THE ROLE OF ABDOMINAL PRESSURE IN RELIEVING THE PRESSURE ON THE LUMBAR INTERVERTEBRAL DISCS

D. L. BARTELINK, LONDON, ONTARIO

From the Department of Anatomy, Medical School, University of Western Ontario

Every writer who has interested himself in the mechanics of the lumbar spine has been struck by the great magnitude of the forces that operate when a person bends forwards and lifts a heavy weight. So long as a person is upright, even if he carries a heavy weight in his hands, the pressure upon the spine is not more than the sum of the upper trunk and the weight—that is, a few hundred pounds. However, if he bends forwards and picks up a heavy weight the spine begins to act as part of a crane and tremendous torque forces appear. Most writers seem to shy away from mentioning the outcome of their calculations and only call the forces " enormous " or " terrific." Bradford and Spurling (1945) calculated that a muscle pull of 1,500 pounds, exerted by the erector spinae muscles, and operating on a lever of two inches, is necessary to counterbalance a load of 100 pounds lifted by the hands at a distance of thirty inches in front of the fulcrum—the lumbo-sacral disc! The pressure in the disc is the sum of these loads—that is, 1,600 pounds—indeed justifying the term tremendous, if one considers that the area of pressure is not much greater than one square inch.

One can object to the assumption of Bradford and Spurling that the lever in front of the fulcrum would be as long as thirty inches. If it is less the pressure on the disc is proportionately smaller. On the other hand, a weight of 100 pounds acting on the long lever is only a modest representation of what actually can be lifted by a strong man; and to this weight should be added the weight of head and shoulders. Let the lever be only fifteen inches, but let us assume that he lifts 200 pounds plus fifty pounds (head, shoulders and thorax), then the pressure in the lumbo-sacral disc will be 2,000 pounds. This calculation is based upon stationary forces. The pressures that appear during violent action according to this reasoning must be considerably higher and can only be characterised as enormous.

How does the spine and especially how do the intervertebral discs stand up under this pressure?

EXPERIMENTS ON THE RESISTANCE OF DISCS TO PRESSURE

Virgin (1951) tested intervertebral discs, removed from the cadaver together with a thin slice of bone on each side, in an Olson compression machine. He found that at a load of about 300 pounds the disc loses some fluid and gets (very slightly) thinner, but that this process is completely reversible if one allows the disc, which is kept in saline, to reabsorb fluid after decompression. At higher loads (no specific load was given; 1,000 pounds was the greatest load mentioned) a condition comparable to the yielding of steel under tension is observed, associated with irreversible changes. Tears in the annulus fibrosus appear, sometimes with prolapse of material from the nucleus pulposus.

I repeated the experiments of Virgin, taking a few precautions that seemed necessary. Preliminary tests had shown that if only a thin slice of bone was left on the disc on each side, as in Virgin's experiments, the bone might tear apart before the annulus suffered damage. I therefore examined discs between two nearly complete vertebral bodies. The sawcuts were made as nearly parallel as possible. The neural arches were removed at the pedicles, because it is possible that some force might be transmitted through the apophysial articulations if these are not entirely vertical. The discs were necropsy specimens, one-half to two days old, that had been kept well refrigerated. So far as our small series (ten discs) allowed us to see, the lapse of time after death has no influence on the resistance of the disc. It might be of value to check this resistance versus time after death on a larger series of specimens to see if the discs in the living body might have a greater resistance than we are now assuming. In view of the low metabolism of the discs it seems improbable that a sudden change would occur immediately after death.

The discs were subjected to accurately measured loads by a Baldwin materials testing machine, kindly put at our service by the General Motors Diesel Plant in this city. At each step of the increasing pressure the deformity was checked by means of a gauge reading to a thousandth of an inch. The discs all behaved in the same way (Fig. 1). First there was a region of settling, where the deformity was rather great relative to the rise in pressure. This was followed by a straight part of the curve where the disc essentially behaved as a perfectly elastic body, the deformity increasing proportionally to the pressure. It should be noted that, during this elastic response, if one allowed the same pressure to stay for a considerable length of time the deformity increased very slowly, probably because minute quantities of fluid were squeezed out of the disc material. This very slow " creep " started to increase rapidly at certain pressure. If at that level (which may be called the yield point) the pressure was raised another 50–100 pounds the deformity increased rapidly with evident complete destruction of the disc. The yield points were different for each disc, and ranged between 350 and 1,400 pounds, with a mean of 710 pounds, in the ten discs that were examined. There was no evidence of a relationship between the slope of the straight part of the curve and the point of yielding.

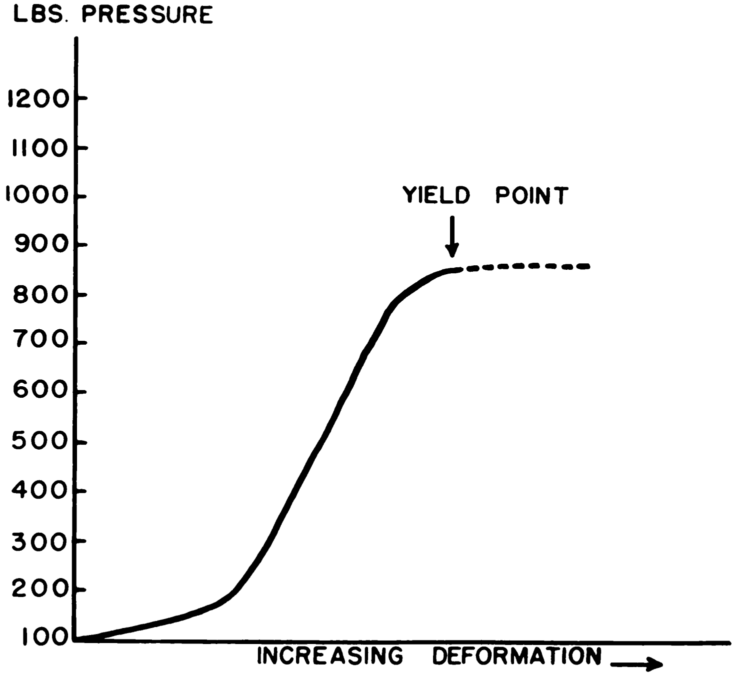

FIG. 1

This graph shows the relationship between deformity and load for an average disc. If the experiment is continued after the yield point has been passed the deformity is seen to increase rapidly, and the load necessary to cause this deformity falls below that of the yield point.

It is necessary to note here that most of the discs that we examined were from people of sixty to eighty years of age. When dissected after the compression experiment nearly all of them showed old tears, and those with marked internal damage showed less resistance than the others. We found some difficulty in obtaining specimens from younger subjects. We were able to test the lumbar 3–4 disc of a man of forty-five who had died of chronic myelogenous leukaemia. His skeleton did not show evidence of involvement. This disc broke down completely with a pressure of 750 pounds. Dissection showed that the chief reason for the collapse was a large number of vertical fractures (fractures in a cranio-caudal direction) some of which were running radially. Corresponding with the fractures, the cartilage plates and the discs showed tears that in the central area were deep enough to let the nucleus material escape, but towards the margin of the disc were much more shallow.

Not many conclusions can be drawn from this experiment, and it seems certainly necessary to do a great number of tests on discs of younger people. Nevertheless it is possible that what has been described above happens more often than we realise. It must be remembered that radiographs generally would not show the kind of fractures just described, and that the skeleton of a person who leads a physically easy life may not be much stronger than that of the man who died from leukaemia. Experiments on the pressure resistance of dissected vertebral bodies suggest that the bony part of the spine is much stronger than the discs. However, conditions in such experiments are more favourable for isolated bodies than if they were combined with discs, because the great hydrostatic pressure that is set up in the nucleus pulposus under load causes tangential forces that act not only on the annulus fibrosus, but also on the adjoining bone. It is possible that under such circumstances the annulus would turn out to be the stronger. Yet the disc would suffer in such a case, especially as the tear

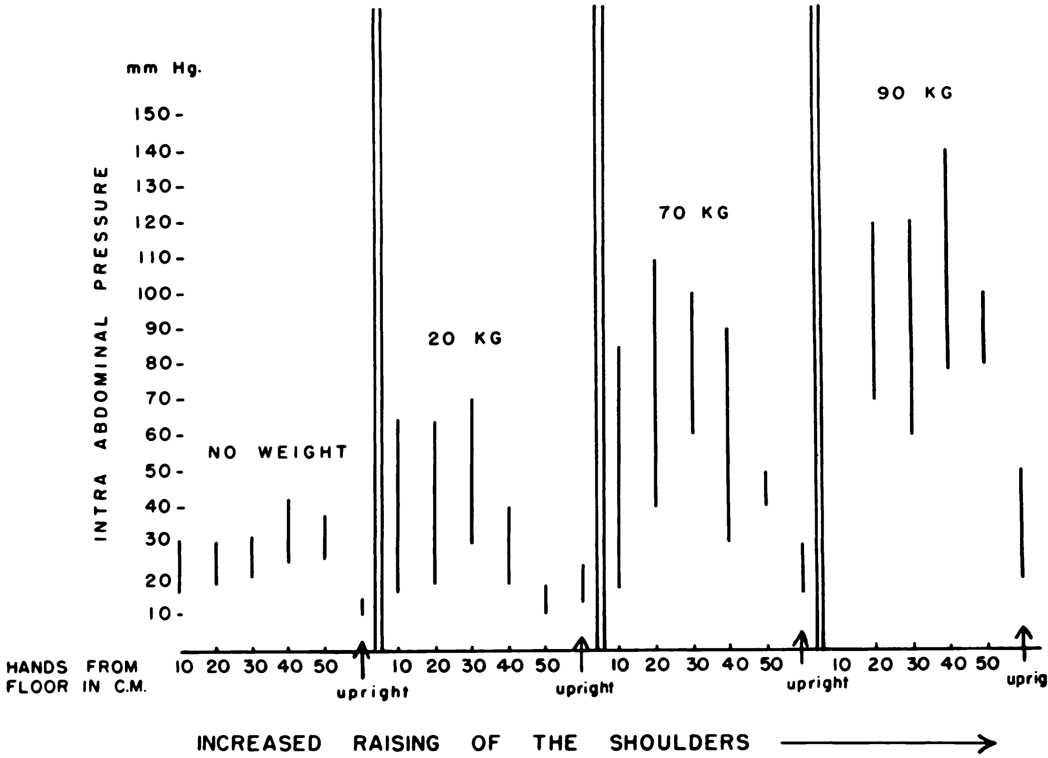

FIG. 2

This graph shows the values of intra-abdominal pressure measured on a powerfully built man aged twenty-three. The pressures were taken with four different loads in the hands. At each of these loads the values were determined in different degrees of bending, designated by giving the distance of the hands from the floor. The vertical lines represent the fluctuations that occurred when the subject breathed, the higher value being the inspiration, the lower the expiration. As is evident the pressures are higher for heavier lifting and are not significantly elevated when the subject is upright.

in the cartilage plate would open up the disc for the entry of blood vessels along the scar tissue that is formed. As the tears in the cartilage plate seem to appear in the centre first, this would explain why most of the degenerative changes of the discs are seen in the centre.

It is evident from these experiments that the intervertebral discs (and the vertebral bodies) in actual life cannot be subjected to the pressures calculated by Bradford and Spurling and by ourselves (above), as they would not be able to withstand them. We have to review our reasoning, and as we can hardly doubt the correctness of the rather simple mechanical calculation we should ask: is there any other structure besides the spine that might take care of part of the load? At first sight it seems unreasonable to assume any pressure transfer through the trunk other than by the spine, because all the structures are soft. However, soft material can be arranged in such a way that use is made of its tensile strength, rather than its rigidity, to transmit presssures—for instance a football.

THEORY OF ADDITIONAL SUPPORT FOR THE SPINE

Heavy weight lifting is always associated with marked increase in the intra-abdominal pressure. It is not even necessary to measure this pressure to know that it is there, because well known symptoms of weight lifting are congestion and redness of the head and frequently expulsion of a hernia. If one measures the pressure, as we did with a balloon in the stomach connected by a narrow plastic tube to a manometer, the pressure is found to increase with the amount of weight lifted, and to be different in bending over to different degrees (Fig. 2). In extreme flexion of the trunk the pressure is not so high as when the hands are ten to fifteen inches away from the floor, in which position the pressure reaches its greatest. If the lifter continues slowly to straighten out, the pressure drops rather rapidly and is already low with the body still bent over 15–20 degrees. In the upright position, whatever the load in the hands, the pressure is usually very low and never significant. The maximum pressures vary with the individual. Athletic people showed pressures of 140 millimetres of mercury, slightly built people sometimes not more than 60 millimetres of mercury. If the body is flexed without a weight being lifted the pressure is only slightly increased. The greater the amount of weight taken in the hands the more the pressure rises, up to the maximum. If a certain position of flexion, with a given load in the hands, is maintained for a few moments one notices that the intra-abdominal pressure fluctuates considerably with the respiration and in the weaker subjects may fall to zero during expiration even with a maximal lifting effort. The pressure rises sharply if the lifter makes a sudden effort to lift a weight that is almost too much for him. During the measurements it was also noted that sudden straightening out of the body after it had been bent over is accompanied by an initial high spike of intra-abdominal pressure; and if a person flexes forwards and suddenly stops this movement a high spike of pressure is seen at the instant of stopping.

In my experiments the equipment to measure the sudden high elevations of pressure was not available. This was unfortunate because I believe that the essential part of the phenomenon studied—namely, the reflex contraction of the abdominal wall muscles—lasts only a very short time. What was seen in the subjects studied was partly this reflex, but partly also the (subconscious) voluntary contraction with which they maintained the position.

All these observations make it clear that there is a relationship between effort involving the trunk, especially sudden effort, and the intra-abdominal pressure. Could this pressure play a significant role in the mechanics of the trunk?

That the tensed abdomen may act as a support is understood if one imagines that in a skeleton one had wedged a large balloon between the costal margin and the pelvis, fastening it to the costal margin. One could then remove the metallic rod out of the spine of the skeleton—maybe replacing it with a cord—and the skeleton would not collapse forward, because the thorax would be supported by the balloon.

In the living body the costal margin also is attached to a sort of " fluid ball " that will resist deformation as soon as the pressure within it is raised. It is easily conceivable that in this way some of the load of the upper trunk is transmitted, via the somatic cavity, down to the pelvis by what could be called an additional or " muscular skeleton " (Fig. 3).

CALCULATION OF THE AMOUNT OF SUPPORT THAT IS PROVIDED BY INTRA-ABDOMINAL PRESSURE

It is interesting to calculate what amount of support would be provided. Let us consider the thrust transmitted by the diaphragm to the lower thoracic cage. If the area of the cross section of the fluid ball at the level of the lower thoracic aperture is 500 square centimetres and if the pressure per square centimetre is 100 millimetres of mercury, then the total force is 68 kilograms or 150 pounds. If it would seem that this is a small force compared with the loads as calculated for the spine, we should not forget that this force acts on a lever of considerable length. This lever is much longer than the one on which the erectores spinae act, and the influence upon reducing the necessary pull of the erectores will be proportionately larger. It is hard to give a reliable figure for the length of the lever of the diaphragmatic thrust, but it would seem safe to say that the pressure in the intervertebral disc need not be so high as calculated, by several hundred pounds. As the fluid ball support is a support of which the magnitude can be and evidently is regulated by the body according to the requirements it is reasonable to assume that the pressures in the spine are kept within safe limits by means of this regulation (so long as it holds). Under very severe circumstances increasing the intrathoracic pressure after closure of the glottis may supply an additional force.

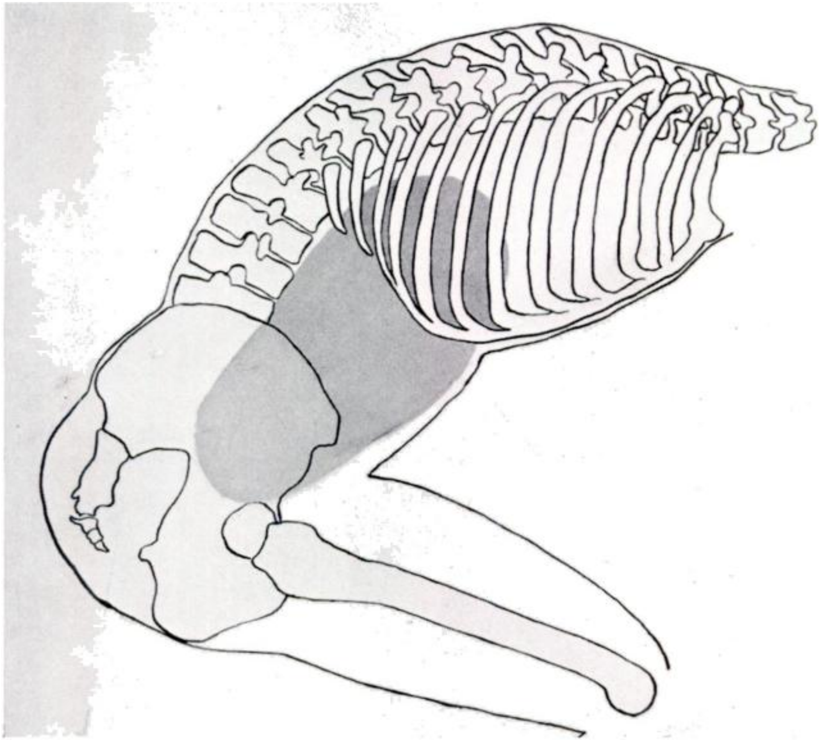

FIG. 3

Diagram to suggest how the abdominal fluid ball, as it is attached to the costal margin, would provide some support for the upper trunk, in case of lifting with the trunk flexed forward.

EXPERIMENTS ON THE BEHAVIOUR OF THE ABDOMINAL WALL DURING LIFTING

One difficulty with the understanding of this mechanism is the distribution of the tensions in the anterior abdominal wall. It might seem that longitudinal pull of the muscles would obviate the thrust under the diaphragm. With electromyographic studies of the abdominal wall during weight lifting it was found that the rectus abdominis muscles, which are mainly concerned in longitudinal pull, do not contract. The influence of the vertical component of the pull of the oblique muscles is uncertain for the moment. The electromyographs suggested that perhaps the main action responsible for raising the intra-abdominal pressure is supplied by the transverse abdominal muscles which do not have a significant vertical component. What we found regarding the absence of action of the abdominal recti during weight lifting fits in perfectly with what Floyd and Silver (1950) found for the behaviour of the abdominal wall during straining: that there is no action of the recti.

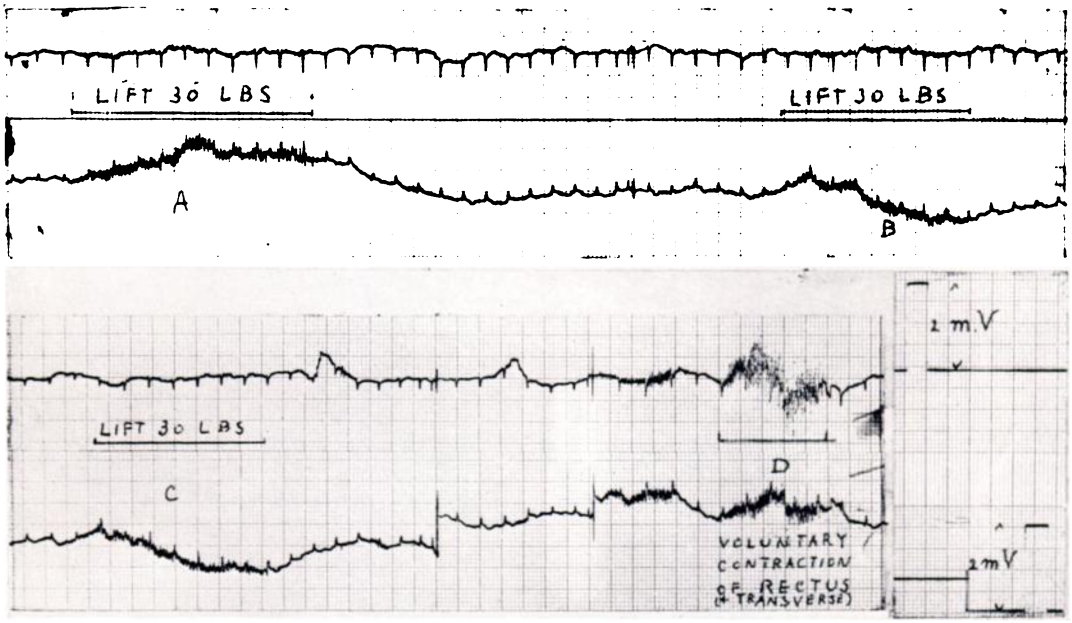

FIG. 4

Electromyographs of the right rectus abdominis muscle (uppermost and third tracings) and of the muscle group composed of the transversalis and the internal and external oblique muscles (second and fourth tracings). The electrodes for this latter group were positioned, one in the right loin close to the lateral margin of the erector spinae, and the other one at the same level anteriorly and about four inches to the right of the midline.

The subject lifted a weight of thirty pounds in the outstretched hands while standing upright, at A, B and C. At D he was asked to force his head down on his chest, which made his recti contract. No weight was lifted at D. The lower right corner tracings show the calibration of each lead for two millivolts.

It is evident that during weight lifting there is no significant contraction of the recti.

The electromyographic study (Fig. 4) in which the muscle action of the abdominal wall was examined during weight lifting was carried out as follows. At first I tried to examine the abdomen of the flexed subject, but found that this was unsatisfactory owing to the shifting of electrodes and poor readings. It seemed that because of the flexion of the trunk the thickness of the abdominal fat became relatively greater and increased the insulation. I therefore made the subject stand upright, and asked him to lift a weight with the horizontally outstretched arms. In experiments with a gastric balloon we had found that in this position also the intra-abdominal pressure rose characteristically. The results are shown in Figure 4. The abdominal recti do not show significant action currents, whereas the lateral muscles do. That the electrodes were correctly placed is shown by the tracing when the recti are voluntarily contracted.

DISCUSSION

The observations and considerations that have been mentioned make it probable that there exists an additional support for the body outside of the spine. This support is the tensed abdomen, the tension appearing through reflex contraction of certain muscles. The reflex probably at least partly is a conditioned reflex. It is interesting to consider that the transverse abdominal muscle anatomically belongs to the same group as the diaphragm and the transverse thoracic muscle. Together with the muscles of the pelvic floor, the origin of which is less certain, they are the muscles that surround the " fluid ball " and by their contraction create the " muscular skeleton " much in the same way as invertebrates are able to create a support that enables them to drive forward the front end of their bodies. The abdominal fluid ball according to this reasoning would be genetically very old, and part of the reflex might even be an inborn reflex.

There is a clinical application of the understanding of this reflex. It is a common clinical observation to find the abdomen of patients with prolapsed or ruptured disc and nerve root pain to be remarkably tense. While spasm of the muscles of the back has easily been understood in " disc trouble," that of the anterior muscles of the abdomen has not been understood. Also it may be that specific training by physical therapy in the raising of the intra-abdominal pressure as a protection for the spine might be of great benefit to patients recovering from " slipped disc " or operations upon the spine.

From observations on a few patients, and also from personal experience, it seems probable that many people could make a better use of the abdominal pressure support to prevent low back pain by putting it into operation voluntarily. The consequences of increased intra-abdominal pressure, especially upon the circulation, are many and seem to deserve further study.

The importance of the abdominal fluid ball support for animals in general—Animals undoubtedly make an extensive use of the protection of their spines by the tensed somatic cavity, and probably also use it as a support upon which muscles of posture find a hold (besides the spine). In this respect it is interesting that the area of the intervertebral discs of a medium-sized gorilla is equal to or smaller than that of a small man (Schultz 1953). The gorilla probably compensates for this by having an enormous somatic cavity and powerful, well developed muscles.

The position of the lungs outside the fluid ball is an obvious advantage. Breathing can go on even when the abdomen is used as a support and cannot be relaxed. This means that the range of flight of an animal having the lungs outside the fluid ball is greater than that of an animal who has its lungs in the single body cavity, which can just make a spurt and then has to stop to breathe. Could it be that it is for this reason that the mammals have developed a diaphragm?

SUMMARY

1. Since the publication by Bradford and Spurling in 1945 of *The Intervertebral Disc*, there has been argument about the figure of 1,600 pounds that they calculated as the load on each lower lumbar intervertebral disc when a person lifts a heavy load with the trunk flexed, especially since experiments have shown that intervertebral discs subjected to increasing pressures yield at values well below this figure. In the author's experiments the discs were destroyed by pressures ranging from 350 to 1,400 pounds, with a mean of 710 pounds.
2. It occurred to the writer that the spine is not necessarily the only structure in the body that can transmit pressure forces from the shoulder to the pelvis. A raised intra-abdominal pressure impacts a thrust under the diaphragm, which will be transmitted to the thoracic spine and the shoulders by means of the ribs. This thrust can take care of part of the lifted weight and thus decrease the load on the spine.
3. In experiments in which the intra-abdominal pressure was measured by means of a small balloon in the stomach it was found that the pressure rose proportionally with the amount of weight lifted.

4. It is suggested that the abdominal fluid ball can exert a longitudinal force only if there is no contraction of the longitudinal muscles (at least anteriorly). Electromyographic studies of the abdominal muscles during weight lifting showed that the transverse and possibly the oblique abdominal muscles contract, but not the recti.

5. It thus seems that the load on the intervertebral discs is not necessarily so great as Bradford and Spurling calculated, but can remain within safe limits. It is hard to give accurate figures for the amount of load that is taken off the spine in this way, but an estimate would put it at several hundred pounds. The importance of a reflex contraction of the abdominal wall during effort as a protective mechanism for the spine must therefore be appreciated. Voluntary contraction may also be called upon to increase the intra-abdominal pressure and so reduce the load on the discs. This is done by many weight lifters.

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REFERENCES

BRADFORD, F. K., and SPURLING, R. G. (1945): The Intervertebral Disc. Springfield, Illinois: Charles C. Thomas.

FLOYD, W. F., and SILVER, P. H. S. (1950): Electromyographic Study of Patterns of Activity of the Anterior Abdominal Wall Muscles in Man. Journal of Anatomy, **84**, 132.

SCHULTZ, A. H. (1953): The Relative Thickness of the Long Bones and the Vertebrae in Primates. American Journal of Physical Anthropology, N.S. **11**, 306.

VIRGIN, W. J. (1951): Experimental Investigations into the Physical Properties of the Intervertebral Disc. Journal of Bone and Joint Surgery, **33–B**, 607.