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THE INFLUENCE OF SPINAL MOVEMENTS ON THE LUMBAR INTRADISCAL PRESSURE AND ON THE TENSILE STRESSES IN THE ANNULUS FIBROSUS

By

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In the late 19th century it was observed that bending movements in the lumbar spine cause a strong protrusion of the annulus fibrosus on one side, combined with a contraction on the other side (*Fick* 1904). This observation has later been verified by several other authors, among them *Brown, Hansen & Yorra* (1957).

The conclusion to be drawn from this is that bending movements in the lumbar spine subject different parts of the intervertebral disc to varying mechanical stresses. No attempt has been made, however, to determine these variations.

The facets have usually been considered as important only in preventing sliding movements and rotation of the vertebrae (*Fick* 1904, *Keyes & Compere* 1932, *Hagelstam* 1949 and others). It is also known that when the arches are separated from the vertebral bodies the column of arches and facets contract while the column containing the vertebral bodies will elongate. This is said to be due to the so called "intrinsic pressure" of the nucleus pulposus (*Petter* 1933) and also to the fact that ligaments and capsules around the posterior bony elements are under some tension (*Hagelstam* 1949, *Steindler* 1955).

On vertical loading of the lumbar spine, arches and facets have been said to carry no load at all (*Fick* 1904, *Spurling* 1953), to carry around 15 % (*Nachemson* 1960) or to be "important force-bearing structures" (*Kelly* 1958).

The purpose of this study has been by means of direct measurements to analyse the stresses that appear in different parts of the loaded lumbar disc tilted in various directions with and without arches, facets and ligaments.

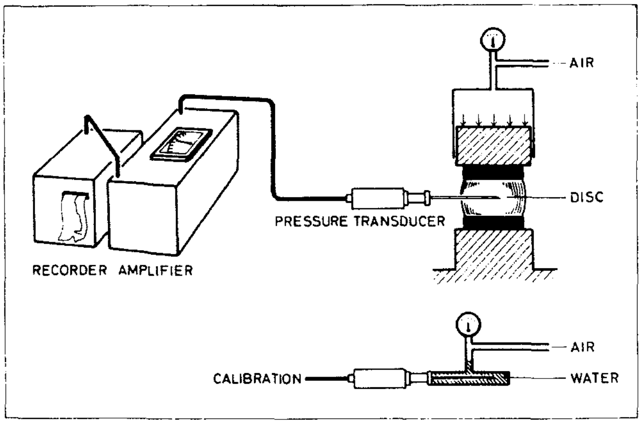


Fig. 1.
Schematic drawing of the apparatus in use.

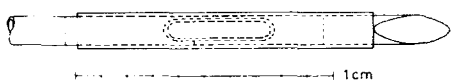
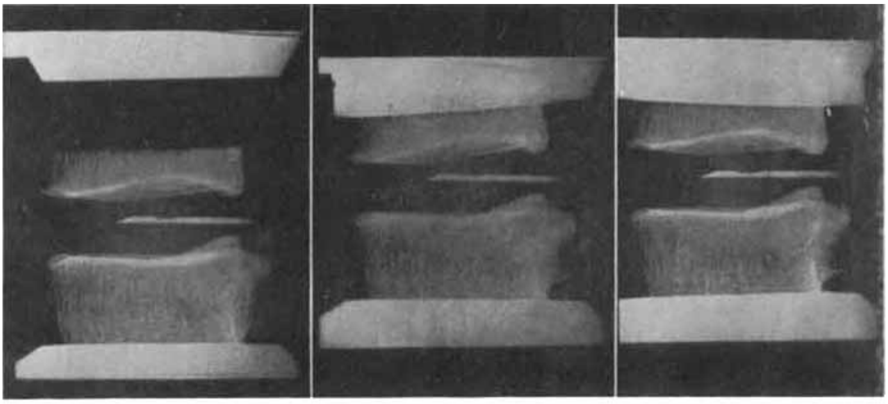


Fig. 2.
Schematic drawing of the needle and the attached plastic tubing (P.E. 90), used for intradiscal pressure measurements.

From a clinical point of view there are grounds for a closer study of these stresses, as the symptoms of low back pain are often discussed in terms of mechanical forces on the lumbar intervertebral discs.

METHODS

By inserting a soldered Luer-Lok needle with a hole in the side near the tip, over which an elastic polyethylene tubing is threaded, into the nucleus pulposus, it is possible to measure the pressure produced by loading a lumbar intervertebral disc via a superior intervertebral body in a vertical direction (*Nachemson* 1960). The procedure is based on the following principle. First, the pressure sensitive gauge, coupled to an electromanometer, is calibrated for known pressures. The gauge is then inserted centrally into the disc. When its position has been checked with roentgenograms in two planes, the specimens are loaded vertically in a compression apparatus worked by compressed air. The load is transmitted to the disc by two planoparallel plates, the lower one of which is fixed, while the upper plate is movable in the vertical direction



a b c

Fig. 3.
Roentgenographic appearance of the disc (no 4/L2) shown in Fig. 5. The pictures demonstrate *a*) the position of the non-tilted disc, between the jaws of the compression apparatus (load is not applied). *b*) forward tilt of 5°. *c*) backward tilt of 5°.

(Figs. 1 and 2). (For a more detailed description of the method, see *Nachemson* 1960).

Readings of the intradiscal pressure were taken at loads of 40, 85, 130, 175 and in some specimens 220 kp. Following this, a brass plate, specially constructed with its load bearing surfaces tilted at an angle of 5° to each other, was mounted onto the upper, movable part of the compression apparatus. On renewed loading, the specimen was subjected to an asymmetrical stress. In all cases the specimens have been loaded with the angle of the plate directed both forward and backward and in some instances sideward as well (Fig. 3). As a check, on conclusion of these tilted loading experiments, the plate was removed and the discs reloaded in the vertical non-tilted direction. In no instance has any difference been noted in the values recorded before and after the tilted loadings. The pressure was always measured with the opening of the pressure sensitive gauge pointing upwards as well as sideways.

Lumbar spines taken at post mortem 12–36 hours after death have been used. If the experiments were not carried out the same day, the specimens were kept 1–5 days in deep-freeze (—25° C) in plastic bags. It has been found that this storage has no appreciable effect on the results (*Nachemson* 1960). The departments of pathology wished to preserve the sacrum. For this reason, the lumbar spine was removed, by sectioning through the lumbo-sacral disc, thus only four lumbar

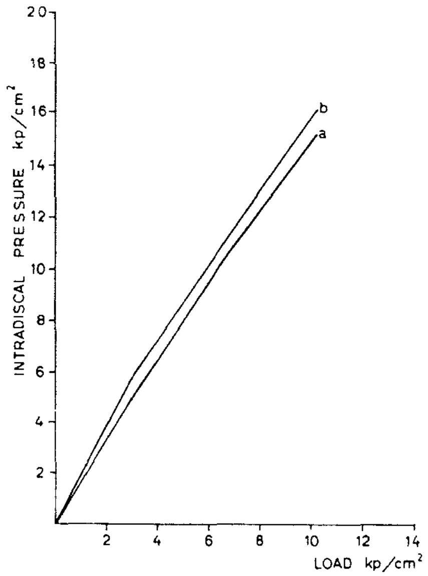


Fig. 4.
Intradiscal pressure in kp/cm² resulting from increasing external load on the disc shown in Fig. 5. *a*) non-tilted. *b*) 5° backward tilt. The basic data are given in Table 3, p. 190.

discs were used during the experiments, viz. the disc just above the lumbo-sacral which has been called L 4, the one above that L 3 etc. In general, the discs were prepared so that they were cut out with slices of adjacent vertebral bodies, 1–1½ cm. thick.

During the experiments is was found that the values obtained from the specimens where the pedicles and joint processes were saved could not be compared to those from the experiments where they were cut off because of the difference in the direction of the applied vertical load. This fact will be subject to further analysis in the discussion.

In the first series (series A) the pedicles and joint processes and attached muscles were removed. The cut surfaces of the vertebral bodies were made as parallel to each other as possible and also parallel to the end-plates of the disc. The parallelism was checked with a water level. Because of technical difficulties, however, it was found that this parallelism not always was exact. The maximum deviation from parallelism has been estimated at about 2°. When not all first four lumbar discs were used in the experiments the rejected specimens had been damaged in some way. This occurred most often at post mortem or when removing the lumbar vertebrae.

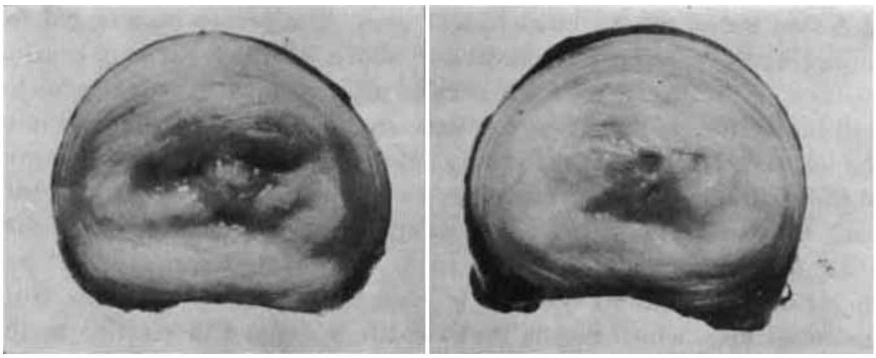


Fig. 5.
Macroscopic view of the disc L2 from a female age 34. The roentgenographic appearance of this disc was shown in Fig. 3, the experimental results in Table 3.

After the experiments the discs were cut through horizontally and their surface area was measured with a planimeter. A graph was drawn for every disc, with the external load in kp./cm.^{2} on the abscissa, and the corresponding intradiscal pressure in kp./cm.^{2} on the ordinata as in Fig. 4. The intradiscal pressures corresponding to external loads of 2, 4, 6, 8, 10 and in some cases 12 kp./cm.^{2} were read from these curves. It was seen that the intradiscal pressure was approximately proportional to and greater than the applied load per unit area. This procedure makes it possible to compare results for different discs.

Since the method described above is not reliable for pressure measurement inside severely degenerated discs (*Nachemson* 1960), this category has been excluded from the present material. All the discs included here have either been normal or showed only slight macroscopic changes in the nucleus pulposus. The nucleus was somewhat fibrous but could be clearly distinguished from the annulus which was intact. It has earlier been proved that discs showing slight macroscopic changes, such as fibrosis of the nucleus pulposus and isolated fissures in the annulus fibrosus, also show hydrostatic behaviour and intradiscal pressures not differing from less degenerated discs.

As mentioned earlier, the discs have been loaded vertically in a compression apparatus, both between two parallel plates and between two plates tilted forwards, backwards and towards the left or right so as to form an angle of 5° with each other. In the first instance, the loading conditions were identical with those studied earlier by the author. It should be pointed out that these conditions do not exactly duplicate the stress on a disc in situ in a straight back. The procedure adopted for preparing the specimens, as described above, in which the load-bearing surfaces of the discs were made parallel after removal of arches, pedicles and facets, means that these surfaces are not parallel in situ, owing to the well-known fact that the spine straightens out somewhat on removal of the posterior bony elements. This means that in a straight, "unloaded" back the discs actually are under a certain amount of pressure (*Petter* 1933, *Hagelstam* 1949, *Steindler* 1955). In the first series (A) it has therefore been found expedient to base the experiments on the truly unloaded disc, which means that the tilt is defined in relation to the isolated specimen and not in relation to the disc in situ. The terms "forward tilt" and "backward tilt" should consequently also be interpreted from this point of view.

In the following series (B) the specimens were prepared so that the two vertebrae adjoining the disc and the joint processes with attached ligaments were saved. Thus a posterior connection was formed from the upper to the lower of these vertebral bodies. Also, the surfaces of the vertebrae were levelled off by a file and the parallelism was checked by water level. The measurements were performed as described above.

After the experiments it was also noted that when the posterior elements were removed the distance between the posterior parts of the vertebrae widened somewhat so that the earlier planoparallel loading surfaces made a forward inclination to each other at an angle of about 3°.

RESULTS

Series A.

Experiments were performed on 29 discs from 10 individuals (Table 1). In no single disc has any deflection been recorded on insertion of the needle in the non-tilted discs, which is entirely consistent with earlier observations. Since all specimens included in this series were practically normal or non-degenerated, their hydrostatic behaviour has been taken for granted (*Nachemson* 1960). Nevertheless, as a check a calculation has been made of the difference between the vertical and the horizontal pressure. In no single measurement has the absolute deviation from the mean exceeded 7 per cent. Neither forward, backward nor sideward tilt has produced any change in the hydrostatic behaviour of the nucleus pulposus.

Twenty-one discs from 6 individuals (nos. 1–6 in Table 1) have been subjected to experiments with forward and backward tilt. The pressure

TABLE 1
Specimens studied.
Series A.

Case no.	Sex	Age years	Main cause of death	Discs tested
1	Female	40	Fractura cranii	L2, L3
2	Male	33	Cirrhosis hepatis	L1, L2, L3, L4
3	Male	35	Fractura cranii	L1, L2, L3
4	Female	34	Intox. barbitur.	L1, L2, L3, L4
5	Male	57	Cirrhosis hepatis	L1, L2, L3, L4
6	Male	33	Nephropathia c. uremia	L1, L2, L3, L4
7	Female	32	Toxic. gravidarum	L1, L2, L4
8	Female	52	Haemorrhagia cerebri	L3
9	Female	20	Tumor col. cervicalis	L1, L3
10	Male	37	Fractura cranii	L1, L3

All discs showed only very small changes in the nucleus and were classified as normal.

TABLE 2
Series A.
Mean values of pressure in nucleus pulposus in kp/cm² ± error of the mean, in the non-tilted position and vertical loading.

Level		L 1	L 2	L 3	L 4
Load Kp/cm²	2	3.18 ± 0.16	3.32 ± 0.35	3.47 ± 0.17	3.30 ± 0.10
	4	6.20 ± 0.60	6.48 ± 0.54	6.47 ± 0.21	6.45 ± 0.33
	6	8.98 ± 0.79	9.40 ± 0.72	9.38 ± 0.29	9.25 ± 0.14
	8	11.78 ± 1.02	12.08 ± 0.97	11.87 ± 0.52	11.75 ± 0.18
	10	14.50 ± 0.85	14.70 ± 1.15	14.62 ± 0.44	14.25 ± 0.27
		n = 5	n = 6	n = 6	n = 4

values obtained with loading in the non-tilted position are set down in Table 2, together with the mean errors. These values agreed entirely with earlier observations. As in earlier studies, it has been shown that each particular load test produces an identical reaction in levels L 1, L 2, L 3 and L 4.

Table 3 shows the results for one particular disc, shown in Fig. 5. This table clearly demonstrates the increase in pressure effected by a 5° tilt in different directions.

The magnitude of the increase in pressure resulting from forward and backward tilt is shown in Table 4, which includes the mean values together with the corresponding maximum and minimum values. The

TABLE 3
Series A.
Prep. 6/L2.
Intradiscal pressures obtained from the L2 disc of a female, age 34, when subjected to vertical loading in the non-tilted, forward and backward tilted position.

	Intradiscal pressure kp/cm²		
Load kp/cm²	Untilted	Tilt 5° forward	Tilt 5° backward
2	3.2	3.8	3.7
4	6.4	7.3	7.2
6	9.5	10.2	10.1
8	12.3	12.9	13.0
10	14.9	15.5	15.9

TABLE 4
Series A.
Increase in intradiscal pressure resulting from 5° forward tilt.

Disc	Mean value kp/cm²	Max. value kp/cm²	Min. value kp/cm²
L1 (n = 5)	1.04	1.41	0.62
L2 (n = 6)	0.80	1.08	0.32
L3 (n = 6)	0.63	1.32	0.06
L4 (n = 4)	0.68	1.48	0.02
Increase in intradiscal pressure resulting from 5° backward tilt.			
L1 (n = 5)	0.78	1.22	0.60
L2 (n = 6)	0.68	0.82	0.54
L3 (n = 6)	0.75	1.34	0.22
L4 (n = 4)	0.40	0.68	0.22
Average Increase	0.72 kp/cm²		

relatively large difference between the maximum and minimum values is probably due to the difficulty of producing entirely planoparallel surfaces in the specimens.

A "sign" test has shown that a 5° forward or backward tilt results in an increase in pressure, which observation is significant at the 0.1 % level. The statistical analysis further shows that this increase in pressure appears to be independent of the external load. A calculation of the correlation between external load and corresponding pressure variations for the different discs gives $r = 0.043$ (not significant). No

TABLE 5
Series A.
Relative increase in intradiscal pressure brought about by 5° tilt for different outer loads.

Load kp/cm^2	Non-tilted intradiscal pressure, mean values L 1-L 4, (kp/cm^2)	% increase by 5° tilt
2	3.35	21.5
4	6.44	11.2
6	9.30	7.7
8	11.93	6.0
10	14.60	4.9

relationship can consequently be demonstrated between external load and variations of increase in pressure.

In addition, the effect of sideward tilt has been investigated in 8 discs from 2 individuals (nos. 5 and 6 in Table 1). It was found that a significant increase in pressure resulted, of the same order of magnitude as with forward and backward tilt. No difference has been noted between the effect of right- and leftward tilt.

As shown in Table 4, the increase in pressure brought about by tilting 5° in the different directions is on the whole equal for the different levels L 1–L 4 and reaches a mean value of 0.72 $kp./cm.^2$.

In Table 5 the relative increase in pressure resulting from 5° tilt for external loads from 2–10 $kp./cm.^2$ has been calculated.

The results reported show that the non-tilted isolated disc specimen, prepared as stated above, shows the lowest intradiscal pressure on vertical loading when compared with corresponding values in tilted positions.

In order to examine the effect of a forward or backward tilt on a preparation loaded corresponding to its position in situ, experiments have been carried out on 7 discs from 4 individuals (cases nos. 7–10). In these tests the load-bearing surfaces of the cut vertebral bodies formed a forward angle of approximately 3° with each other following removal of the posterior elements.

The results are set down in Table 6, which shows that the mean increase in pressure, still regardless of the external load, per unit area, is nil for forward tilt, while the corresponding value for backward tilt is 1.5 $kp./cm.^2$. The backward tilt will in these discs be 8° according to the above-mentioned inclination of the load-bearing surfaces.

TABLE 6

Series A.

Increase or decrease in intradiscal pressure by 5° forward and backward tilt in specimens with non-parallel loading surfaces (c:a 3° forward angle).

Case no. / Disc	Forward tilt 9 L1	10 L1	7 L2	8 L3	9 L3	10 L3	7 L4	Backward tilt 9 L1	10 L1	7 L2	8 L3	10 L3	7 L4	9 L3
Load kp/cm²	Change in intradiscal pressure kp/cm²													
2	+0.1	+0.3	+0.4	−0.1	−0.2	+0.3	+0.1	+0.7	+0.9	+0.7	+1.0	+1.1	+0.9	+1.5
4	−0.1	+0.5	+0.3	−0.2	−0.3	+0.1	−0.1	+1.0	+1.6	+1.0	+1.4	+1.6	+0.9	+2.7
6	±0	+0.6	+0.4	−0.4	−0.2	−0.2	−0.3	+1.3	+1.9	+1.3	+1.6	+1.6	+0.9	+3.6
8	+0.1	+0.5	+0.2	−0.8	−0.4	−0.1	−0.6	+1.4	+2.0	+1.2	+1.6	+1.6	+1.0	+3.5
10	+0.4	+0.6	+0.1	−1.0	−0.4	−0.1	−0.7	+1.6	+2.1	+1.1	+1.7	+1.6	+1.3	+3.0

Forward tilt: Mean change −0.034 kp/cm². Differs not significantly from 0.

Backward tilt: Mean change +1.53 kp/cm². This increase differs significantly at the 0.1 % level from the increase shown in table 4.

TABLE 7
Specimens studied.
Series B.

Case no.	Sex	Age years	Main cause of death	Discs tested
11	Male	54	Tumor cerebri	L2, L4
12	Male	53	Asthma bronchialae	L1, L3
13	Female	30	Embolia pulm	L2, L4
14	Female	20	Tumor med. spinalis	L1, L3
15	Female	56	Aneurysma cerebri	L3
16	Male	34	Fractura cranii	L1, L3

All discs showed only very small changes in the nucleus and were classified as normal.

Series B.

Eleven lumbar disc specimens from 6 individuals were studied (Table 7).

When inserting the pressure sensitive gauge in the unloaded disc specimen with arches and facets still attached, intradiscal pressures between 0.5–1 kp./cm.^{2} were recorded (mean value 0.7 kp./cm.^{2}). As earlier shown in series A, the intradiscal pressure in the unloaded isolated disc specimen is zero. Thus this pressure must depend on the tension in the ligaments and capsule surrounding the posterior bony elements. After reading the pressure of the unloaded disc the amplifier was put in zero-position and measurements were made to record the intradiscal pressures for the increasing loads, as said above. The increase in intradiscal pressure was linear to the outer applied load and no deviation from the hydrostatic behaviour was noted. First the specimens were loaded without tilt, then with a 5° forward, backward and sideward tilt. Between the series unloading was performed. Finally the intradiscal pressure was measured for increasing vertical loads without tilt. In no single case did the result from the last series of vertical load deviate from the first one. The experiments in the tilted position had thus not changed the experimental conditions, as was noted already in series A.

In Table 8 the results from the different discs are presented. A statistical analysis of the results in this table shows that there is a significant difference between the increase in intradiscal pressure caused by a 5° forward tilt on the one hand and a 5° backward tilt on the other (t-test of the difference gives $t = +8.412$).

TABLE 8

Series B.

Increase in intradiscal pressure resulting from 5° tilt in different directions in specimens with attached laminae and facets.

Case No.	Disc	Load kp		5° forwards kp cm²	5° rightwards kp/cm²	5° backwards kp cm²	5° leftwards kp/cm²
		40		0.0	+0.6	+0.9	+0.2
11	L2	85		−0.1	+0.6	+0.7	+0.1
		130		−0.2	+0.5	+0.5	+0.2
		175		−0.3	+0.7	+0.7	0.0
			$\bar{m}$	−0.15	+0.6	+0.7	+0.125
		40		0.0	+0.4	+0.4	+0.2
	L4	85		−0.1	+0.6	+0.4	+0.2
		130		−0.3	+0.8	+0.6	−0.3
		175		0.0	+0.6	+0.4	−0.2
			$\bar{m}$	−0.1	+0.6	+0.45	−0.025
		40		0.0	+0.8	+0.6	+0.4
12	L1	85		0.0	+1.0	+0.5	+0.6
		130		0.0	+1.4	+0.9	+0.7
		175		0.0	+1.3	+1.3	+0.6
			$\bar{m}$	0.0	+1.125	+0.825	+0.575
		40		0.0	+0.2	+0.2	+0.2
	L3	85		0.0	+0.2	+0.3	+0.2
		130		−0.2	0.0	+0.2	+0.2
		175		0.0	0.0	+0.2	+0.6
			$\bar{m}$	−0.05	+0.1	+0.225	+0.3
		40		0.0	+0.1	+1.0	+0.2
13	L2	85		0.0	+0.2	+1.2	+0.1
		130		0.0	+0.2	+0.9	0.0
		175		−0.1	0.0	+1.3	−0.1
			$\bar{m}$	−0.025	+0.125	+1.1	+0.05
		40		+0.1	+0.2	+0.3	+0.3
	L4	85		−0.1	+0.4	+0.2	+0.1
		130		−0.2	+0.3	0.0	0.0
		175		−0.3	+0.2	−0.1	−0.1
			$\bar{m}$	−0.125	+0.275	+0.1	+0.075

TABLE 8 (cont.)

Case No.	Disc	Load kp	5° forwards kp/cm²	5° rightwards kp/cm²	5° backwards kp/cm²	5° leftwards kp/cm²
		40	0.0	+0.3	+0.9	+0.9
14	L1					
		130	—0.3	+0.2	+0.8	+0.8
		175	—0.9	0.0	+0.8	+0.6
		$\bar{m}$	0.375	+0.15	+0.825	+0.725
		40	0.0	+0.6	+1.2	+0.1
	L3	85	+0.2	+0.5	+1.6	+0.3
		130	—0.1	+0.3	+1.1	—0.1
		175	+0.1	+0.1	+1.0	—0.2
		$\bar{m}$	+0.05	+0.375	+1.225	+0.025
		40	+0.1	+0.3	+0.5	+0.3
15	L3	85	—0.1	+0.3	+0.5	—0.1
		130	0.0	+0.1	+0.3	0.0
		175	+0.1	+0.1	+0.4	—0.1
		$\bar{m}$	+0.025	+0.2	+0.425	+0.025
		40	—0.3	0.0	+1.0	+0.6
16	L1	85	—0.4	+0.4	+1.3	+0.9
		130	—0.8	+0.6	+1.1	+0.6
		175	0.0	+1.0	+1.7	+0.5
		$\bar{m}$	—0.375	+0.50	+1.275	+0.65
		40	+0.5	+0.6	+1.1	+0.6
	L3	85	+0.3	+0.7	+1.7	+0.6
		130	+0.5	+1.0	+1.0	+0.8
		175	+0.5	+1.0	+1.0	+0.9
		$\bar{m}$	+0.45	+0.825	+1.2	+0.725
Mean values whole material			—0.06	+0.45	+0.76	+0.30

TABLE 9

Series B.

Increase in intradiscal pressure resulting from 5° sideward tilt and increasing vertical load in specimens with and without attached arches and facets.

(After the removal of the posterior bony elements the earlier planoparallel surfaces of the cut vertebrae have not been made parallel again).

Average increase (kp/cm^2).

Case no.	Disc	5° rightw. tilt with arches and facets	5° rightw. tilt without arches and facets	5° leftw. tilt with arches and facets	5° leftw. tilt without arches and facets
14	L1	+ 0.2	+ 0.7	+ 0.7	+ 0.6
	L3	+ 0.4	+ 0.8	0.0	+ 1.1
15	L3	+ 0.2	+ 0.5	0.0	+ 0.2
16	L1	+ 0.5	+ 1.1	+ 0.7	+ 1.6
	L3	+ 0.8	+ 1.5	+ 0.7	+ 0.5
Mean values of all observations (n)		+ 0.4 (20)	+ 0.9 (25)	+ 0.4 (20)	+ 0.8 (25)

The difference between 5° sideward tilt to the left and to the right is not significant ($t = +1.212$). A forward tilt of 5° on disc preparations with intact arches and facets gives no rise in intradiscal pressure compared with the same vertical load in the untilted position. A backward tilt of 5° gives compared to the untilted case an increase of 0.76 kp./cm.^{2}.

In Table 9 the differences of pressures in kp./cm.^{2} are shown which were observed on increasing vertical loads in the untilted position and on 5° sideward tilt both in the intact preparations and in the same preparations after resection of the posterior elements. In the last-mentioned series, however, the load bearing surfaces were not made planoparallel. Such experiments were performed on 5 discs from 3 individuals according to Table 9.

DISCUSSION

The results in series A show that the intradiscal pressure in a lumbar intervertebral disc at a tilt forwards, backwards or sidewards at vertical loads of 2–10 kp./cm.^{2} is higher than the intradiscal pressure at the same vertical load in a non-tilted disc. The explanation of this phenomenon is probably connected with the fact that the lateral expansion of the annulus varies nonlinearly with a decrease in distance between the vertebral bodies, so that the greater the decrease in distance, the less the increase of the lateral expansion per unit of compression (Fig.

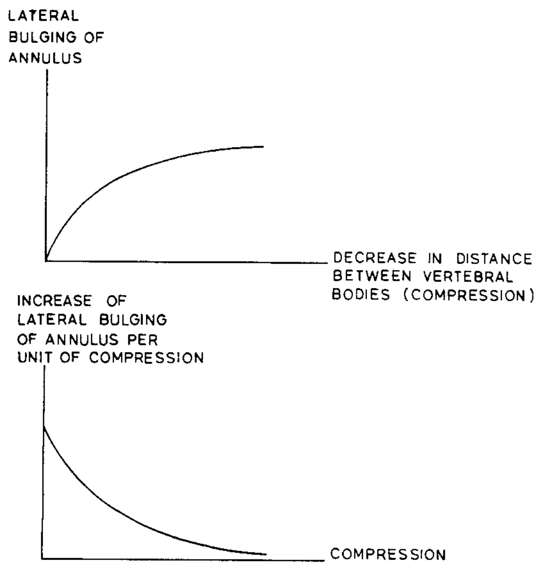


Fig. 6.
The compression of a disc gives a lateral bulging of the annulus. This bulging, however, varies nonlinearly with the compression. When compression increases, the increase in lateral bulging decreases.

6). The same property also applies to the changes of areas inside the lateral bulge on a vertical section of the disc as shown in Fig. 7.

On comparison of a non-tilted with a tilted disc, loaded with the same total force, approximately half of the circumference of the annulus will in the latter be more and the other half less compressed than in the non-tilted disc.

Due to the earlier mentioned nonlinearity there will in the tilted case be a tendency to somewhat less space left to the nucleus. Since the nucleus has a very low compressibility (*Fick* 1904, *Joplin* 1935, *Happey et al.* 1953), the pressure inside the nucleus will consequently be higher. The fact that this tendency, expressed as a percentage, is most pronounced with lower external loads (Table 5) is immediately explained by the circumstance that the nonlinearity is most marked for slight compressions, so that the variation in the lateral bulging per unit of compression is greatest for these lower loads.

It has been mentioned before that the procedure adopted for preparing the specimens involves that the discs in series A, when loaded "vertically", have been subjected to a somewhat asymmetrical stress in the vertical plane in relation to their position in situ. However, the re-

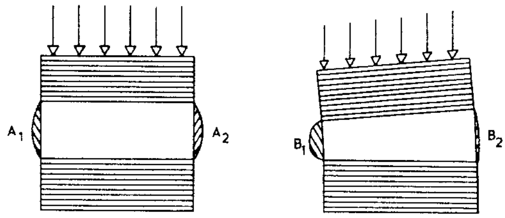


Fig. 7.
A tilt of 5° in a vertically loaded isolated disc specimen will result in a tendency to lessening of the space occupied by the nucleus pulposus and thus to an increase of the intradiscal pressure.

Technical comment

In the Fig. 7 the area B_1 is 10 % larger than the area A_1, whereas the area B_2 is 30 % smaller than the area A_2. These percentages are somewhat arbitrarily chosen but the trend can be estimated by the following calculation. An area such as A_1, A_2, B_1 and B_2 is called A (see Fig. 8), the corresponding distance between the vertebral bodies is called l and the length of the arc (annulus fibrosus) is called l_0.

One finds:

$$A \approx \frac{l_0^2}{\sqrt{6}} \sqrt{1 - \frac{l}{l_0}}$$

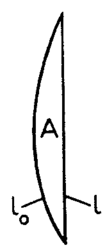


Fig. 8.
Thus, for instance, for a disc with $l_0 = 12$ mm., if $A_{1\cdot 2}$ corresponds to $l = 11$ mm. B_1 to $l = 10.5$ mm. and B_2 to $l = 11.5$ mm., then B_1 will be about 20 % larger than A_1 whereas B_2 will be about 30 % smaller than A_2.

sults also show that non-tilted discs, as defined in series A, assume as it were a position of repose, as the intradiscal pressures in this position in practically all experiments fall below those obtained at a tilt, whether forwards, backwards or sidewards.

The fact that the non-tilted disc as defined above, represents a minimum of the intradiscal pressure leads to an estimation of the relation between tilt and increase of intradiscal pressure, as shown in Fig. 9.

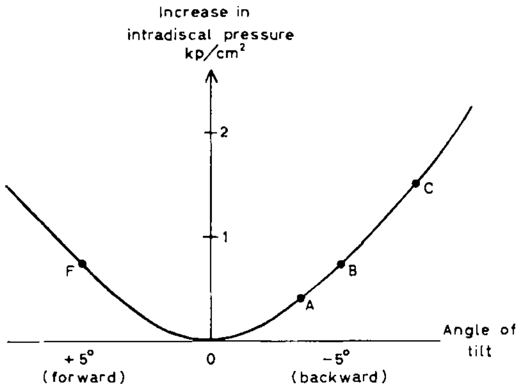


Fig. 9.
Relation between tilt and increase in intradiscal pressure. O = non-tilted isolated disc-specimen. A = zero position in situ. B and F = increase noted by 5° backward and forward tilt. C = increase noted by about 8° backward tilt.

Thus it can be expected that a tilt of more than 5° may lead to an appreciably larger increase in intradiscal pressure, a fact which is also supported by results obtained with the specimens shown in Table 6, where there has been a backward tilt of about 8°. The surfaces of the cut vertebrae in these specimens were already in the unloaded position at a 3° forward angle to each other. With the brass plate in the 5° backward tilt position this means a backward tilt of about 8° in these cases.

According to these results the increase following from 8° backward tilt will be 1.5 kp./cm.². The increase from 5° to 8° of backward tilting will thus raise the change in intradiscal pressure more than 100%.

When tilting 5° forward from the "in situ" position (Table 6. Forward tilt), no change in intradiscal pressure was seen. The explanation for this follows immediately when looking at Fig. 9. In this case the movement starts at the point A and stops in the middle between O and F.

It has earlier been shown that the vertical stress in the annulus is *comparatively* small on vertical loading, owing to the relatively high pressure in the nucleus pulposus. The tangential stress, however, is rather high and it has been calculated to exceed the total load per unit of area 3–5 times at least in the dorsal part of the annulus (*Nachemson* 1960).

The increase in intradiscal pressure resulting from tilt will thus increase this tangential stress even more. The relationship between the tangential stress in the dorsal part of the annulus and the intradiscal pressure is given in the following formula:

$$\sigma_{td} = \frac{2b\,(2b + a_v)}{a_d\,(4b + a_d + a_v)}\, p_n$$

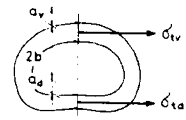


Fig. 10.

where p_n means the measured intradiscal pressure and the other symbols are explained by Fig. 10.

Now for the disc shown in Figs. 4 and 5 the following values were found (Table 3):

a_v = 7 mm., 2b = 25 mm., a_d = 4 mm., p_n = 6.4 kp./cm.^{2} non-tilted resp. 7.2 kp./cm.^{2} at backward tilt, for the external load of 4 kp./cm.^{2}, while for the external load of 10 kp./cm.^{2} p_n = 14.9 resp. 15.9.

With a load of 4 kp./cm.^{2}, backward tilt will produce an increase of σ_{td} from 20.6 to 23.2 kp./cm.^{2}, whereas the corresponding increase for a load of 10 kp./cm.^{2} will be from 48.1 to 51.3 kp./cm.^{2}. If the backward tilt had been increased to about 8° there would according to the results shown in Table 6 have been corresponding increases of σ_{td} to 25.9 kp./cm.^{2} and 54.1 kp./cm.^{2}, respectively.

Tilting will consequently not only appreciably increase the vertical stress in the annulus on the side which is most compressed, but also increase the tangential stress in the entire annulus, which in the narrower dorsal part in some cases may cause a stress which is up to 25 per cent higher than that produced by vertical loading. With a backward bending movement the annulus will here simultaneously be subjected to a very heavy stress both in the vertical and horizontal directions. It can probably be said that this may form the mechanical background for ruptures of the annulus in the lumbar intervertebral disc.

When discussing the results obtained in series B it must be clear that it is not possible directly to compare the two series, as the direction of the applied load varies between them. In series B the specimens when subjected to untilted loading have the same or nearly the same position as when in situ in the vertebral column. Even unloaded the intradiscal pressure in such specimens is between 0.5 and 1.0 kp./cm.^{2}. When the posterior elements are cut off, the earlier planoparallel weight-bearing surfaces form a forward angle of about 3° with each other. Thus the "in situ" position in itself means backward tilt of the disc of about 3° compared to the so-called resting or zero-position of the disc.

In the "isolated" specimens of series A it was shown that an increase from 5° to 8° backward tilt will raise the change in intradiscal pressure more than 100 % from 0.7 to 1.5 kp./cm.^{2}.

When a specimen with arches and facets still attached is loaded vertically at a tilt of 5° forwards no significant rise of intradiscal pressure was noted compared to the rise in intradiscal pressure in the untilted and vertically loaded specimen. On loading at a 5° backward tilt the increase in intradiscal pressure that occurs is independent of the outer applied load and reaches about 0.8 kp./cm.^{2}. If the pressure of about 0.7 kp./cm.^{2} observed from the start in these preparations already when unloaded is added there will subsequently be an increase of intradiscal pressure of about 1.5 kp./cm.^{2}. From Fig. 9 is seen that a backward tilt of 8° in the isolated disc specimen gives an increase in the intradiscal pressure of about 1.5 kp./cm.^{2}. In these cases there was no pressure when the needle was inserted in the unloaded specimens.

If those pressures that were noted when inserting the needle in the unloaded specimens with arches and facets still attached are taken into consideration the increase of intradiscal pressure brough about by a 5° backward tilt will also be 1.5 kp./cm.^{2}. Thus the posterior elements in the intact specimen which is tilted 5° backward and at the same time loaded vertically do not have any certain unloading function on the disc. Nor have the posterior elements any significant effect on the rise in intradiscal pressure at a forward tilt of 5°. When the disc is loaded vertically resp. at a tilt of 5° forwards as defined in these cases there will be a symmetrical shift around the so-called zero-position of the disc (O in Fig. 9).

An analysis of the effect of 5° sideward tilt in the intact specimen shows that the posterior elements do not have any significant effect on the intradiscal pressure (Table 9). If it is taken into consideration that there exists a difference in pressure of about 0.7 kp./cm.^{2} between the unloaded intact specimens on the one hand and the isolated discs on the other hand and that this difference is due to a 3° backward tilt, one finds that the absolute pressure at the sideward tilt does not significantly differ in the two separate loading conditions. If at the external vertical load P the resultant intradiscal pressure is P_1 resp. P_2, then in the discs without arches the "total" intradiscal pressure $= P_1 +$ the effect of sideward tilt. With arches and facets the pressure will be $= P_2 + 0.7$ kp./cm.^{2} + the effect of sideward tilt.

Thus it looks as if the facets and surrounding ligementous structures do not have any significant effect on the pressure in the nucleus pulposus when the specimen is vertically loaded and at the same time tilted 5° forward, backwards and sidewards. It has earlier been stated (*Nachemson* 1960) that the weight-bearing capacity of the posterior bony elements was about 15 % at loads in the vertical direction. This observation, however, was based on comparison between two series which can not be directly compared. It is now clear that when arches and facets are removed and the weight-bearing surfaces made planoparallel to each other, there is not the same loading condition as in the intact specimen. The "intrinsic" pressure of 0.7 kp./cm.^{2} in the intact specimen which is exerted by the ligaments and capsules around the posterior bony elements was not taken into account. If the posterior bony element have any weight-bearing capacity at loads in the vertical direction it must certainly be very small, at least for loads up till 220 kp.

The human spine is subjected to relatively high loads in the vertical direction and yet it must have good bending properties. The investigations have shown that the vertically applied load to a relatively high extent is taken up by the nucleus pulposus, thus releasing the vertical stress on the annulus fibrosus. When the disc is tilted the intradiscal pressure increases, thus relatively releasing the annulus fibrosus from higher vertical stress. In that way tilting movements are made easier. If the annulus had to carry most of the total vertical load it would be rather much compressed and tilting would have been made more difficult due to the fact that further compression on the tilted side of the already compressed annulus would be almost impossible.

SUMMARY

Normal and slightly degenerated lumbar intervertebral disc specimens (L 1–L 4) taken at autopsy from 16 individuals between 20 and 57 years of age have been studied to evaluate the effect of forward, backward and sideward tilt on the intradiscal pressure.

In a vertically loaded and tilted disc the hydrostatic properties of the nucleus pulposus are not affected.

In disc-preparations containing one disc and parts of adjoining vertebral bodies it has been found that compared to the intradiscal pressure in the non-tilted case, the pressure in healthy or slightly degenerated specimens shows an increase on tilted loading. No difference was ob-

served between L 1, L 2, L 3 and L 4 in this respect. The recorded increase in pressure in absolute measure at a tilt of 5° is about 0.7 kp./cm.^{2} independently of the applied load in the interval 2–10 kp./cm.^{2}.

The percentage increase produced by a tilt of 5° will be for an external load of 2 kp./cm.^{2}: 22 %, for 10 kp./cm.^{2}: 5 %. The increase in pressure and the relative diminution of this increase with higher loads is explained by the fact that the lateral bulging of the annulus fibrosus on tilted loading follows a nonlinear pattern, so that the nucleus pulposus has relatively less volume at its disposal with vertical loading on a tilted than on a non-tilted disc. With increasing loads this effect will, expressed as a percentage, become less and less pronounced.

The relation between tilt and increase in intradiscal pressure has been estimated and it can on the basis of the experimental findings of this examination be expected that a tilt of more than 5° may lead to an appreciably larger increase in intradiscal pressure. The increase of backward tilt for example from 5° to 8° resulted in a more than double increase of pressure from 0.7 kp./cm.^{2} to 1.5 kp./cm.^{2} compared with the pressure in the non-tilted disc.

It can thus be demonstrated that a backward tilt not only will subject the dorsal part of the annulus fibrosus in a normal lumbar disc to an increased vertical stress, but also to a tangential stress which per unit of area may be 6 or 7 times the external load. This fact may form the mechanical background to the production of dorsal annulus ruptures in the lumbar intervertebral discs.

In lumbar disc specimens with arches and facets still attached there exist a small "intrinsic" pressure of 0.7 kp./cm.^{2}, probably exerted by the capsules and ligaments surrounding the posterior bony elements. When these elements are removed no intradiscal pressure can be recorded in the unloaded discs.

The changes in intradiscal pressure caused by 5° forward, backward or sideward tilt in these specimens when subjected to vertical loading up till 220 kp. are not influenced by the posterior bony or ligamentous elements. Thus arches and facets do not have any significant effect on the tensile strains in the annulus fibrosus resulting from a forward, backward or sideward tilt of 5°.

The results that are presented clearly demonstrate the mechanism by which the lumbar discs manage to combine their function of withstanding a heavy vertical stress with the ability to tilt in various directions.

RESUME

Des spécimens de disques intervertébraux lombaires normaux ou légèrement dégénérés (L 1–L 4), prélevés à l'autopsie chez 16 individus âgés de 20 à 57 ans, ont été étudiés afin d'évaluer l'effet de l'inclinaison antérieure, posteérieure et latérale sur la pression intradiscale.

Dans un disque chargé verticalement et incliné, les propriétés hydrostatiques du noyau pulpeux ne sont pas affectées.

Dans les préparations discales contenant un disque et des parties des corps vertébraux adjacents, on a constaté que, comparée à la pression intradiscale dans les cas non-inclinés, la pression a tendance à d'accroître chez les spécimens normaux ou légèrement dégénérés qui subissent une charge en position inclinée. Aucune différence n'a été observée à cet égard entre L 1, L 2, L 3 and L 4. L'augmentation maximum de la pression en chiffre absolu à une inclinaison de 5° est d'environ 0,7 kg/cm^2, indépendamment de la charge appliquée dans l'intervalle entre 2 et 10 kg/cm^2.

L'augmentation proportionnelle à une inclinaison de 5° est pour une charge externe de 2 kg/cm^2: 22 %, pour 10 kg/cm^2: 5 %. L'augmentation de la pression et la diminution relative de cette augmentation à des charges plus élevées s'explique par le fait que le gonflement latéral de l'anneau fibreux sous charge inclinée ne suit pas une formule linéaire. Le volume du noyau pulpeux est relativement moindre lorsqu'il est posé avec une charge verticale sur un disque incliné que sur un disque non incliné. Avec des charges accrues, l'effet proportionnel sera de moins en moins prononcé.

Le rapport entre l'inclinaison et l'augmentation a été évaluée et sur la base des trouvailles expérimentales résultant de ces études, on peut considérer qu'une inclinaison de plus de 5° signifie une augmentation beaucoup plus forte de la pression intradiscale. C'est ainsi que l'augmentation de 5 à 8° de l'inclinaison postérieure provoque une augmentation de pression de plus du double, soit de 0,7 kg/cm^2 à 1,5 kg/cm^2, comparée avec la pression sur un disque non-incliné.

Il peut donc être démontré qu'une inclinaison postérieure non seulement fait subir à la partie dorsale de l'anneau fibreux d'un disque lombaire normal une tension verticale accrue, mais aussi une tension tangentielle qui peut atteindre par unité de surface 6 ou 7 fois la charge externe. Ce fait peut former l'arrière-plan mécanique des ruptures dorsales de l'anneau dans les disques intervertébraux lombaires.

Dans les spécimens de disque lombaire avec arcs et facettes encore

attachés, il existe une petite pression intrinsèque de 0,7 kg/cm² probablement exercée par les capsules et les ligaments entourant les éléments osseux postérieurs. Lorsque ces éléments sont retirés, aucune pression intradiscale ne peut être enregistrée sur ces disques non chargés.

Les changements de pression intradiscale causés par une inclinaison antérieure, postérieure et latérale de 5° chez ces spécimens soumis à une charge verticale allant jusqu'à 220 kg ne sont pas influencés par les éléments osseux ou ligamenteux postérieurs. Les arcs et les facettes n'ont aucun effet important sur la sensibilité de l'anneau fibreux à la tension résultant d'une inclinaison antérieure, postérieure ou latérale de 5°.

Les résultats qui sont présentés démontrent clairement le mécanisme par lesquel les disques lombaires combinent leur fonction de résistance à un lourd effort vertical avec la possibilité d'une inclinaison dans des directions variées.

ZUSAMMENFASSUNG

Normale und leicht degenerierte, lumbale disci intervertebrales (L1–L4), die anlässlich der Autopsie von 16 Personen im Alter von 20–57 Jahren erhalten worden waren, wurden untersucht um die Wirkung der vorwärts, rückwärts und seitwärts Beugung auf den intradiskalen Druck zu bestimmen.

Bei einem vertikal belasteten und geneigten Discus werden die hydrostatischen Eigenschaften des Nucleus pulposus nicht angegriffen.

An Diskuspräparaten, die einen Diskus und Teile der anliegenden Wirbelkörper enthielten, wurde gefunden, dass im Vergleich mit dem intradiskalen Druck bei dem nicht geneigten Falle, der Druck in gesunden oder leicht degenerierten Exemplaren eine Zunahme bei schräger Belastung aufweist. Keine Verschiedenheit wurde in dieser Hinsicht zwischen L1, L2, L3 und L4 bemerkt. Die aufgezeichnete Druckzunahme in absoluter Messung bei einer Neigung von 5° ist ungefähr 0,7 kp/cm² unabhängig von der angewandten Belastung im Zwischenraum 2–10 kp/cm².

Die percentuelle Zunahme, welche bei einer Neigung von 5° erzeugt wird, wird für eine äussere Belastung von 2 kp/cm²: 22 %, für 10 kp/cm²: 5 % sein. Die Druckzunahme und die verhältnismässige Abnahme dieser Zunahme bei grösserer Belastung kann durch die Tatsache erklärt werden, dass die laterale Herausschwellung des annulus

fibrosus bei schräger Belastung einem nichtlineären Muster folgt, so dass der nucleus pulposus verhältnismässig weniger Volumen bei vertikaler Belastung auf einen geneigten als auf einen nicht geneigten Diskus zur Verfügung hat. Mit zunehmender Belastung wird dieser Effekt, ausgedrückt in Percenten, immer weniger ausgesprochen werden.

Die Beziehung zwischen Neigung und Zunahme an intradiskalem Druck ist geschätzt worden und es ist auf Grundlage der experimentellen Befunde dieser Untersuchung zu erwarten, dass eine Neigung von mehr als 5° zu einer bedeutend grösseren Zunahme des intradiskalen Druckes führen kann. Die Zunahme der Rückwärtsneigung von 5° bis zu 8° ergab zum Beispiel eine mehr als doppelte Druckzunahme von 0,7 kp/cm^2 bis zu 1,5 kp/cm^2, verglichen mit dem Druck in dem nichtgeneigten Diskus.

Es kann daher gezeigt werden, dass eine Rückwärtsneigung den dorsalen Teil des annulus fibrosus in einem normalen lumbalen Diskus nicht nur einer zunehmenden vertikalen Beanspruchung unterwerfen wird, sondern auch einer tangentialen, die per Flächeneinheit 6–7 malgrösser sein kann als die äussere Belastung. Diese Tatsache bildet möglicherweise den mechanischen Hintergrund für die Entstehung vor dorsalen Annulusberstungen der Lendezwischenwirbelscheiben.

In lumbalen Diskuspräparaten, an denen Bögen und Fazetten noch vorhanden sind, besteht ein kleiner „innerer" Druck von 0,7 kp/cm^2, der wahrscheinlich von den Kapseln und Bändern, die die rückwärtigen Knochenelemente umgeben, ausgeübt wird. Wenn diese Elemente entfernt werden, kann man keinen intradiskalen Druck am unbelasteten Diskus verzeichnen.

Die Veränderungen im intradiskalen Druck, welche durch 5° Vorwärts-, Rückwärts- oder Seitwärtsneigung in diesen Präparaten hervorgerufen werden, wenn sie einer vertikalen Belastung bis zu 220 kp unterworfen werden, werden nicht von den rückwärtigen knöchernen oder Bandelementen beeinflusst. Es haben daher Bögen und Fazetten keinen bedeutsamen Effekt auf die Dehnungsbeanspruchungen des Annulus fibrosus, die sich aus einer Vorwärts-, Rückwärts- oder Seitwärtsneigung von 5° ergeben.

Die hier vorlegten Ergebnisse zeigen in klarer Weise den Mechanismus durch den die lumbalen Zwischenwirbelscheiben es vermögen ihre Funktion des Widerstandes gegen schwere vertikale Beanspruchung mit der Fähigkeit sich in verschiedenen Richtungen zu neigen, zu vereinen.

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