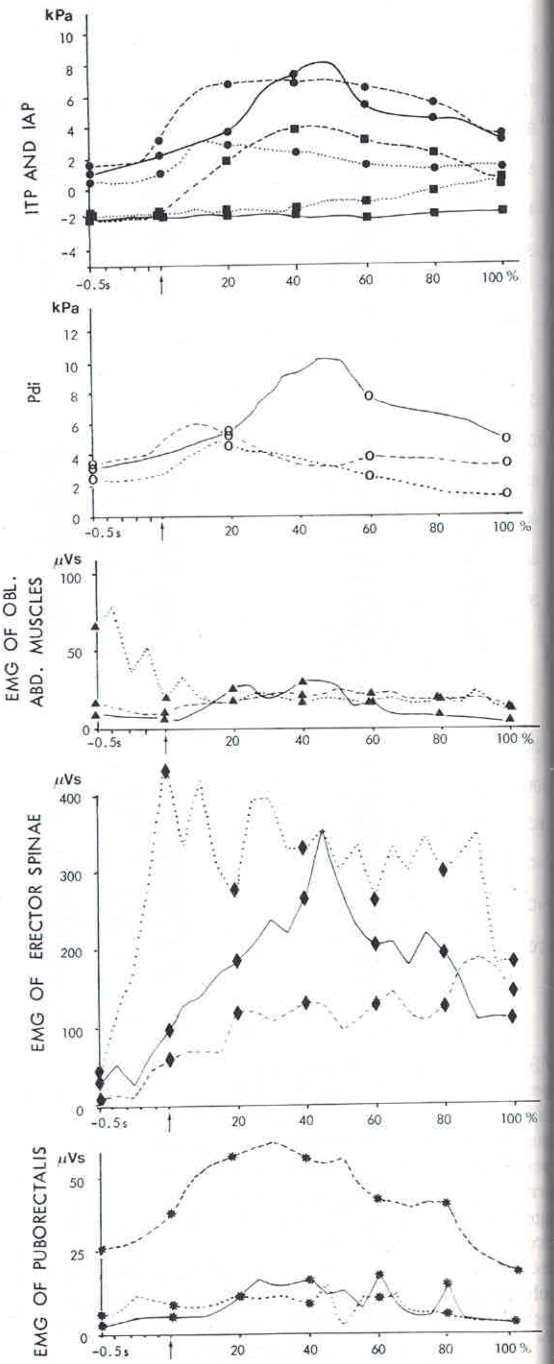

Fig. 4. Graphs illustrating 3 healthy subjects performing a leg lift with 25 kg. The top graph gives IAP (●) and ITP (■), then in descending order the transdiaphragmatic pressure difference (P_{di}), the EMG of the obl. abd. muscles, the EMG of the erector spinae muscle, and the EMG of the puborectalis muscle. All three lifts start at ↑ and end at 100% (of the lifting time). Prior to ↑ time denotes in absolute values. Subject A: ——; Subject B: - - -; Subject C: · · · ·. For further explanation, see text.

Table IV. *Correlation between the maximum transdiaphragmatic pressure ($P_{\mathrm{di\,max}}$) during Mueller manoeuvre and the maximum intra-abdominal pressure (peak IAP) during lifting*

		Patients				Weightlifters			
		Lifting		Lowering		Lifting		Lowering	
Lifting technique	Weight (kg)	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Leg lifting	10	0.45	<0.05	0.49	<0.05				
	25	0.52	<0.05	0.52	<0.05	−0.28	NS	−0.31	NS
	40	0.31	NS	0.48	<0.05	−0.36	NS	−0.54	NS
Back lifting	10	0.35	NS	0.38	NS				
	25	0.56	<0.01	0.50	<0.05				
	40	0.61	<0.01	0.60	<0.01	−0.07	NS	−0.09	NS

the IAP of the different muscles surrounding the abdominal cavity. This is complicated by the possibility that the muscles may well contract so as to increase the pressure but may also contract due to an increased pressure from within. We then have to consider the timing of the different activities during lifting.

The activity of the diaphragm can be judged by following the transdiaphragmatic pressure difference.

From about 140 graphs illustrating lifts with 25, 40, and 55 kg by the three groups, we tried to analyse the interplay between the diaphragm, the oblique abdominal muscles, and the puborectalis muscle during lifting, and the relationship between them and the IAP.

Fig. 4 shows three different subjects doing the same lift with different patterns. Figs. 5 and 6 each show a pair of graphs from one subject lifting the same load before and after abdominal muscle training with the same technique but with different muscular responses and pressures. The results of the analysis may be summarized as follows.

(*a*) The important function of the *diaphragm* is reflected by the close correlation between the transdiaphragmatic pressure difference (P_{di}) and the peak IAP during lifting (Table V). This correlation could also be shown throughout the lift in many instances, as can be seen in Figs. 4 (subject A), 5 *b* and 6 *b*.

(*b*) The *oblique abdominal muscles*. The myoelectrical activity showed that they were regularly activated during lifting. The activity rose sometimes simultaneous with the pressure rise (Figs. 5 *b*, 6 *b*), sometimes without any pressures response (Fig. 5 *a*).

(*c*) The *puborectalis muscle*. The myoelectrical activity showed that it was regularly activated during lifting (Fig. 4), but the rise in activity varied among the 3 subjects. In subject B the rise in activi-

Table V. *Relation between peak IAP during lifting and the co-incident transdiaphragmatic pressure difference (P_{di})*

The weightlifters did not lift 25 kg with backlifting

		Patients				Weightlifters			
		Lifting		Lowering		Lifting		Lowering	
Lifting technique	Weight (kg)	*r*	*p*	*r*	*p*	*r*	*p*	*r*	*p*
Leg lifting	25	0.90	<0.0001	0.82	<0.0001	0.97	<0.001	0.92	<0.05
	40	0.90	<0.0001	0.84	<0.0001	0.91	<0.001	0.95	<0.001
Back lifting	25	0.83	<0.0001	0.85	<0.0001	–	–	–	–
	40	0.91	<0.0001	0.88	<0.0001	0.97	<0.001	0.86	<0.01

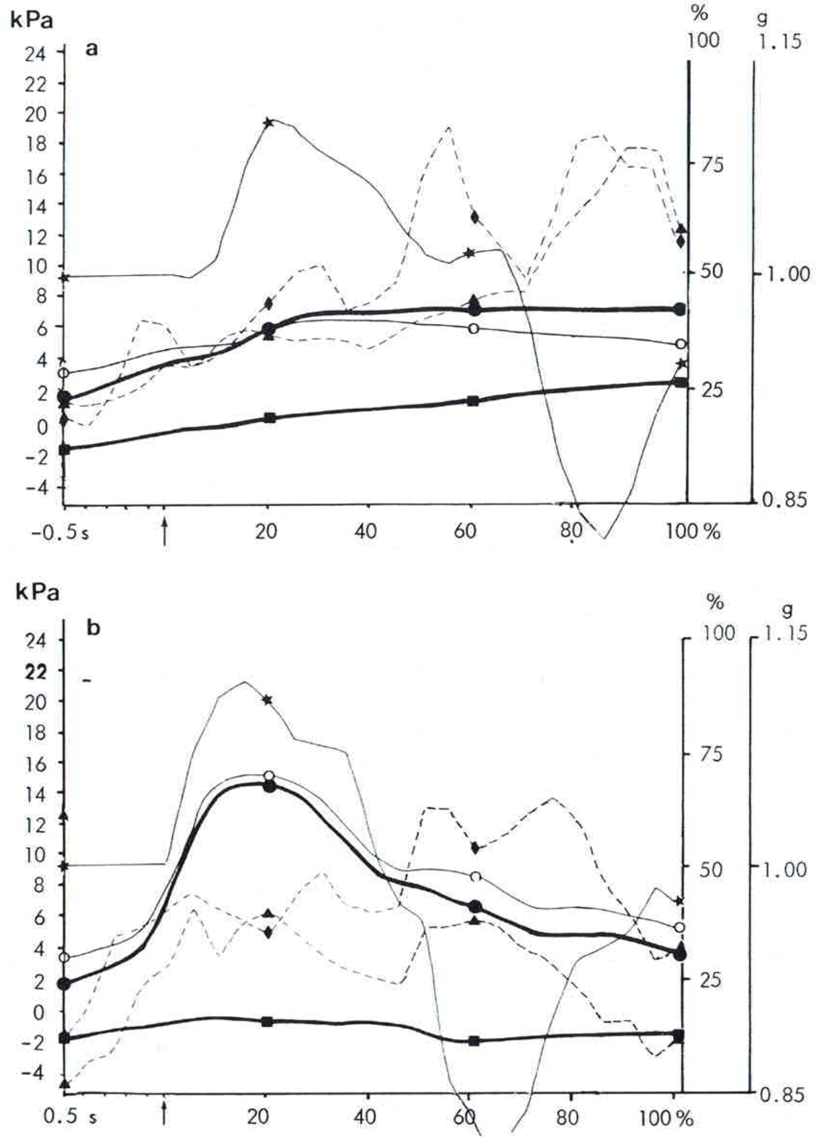

Fig. 5. Patient D lifting 40 kg with leg lift before (*a*) and after (*b*) 5 weeks of isometric abdominal muscle training. ↑ denotes the lift-off. Prior to that point is 0.5 s in absolute values, while the lifting time is normalized and expressed in percentages of the whole time (from 0 to 100 %). IAP, ITP and P_{di} are expressed in absolute values (*left scale*). EMG activity is expressed in percentages (*right scale*) of the highest value registered at any of the four lifts performed by the same subject with the same technique and with the same weight. The activity level is thus comparable between Fig. 5*a* and 6*b*. IAP: ●–●. EMG obl. abd. m.: ▲---▲. ITP: ■—■. EMG erector spinae m.: ⧫---⧫. P_{di}: ○—○. Acceleration of the box ★—★ (second right scale).

ty coincided with the lift-off, and the pressure rose early in the lifting. In subject A the rise of activity came after 10 % of the lifting time, and the pressure rose gradually during the first 50 % of the lifting time. In subject C there was a rather weak activity and only a small pressure rise. During lowering, the activity was generally lower than during lifting.

When asked to contract the pelvic floor muscle deliberately during lifting, the 3 subjects differed in activity. Subject B increased his previously high activity and his peak IAP rose from 7.4 to 18.6 kPa

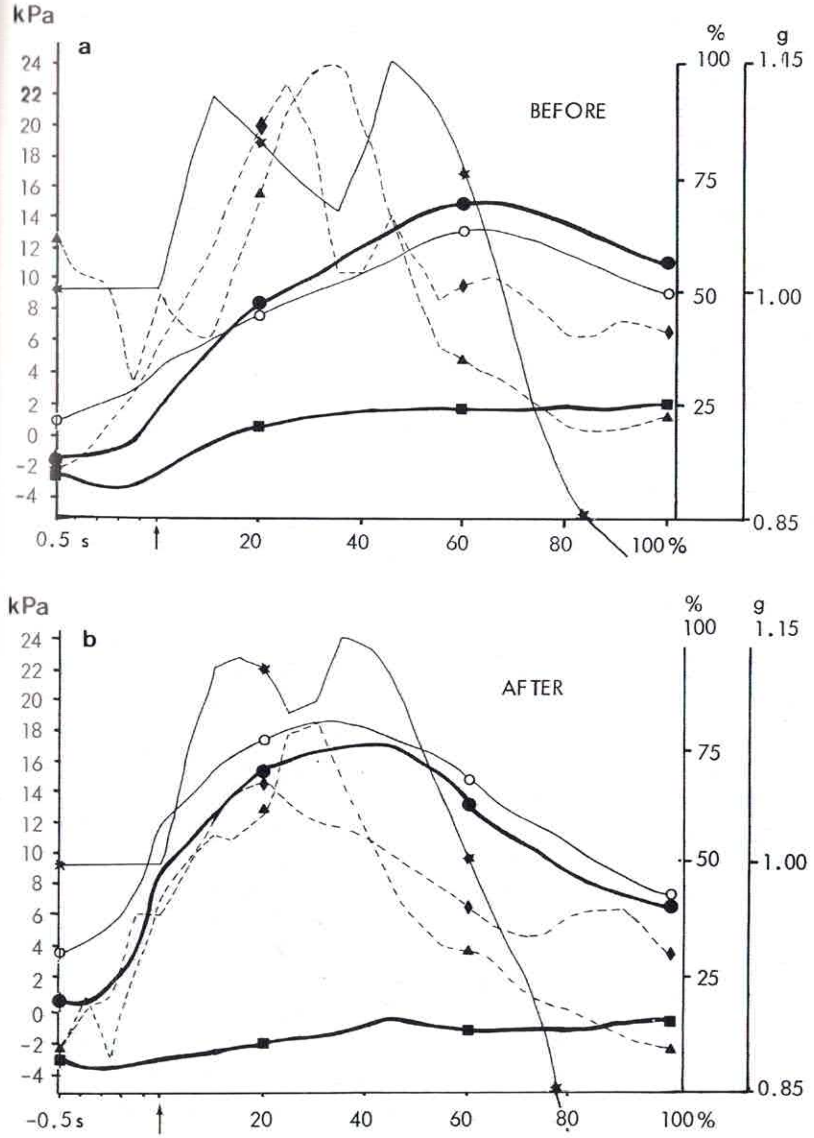

Fig. 6. Weightlifter F lifting 55 kg with leg lift before (*a*) and after (*b*) 5 weeks of isometric abdominal muscle training. For explanation, see Fig. 5.

during lifts of 25 kg, despite the facts that the lift was otherwise unchanged and the acceleration of the box was reduced. When subject A was asked to lift while contracting the pelvic floor muscles deliberately, he increased the activity of the oblique abdominal muscles instead and the peak IAP rose from 8.5 to 11.7 kPa. Subject C, on the other hand, activated both the puborectalis and the oblique abdominal muscles, but there was no increase in the IAP.

It should also be mentioned that there was no detectable activity at rest, whether standing or sitting (sensitivity 125–250 μV/cm). This was also usually true for the instances when the subjects were standing upright with the load in front of the body. On the other hand, the muscle was always activated during trunk muscle strength tests and during the Valsalva and the Mueller manoeuvres.

(*d*) The *intrathoracic pressure* showed great individual variations (Fig. 7). The pressure was negative throughout the lift, gradually rising from negative to positive values during the lift, or positive throughout the lifting procedure.

The graphs in Fig. 4 show that subjects A and C produced about the same negative ITP throughout the lifts, while subject B had an elevated and posi-

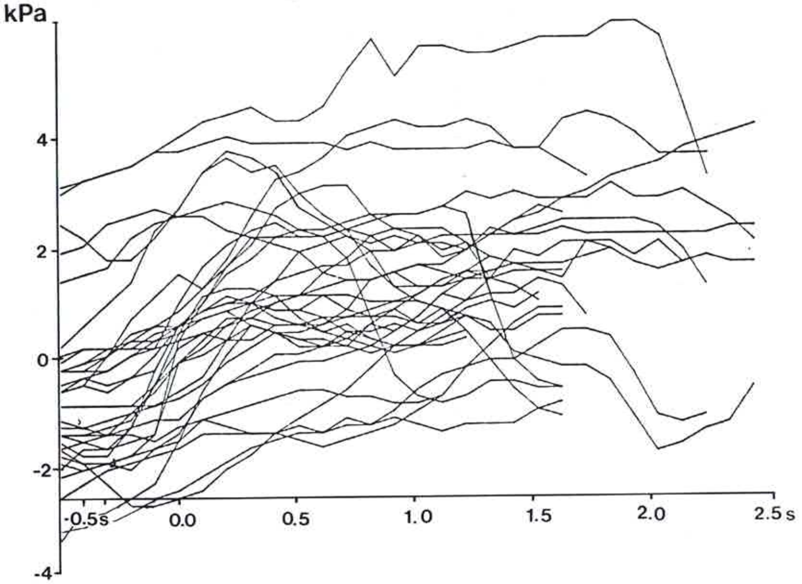

Fig. 7. The intra-thoracic pressure during leg lifting of 25 kg by the low-back patients. Each line represents one lift starting 0.5 s before the lift-off and denoting the real lifting time.

tive ITP, with the shape of the graph similar to that of the simultaneous IAP.

There was no correlation between the peak IAP and the simultaneous ITP among the patients. As for the weightlifters, there was a significant correlation in all lifts with 25, and 40 kg (r=0.77–0.86, p<0.05) and in lowerings with 40 kg (r=0.76–0.80, p<0.05).

DISCUSSION

The first point is whether the methods used justify any conclusions about a cause and effect relationship, between myoelectrical activity around the abdominal cavity and the pressure within the cavity.

The time interval from the myoelectrical activity to the mechanical response, i.e. the electromechanical lag, was estimated to 0.02–0.05 s for the biceps and triceps brachii muscles (33) and up to 0.05–0.10 s for the abdominal muscles acting on the rise in IAP (16). The time lag due to the passage of the pressure wave through the abdominal cavity was negligible (less than 0.00013 s), and there was no noticeable distortion from the pressure recording system. We must, however, take into consideration that a pressure rise within the cavity may by itself elicit stretch reflexes from the muscles that make up the wall of the cavity. As for the diaphragm, Newsom-Davis (32) found a mean latency of phrenic nerve conduction in normal adults amounting to 7.7±0.8 msec. Assuming an average conduction velocity of 70 m/s for the nerves supplying the anterior abdominal and the pelvic floor muscles we may estimate an overall time lag of 0.01–0.02 s for the monosynaptic stretch reflexes from stimulation to response—and perhaps a further rise in IAP after an electromechanical delay.

Considering our periods of 0.1 s for integration of EMG and averaging of the pressures, it seems clear from the above that it is impossible to distinguish exactly which muscular activity proceeds and which follows the pressure rise in every instant. It does seem possible, however, to evaluate the relative importance of the different muscles around the abdominal cavity.

As regards the muscles in the pelvic floor, i.e. the great levator ani muscle that has a dome-shaped form, sometimes called the diaphragm of the pelvis, we chose to pick up the activity from the puborectal muscle, which is easy to identify from the ampulla and previously investigated by others (23, 38), but not during lifting. The muscle is known to be activated when straining and coughing.

As intramuscular wire electrodes may become displaced, deformed or fractured during contractions (24), we preferred to place them outside the muscle but close to it. With an interelectrode distance of about 1 cm we also picked up myoelectrical activity from a greater part of the muscle, but yet no continuous activity from the surroundings. The wires were not found to be distorted after withdrawal.

Intrathoracic (ITP) and intra-abdominal (IAP) pressures

The following physiological formulas should be considered:

1. ITP = P_{alv}–P_{el}
   ITP = pressure within the oesophagus
   P_{alv} = the pressure within the alveolae and trachea
   P_{el} = lung recoil pressure
   P_{alv} is equal to the pressure in the open air when the airways, i.e. the glottis, are open, except for the small variations of ±0.1–0.2 kPa during natural breathing P_{el} is dependent on the air volume within the lungs, varying between about 4 kPa after maximal inhalation to about 0.5 kPa after maximal expiration (17).

   The pressure within the oesophagus (ITP) is equal to the pleural pressure on the same level. There is a small vertical pressure gradient with increasing values downwards. The gradient amounts to about 0.4 kPa between the upper and lower parts of the oesophagus (35).
2. P_{di} = IAP−ITP = $(2 \cdot T)/R$ (Laplace Law)
   P_{di} = transdiaphragmatic pressure difference
   T = tension (active or passive) in the diaphragm
   R = radius of the curvature of the diaphragm

   In this context IAP should actually be measured just below the diaphragm instead of the stomach and the ITP close above the diaphragm. The error of P_{di} due to the methods of measurement, maximally about 1 kPa, varied in all the subjects in the same way according to the trunk position, and was disregarded.

   P_{di} is zero when the diaphragm is relaxed and rises with increased tension of the diaphragm, whether due to active contraction or passive stretching (8). Grassino et al. (14) found a curvilinear relationship between P_{di} and the EMG of the diaphragm during static contractions. Sears et al. (37) found a nearly linear relationship between P_{di} and the EMG of the diaphragm during Mueller manoeuvre. The average variation of P_{di} during quiet breathing in the standing position was 0.85 kPa for men, according to Gilbert (13). By the Laplace Law, these variations may, of course, be attributed both to varying tension and to varying radius. It should also be considered that the diaphragmatic muscle obeys the force–length relationship and produces a higher tension when elongated than when flattened.
3. The abdominal cavity contains mainly fluid and semisolid material and is thus practically incompressible, except for the small amounts of gas that may occur in the stomach and the colon. The walls are flexible, and a muscular contraction somewhere will result in a protrusion somewhere else, if possible; otherwise the pressure will rise quickly.
4. There is always a 'force balance' (4) between the intra-abdominal pressure and the tensile forces in the abdominal wall, equal to the Laplace law for the diaphragm. This means that a rise of IAP will necessarily be resisted by an increased tension, active or passive, in the wall and/or by a reduced radius of the curvature of the abdominal wall and the pelvic floor.

Respiration

The different respiration steps in this study did not affect the IAP significantly in any instance, though the oblique abdominal muscles were more activated in some lifts during expiration, with or without facilitation. This might seem surprising, as everybody knows that one should inhale before lifting heavy burdens. The main point, however, is not the phase of respiration, but the closure of the airways, preferably by closing the glottis. This enables us to build up a positive ITP which will support the diaphragm from above and thus diminish the demands on that muscle, by reducing the P_{di}. In other words, if the glottis is closed, a higher IAP may be possible with less effort from the diaphragm. This was done spontaneously by many patients (those with positive ITP in Fig. 7) and was even more common among the weightlifters, especially when they do real lifts with a barbell (22).

Compton et al. (5) recorded intrathoracic pressures up to 34.6 kPa among two weightlifters performing the "clean and jerk" and investigated the circulatory effects.

When lifting during expiration the abdominal muscle activity increased, which may be due to these muscles' expiratory function especially towards the end of expiration. The activity did not affect the IAP, however, either with or without facilitation.

P_{di} during maximal diaphragmatic effort, i.e. the Mueller manoeuvre, was found to be fairly well correlated to the peak IAP during lifting in the patients but not in the weightlifters. In both groups, there was, however, a very good correlation between the peak IAP and the P_{di} during lifting. Thus it seemed as though the weightlifters did not use the capacity of their diaphragms wholly.

The building up of the IAP

As for the interplay between the muscles lining the abdominal 'ball', it should first be mentioned that there are obviously several ways of doing the same lift (Fig. 4). Subject A was a 'high pressurizer' with a pretty good co-ordination between the diaphragm, the oblique abdominal, and the puborectalis muscles, and an ability of the diaphragm to create a high P_{di}. Subject B was 'expert' at activating the puborectalis muscle, which seemed to be the prime mover, while the diaphragm could not respond to the IAP but gave way. As he had obviously closed his glottis, the ITP increased and thus the whole trunk was pressurized. Subject C started with a fairly active abdominal muscle but there was only a small peak IAP. Something is lacking, probably the co-ordination, perhaps the capacity of the diaphragm.

Secondly, we may conclude from Figs. 5–6, that it is possible to influence the mechanism of the IAP rise, although previous studies (18, 20, 29) have shown, that it cannot generally be accomplished by abdominal muscle training. We cannot say, why the two subjects in Figs. 5–6 managed to increase the IAP, but probably *how*. The co-ordination before the lift-off seemed to have improved (Figs. 5 *b*, 6 *b*). Perhaps a pre-programming after having performed a great many lifts in our laboratory? Fig. 6 *a* shows that a high activity of the oblique abdominal muscles alone does not suffice.

As regards the transverse abdominal muscle, we do not know anything about its activity during lifting. Due to the direction of its muscle fibres, it should be useful for pressurization without giving any bending moment or spinal compression.

It should be pointed out that the activity of the erector spinae muscle is reduced in Fig. 6 *b* compared with Fig. 6 *a* during the phase when the IAP is elevated. This was seen in a fairly large number of comparable lifts, and might indicate that the load on the erector spinae muscle was reduced when the IAP increased.

Lastly, the two pairs of graphs in Figs. 5 and 6, gave about the same shape of the acceleration curve for each couple. Nor could we find any differences, when, for each couple, we made comparisons of the curves from the electrogoniometer or of the video records. There were no differences as regards the lever of the box or the lifting time, that might explain the differences in IAP.

So far, the causal factors of the IAP rise during lifting has not been clarified. Bartelink (2), Morris et al. (31), Grillner (16), and others suggested that the IAP increase is due to a reflex mechanism, but the form of such a reflex was not considered. Kumar (26), and Kumar & Davis (28) studied the afferent component and suggested that stretch receptors in either the tendons or the muscular tissue of the erector spinae muscle could be responsible, "if a reflex exists" (28). As for the assumed efferent component of such a reflex, there are, to our knowledge, no studies on the contributions paid by the diaphragm and the pelvic floor muscles. Kumar (26, 27) found a close correlation between peak IAP and external oblique activity, but this does not necessarily mean a cause and effect relationship. Recent studies (11, 19) have shown that the oblique abdominal muscles are only slightly activated during lifting as compared with their maximum activity during trunk flexion strength tests. It was also shown that low-back patients could produce the same IAP during lifting as healthy controls in spite of a reduced abdominal muscle strength. The result of the present study agrees with the earlier conclusions, that the oblique abdominal muscles are of minor importance for the rise of IAP (18, 19, 20).

The rectus abdominis muscle was not taken into account, as it is only occasionally activated during lifts up to 40–50 kg (11, 31).

CONCLUSION

The IAP rise during lifting seems to depend on a good co-ordination between the muscles surrounding the abdominal cavity, i.e. the diaphragm, the oblique abdominal muscles, and the muscles of the pelvic floor (the puborectalis muscle). The diaphragm as reflected by the P_{di} (transdiaphragmatic pressure difference) seems to be the most important one for the pressure level, as there is a significant correlation between the peak IAP during lifting and the maximum P_{di} among low-back patients, and between the peak IAP and the coincident P_{di} during lifting among both patients and weightlifters.

The oblique abdominal muscles were previously seen to be of minor importance to the IAP during lifting (18, 19, 20), and this study confirms that a one-sided activation of that muscle is not sufficient for an IAP rise during lifting. The few recordings of the pelvic floor muscle suggest that this muscle may be fairly important for the rise of IAP. The transversus abdominis muscle is probably of some importance, but we lack information about it. If the diaphragm is too weak to withstand the pressure from below, closure of the glottis seems to help to maintain the IAP rise. Otherwise the type of respiration seems to be less important.

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