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THE WEIGHT-CARRYING FUNCTION OF THE HUMAN SPINE

By

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INTRODUCTION

It is generally accepted that the S-shape of the human spine is a consequence of the upright position. The kyphotic curves are considered to be inherited from quadruped ancestors and are present at birth but the lordotic curves develop later, the lumbar lordosis not until an erect position is adopted.

The weaknesses of an S-shaped column as compared to a straight one are obvious but it has been emphasized that if a weight-carrying column has to be curved then a double curved one is stronger than a singly curved, C-shaped column (*Strasser* 1913). Further, it is claimed that the S-shaped spine acts as a spring, damping the force of impacts travelling upwards from the feet towards the head. Since the works of *H. v. Meyer* (1853) it has been assumed that the spine is in a passive equilibrium with the curves evenly distributed on both sides of the line of gravity. This line is assumed to pass through the atlanto-occipital joint and to intersect the spine at C_6, Th_9 and S_3 (see fig. 1). *Steindler* (1955) adopts this view in writing: ... "the spine as a whole approaches the line of gravity" ... "each curve is compensatory to its neighbour with the result that the line of gravity as it passes upward ... intersects with all four curves of the spine at certain levels". What is meant by "the line of gravity", however, is not defined. It follows from this assumption that gravity would tend to increase *all* the curves of the movable spine, e.g. it would tend to bend the spine backwards in the lumbar portion. This point of view is also clearly exhibited by an illustration from a German textbook of anatomy (*Braus* 1929) from which fig. 2 has been taken. As gravity would tend to increase the lumbar lordosis, the forces that counteract it must act ventrally on the spine, and if muscular work is not involved, it must be the long anterior ligaments of the spine that carry the burden. This conclusion has also been drawn e.g. by *Steindler*.

Against the conception of the spine as a passively balanced spring several objections have been raised. *Duchenne* (1885) and *DuBois Reymond* (1903) gave good reasons for their view that it is impossible to maintain the upright position of the spine without muscular work. The former concluded from his direct observations of muscle actions in normal subjects and in pathological cases, that the flexors of the lumbar spine (i.e. the abdominal muscles) and the extensors of the spine (muscles of the back) must work synergetically in order to keep it erect. Both views have to a large degree survived, so that the common explanation of the function of the spine and its muscles to day seems to be that 1) gravity tends to increase all curves of the spine (cf. fig. 1) which acts as a compressible spring; 2) the muscles in front and back of the spine keep it in balance, and the relative strength of abdominal and back muscles determine the individual shape of its curves. It is easy to see that in such case it would be illogical to be interested in the strength of the lower back muscles as these only would assist gravity in increasing the lordosis, thus making it even harder for the abdominal muscles to compensate for this tendency.

The idea that posture is maintained either passively or by the synergetic action of two antagonistic muscle groups has been rejected for other joints of the body, most clearly in the case of the ankle-joints. For these joints it was found that the line of gravity passes ventrally to the frontal axis of the joints (*DuBois Reymond* 1903, *Hellebrandt et. al.* 1937) and that there is continuous activity in the soleus muscles of the calf to compensate for the pull of gravity (e.g. *Åkerblom* 1948, *Joseph* and *Nightingale* 1952). The muscles in front of the ankle joints, however, are inactive, unless the postural sway carries the line of gravity behind the axis. The activity of the antigravity muscles is brought about by reflexes from the muscle-spindles in the stretched calf muscles, and it is in good accordance with the generally accepted view on reflexes that only one set of the antagonistic pair of muscle groups in front and back of the ankle joint is active at a time: A muscle reflex includes not only the activation if the direct effectors but also the inhibition of their antagonists (cf. *Sherrington* 1947).

This principle, valid for the muscles around the ankle-joint, is most probably also valid for other antigravity muscles, including the muscles of the trunk. For the spine the muscles in front and back would then

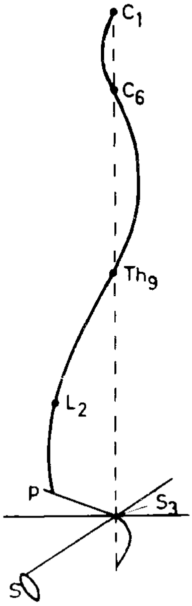

Fig. 1.
Postulated course of the line of gravity in relation to the curves of the spine (*v. Meyer* after *Steindler*).

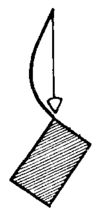

Fig. 2.
The spring-like action of the lumbar spine as postulated by *Braus*.

serve, not by acting synergetically as a set of backstays to a mast, but rather one set at a time, as the guy of a derrick (see fig. 3). In the present work this hypothesis has been put to a test in two ways: 1) It has been attempted to determine the location of the line of gravity in relation to the spinal column, especially to its lumbar portion in the standing position. 2) The activity of the trunk muscles has been registered electro-myographically in a number of subjects in an easy standing position. The two series of investigations are complementary in the way that if the position of the line of gravity is known then it can be predicted what muscles must be antigravity-muscles, and vice versa.

DETERMINATION OF THE LINE OF GRAVITY

It must be emphasized that for each body segment, the "line of gravity" is the vertical line passing through the center of gravity of that part of the body which lies above the joint which is to be studied. In the present investigation we shall choose to study the passage of the line of gravity relative to the 4th lumbar vertebra, the vertebra that lies most ventrally in the lumbar lordosis. First, it was attempted to localize the common line of gravity for head, arms and trunk in relation to some easily recognizable line. Second, the position of this new line was determined in relation to the center of the body of the 4th lumbar vertebra. As this new line the vertical line through the outer ear-opening was chosen. In the normal position of the head the ear-opening lies almost in the same frontal plane as the axis of the atlanto-occipital joint and as the hip joint.

The method for locating the line of gravity was that suggested by *DuBois Reymond* (1903) (see fig. 4). P is the body weight, p is measured by a strain gauge arrangement under the platform, the length, l, of which is known. It follows that $a = \frac{p}{P} \times l$. The position of a plump line though the ear-opening in relation to the rear support of platform is also measured and so the line of gravtiy can be located in relation to this line. As only the line of gravity for the head, arms and trunk is of interest when dealing with the lumbar spine, a procedure suggested by *Åkerblom* (1948) was adopted: The subject and the platform were immersed in water reaching to the upper edge of the sacral bone, thus making the legs and buttocks practically weightless. The weight P, in the above formula was then reduced by the weight of the immersed legs as estimated from the volume of water they displaced.

Five series of measurements of this kind have been performed on 3 male subjects, 20–25 years old. On an average the line of gravity for head, arms and trunk was found to lie 1.3 cm. in front of the vertical through the ear-opening, but the variation was considerable, even in the same subject, the range being —3 cm. to + 4.2 cm. This variation is not only due to the uncertainty of the measuring: a critical evaluation of its different steps (volume and weight measuring, calibration errors etc.) revealed a maximum error of about 1 cm. if all errors had the same direction. The variations found in the position of the line of gravity for the upper part of the body, therefore, are no doubt real and show that it can shift several cm. backwards and forwards in relation to the vertical through the ear-opening. In spite of this uncertainty the vertical through the ear-opening will be used as the best approximately to the real line of gravity, but it must be remembered, that this real line of gravity most probably lies about 1 cm. ventrally to the ear line.

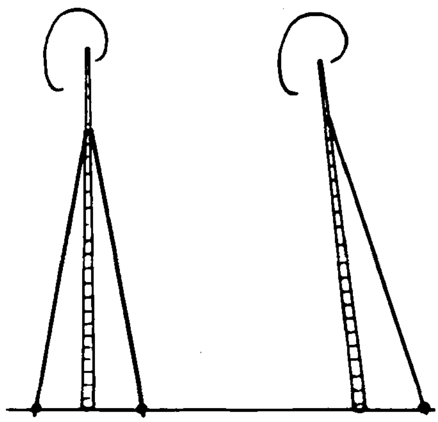

Fig. 3.
The "mast-and-backstays" principle (left) and the "guy-and-derrick" principle (right) of muscular action on the spine.

The position of the plumb line through the ear-opening in relation to the curvatures of the spine has now been investigated in two ways. 1) X-ray pictures of the spine as seen from the side have been taken in 6 adult males and 1 adult female in a free standing position with the vertical through the ear-opening marked. 2) The position of the line has been calculated on the basis of anthropometric measurements on 201 boys, aged 7 to 16, made by *Asmussen & Heebøll-Nielsen* (1959).

The X-ray pictures (see fig. 5) showed that the vertical through the ear-opening on an average fell 1 cm. in front of the center of the body of the 4th lumbar vertebra, the range being —2 cm. to + 6 cm. All other vertebrae, with the exception of the two upper cervicals lie behind this line, Th_{7-8}—which correspond to the top of the kyphosis—for instance 5 to 10 cm. (avg. 8 cm.) behind it. Considering that the real line of gravity for this part of the body on an average lies 1.3 cm. ventrally to the ear line, it seems reasonable to assume that on an average and for the majority the line of gravity runs ventrally to the center of the most prominent lumbar vertebra, L_4. There seems to be no support whatever for the assumption that this vertical intersects with the spine as shown e.g. in *Steindler's* drawing (see fig. 1).

The anthropometric measures necessary for calculating the distance *ear line—center of* L_4 (d in fig. 6) were the vertical distance from the deepest point in the lumbar lordosis to the ear-opening (l in fig. 6) and the angle, v between a line from the joint to the ear-opening and the vertical. d in fig. 5 can be calculated from $d = l \times tg\, v$ and is the distance from the skin covering the tip of processus spinosus of L_4 to the ear line. The distance from the tip of proc. spin. L_4 to the center of the body of the same vertebra is estimated from the relative distance found from 1) the above mentioned X-ray pictures 2) measurements on different anatomical preparations 3) anthropometric data from *Martin & Seller,* (1958). It was found that the mean height of a lumbar vertebra is 5.26 pct. of the total length of the presacral spine; this again is 32 pct. of total body height. Further the ratio

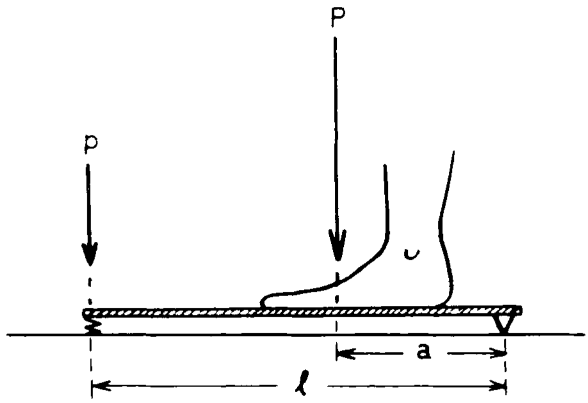

Fig. 4.
Method for determination of the course of the line of gravity. *P* bodyweight. *p* pressure on front end of platform. *l* length of platform. *a* distance from knife at rear end of platform to line of gravity.

height: sagittal diameter (including proc. spin.) of a lumbar vertebra = 0.35 and the ratio
height of corpus: sagittal diameter of corpus of a lumbar vertebra = 0.79.

By means of these ratios, and assuming the layer of skin etc. on the proc. spin. to be 0.3 cm. thick, the following data were found in the 201 boys:

Height of boys cm.	120–129	130–139	140–149	150–159	160–169	170–
Number	30	37	48	37	29	20
Ear line-center of L_4	1.4 cm.	1.7 cm.	0.4 cm.	0.1 cm.	0.9 cm.	2.9 cm.

The weighted mean was 1.05 cm.

The result of these calculations, based on anthropometric measurements, again suggests that on an average the line of gravity for the

Fig. 5.
X-ray picture of vertebral column with plumb line through ear-opening marked. Slightly retouched. Male subject, easy standing.

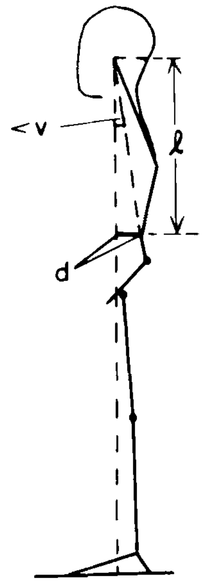

Fig. 6.
Measuring points, angles and distances used for estimation of distance *d* from deepest point at the lumbar lordosis to vertical through ear-opening.

head, arms and trunk runs about 2 cm. in front of the centre of the most prominent vertebra in the spine, L_4. The range and distribution of the individual values around the means will be discussed under "Discussion".

THE ACTIVITY OF THE TRUNK MUSCLES IN STANDING

Paired skin electrodes, about 6 mm. in diameter, were fixed to the skin by means of adhesive tape. One pair was placed on the lumbar part of the erectores spinae, one on the dorsal part of the same muscle and one on the m. rectus abdominis between the xiphoid and umbilicus. The subjects were standing in an easy position with the eyes directed horizontally towards a mark on the wall. The electromyograms were recorded after proper amplification by a "*Disa*" electromyograph

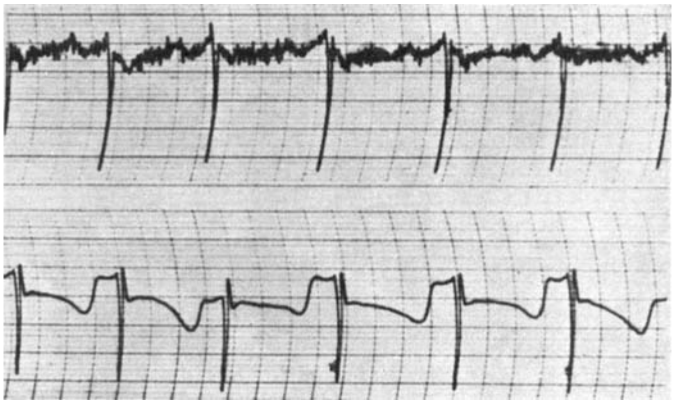

Fig. 7.
Electromyograms. Above: Lumbar portion of erectores spinae. Below: Abdominal muscles. Easy standing, typical distribution of activity (*large spikes are e.c.g.s.*).

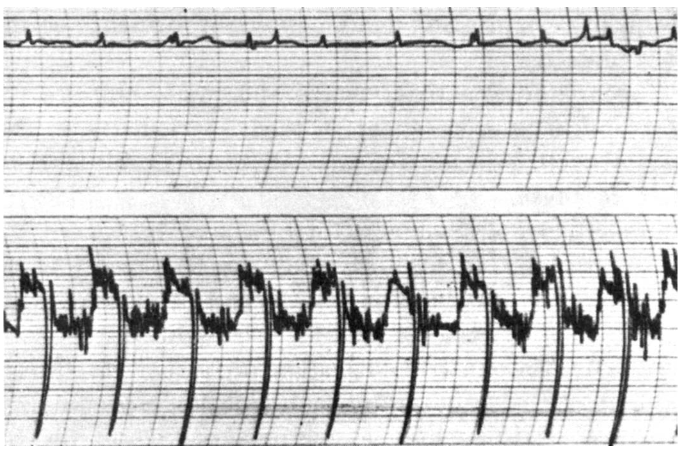

Fig. 8.
Electromyograms. Above: back muscles, below: abdominal muscles. Easy standing, atypical distribution of activity, found in 3 cases out of 22.

by an inkwriting recorder after and during several minutes of standing. Some twenty subjects were investigated, males and females, aged 20–50 years.

One common feature of all the recordings was that only one set of the antagonists abdominal muscles—back muscles were active at a time. In the majority the back muscles were the active muscles, but in 3 cases the abdominal muscles were the active ones.

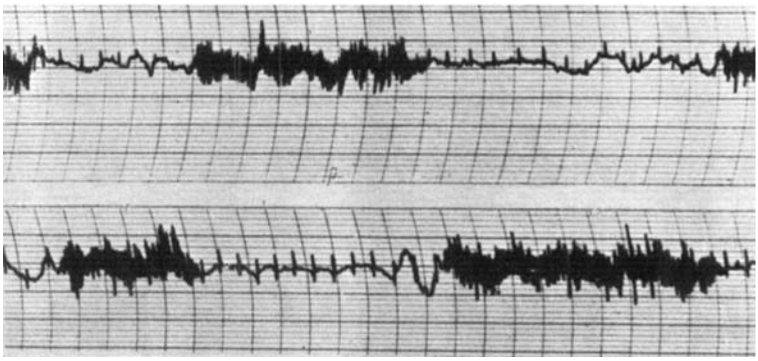

Fig. 9.
Electromyograms. Above: back muscles, below: abdominal muscles. Shift of activity on voluntary leaning forward and backward ih the hip joint.

When it was the back muscles that were active, the activity was continuous (fig. 7). The normal postural sway took place predominantly in the ankle joints and had no apparent influence on the activity of the back muscles.

In the 3 who showed activity in the abdominal muscles (fig. 8) the lumbar back muscles were silent. A slight periodicity in the activity of the dorsal back muscles and also in the abdominal muscles was seen in one of these.

On voluntarily leaning slowly forward and backward in the hip joint the activity shifted abruptly from back muscles to abdominal muscles without any overlapping (fig. 9) but sometimes with a small interval of silence between the two muscle groups.

The results of the electromyographic investigation thus was that in the majority of the subjects the back muscles, especially the lumbar portion of the erectores spinae, were active while the abdominal muscles were silent. Only in 3 out of some twenty the opposite was the case. In no cases were both set of muscles active simultaneously. (The obliquus abd. externus was studied in a few cases. It showed weak periodic activity synchronous with the respiration or no activity at all).

DISCUSSION

The attempts to locate the line of gravity in relation to the spine showed that in the majority of cases this line runs in front of the most prominent lumbar vertebra, L_4. This is in contrast to the view expressed by *v. Meyer* and more recently by *Steindler* and others, cf.

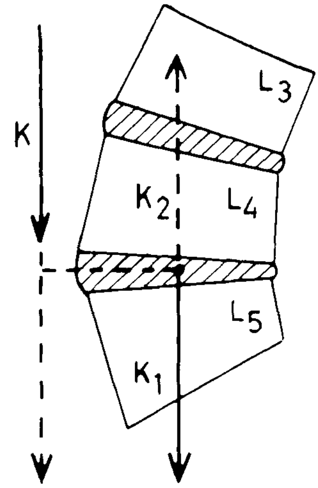

Fig. 10.
Schematic drawing showing the action of the pull of gravity (*K*) in relation to a frontal axis through the intervertebral disc between L_4 and L_5.

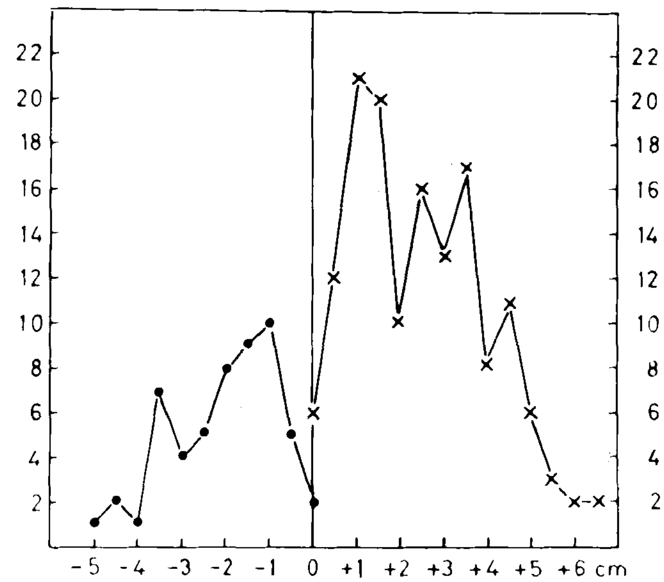

Fig. 11.
Distribution curve for 201 boys, showing the frequency of negative (●) and positive (×) distances from midpoint of L_4 to vertical line through ear-opening. Direction *ventral* is reckoned positive.

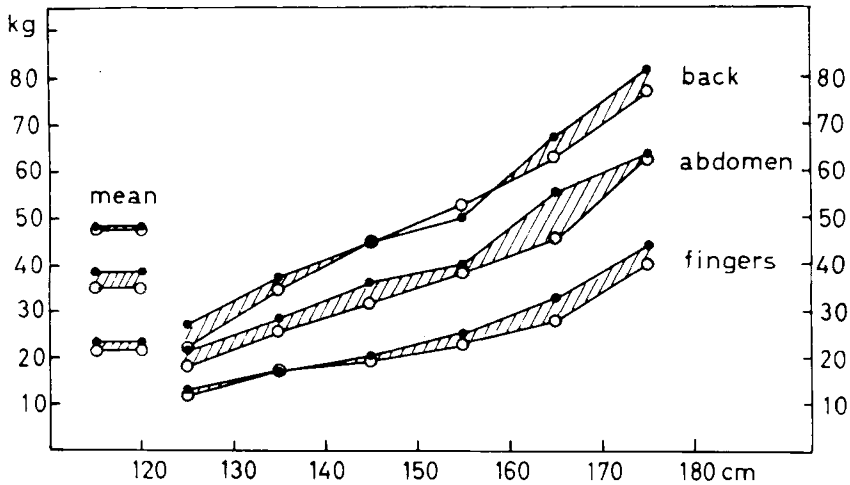

Fig. 12.
Strength of backmuscles, abdominal muscles and finger flexors (handgrip) in relation to body height in 201 boys. Full circles: Boys with ear-line passing ventrally to midpoint of L_4 (75 per cent). Circles: Boys with ear-line passing dorsally to midpoint of L_4 (25 per cent).

figures like fig. 1. The effect of gravity on the spine can therefore not be as described by these authors, viz. a compressing one, tending to accentuate all curves of the spine, including the lumbar lordosis. The effect must be as showed schematically in fig. 10. The pull of gravity, K, is moved as K_1 to a point in the middle of the discus between L_4 and L_5 through which the axis of movement is considered to pass. To do this a pair of forces, K-K_2, is added with a torque $K \times a$, where a is the distance from the axis to K. K_1 will be absorbed by the elastic resistance of disci, vertebrae etc., while $K \times a$ will tend to move the system counter clock-wise, i.e. it will tend to straighten out the lumbar lordosis. From the shape of the spine it is justifiable to assume that the segmental lines of gravity run ventrally to all the other vertebrae also. The result will be that gravity tends to pull the spine forwards, and the muscles that must act to prevent a fall must be the muscles of the back. Activity in the flexors of the spine (abdominal muscles) should be unnecessary.

These conclusions are corroborated by the electromyographic findings which, in the majority, showed continuous activity in the back muscles, silence in the abdominal muscles.

In the majority, therefore, the spine does not act as a loaded spring, but rather as an S-shaped clothes-peg, fixated at the lumbo-sacral joint and carrying the weight of the upper part of the body as would the peg a hat hung on it.

As mentioned previously there was a quite considerable scatter of the results around the average. For the 201 boys it was found that the vertical through the ear-opening on an average passed about 1 cm. ventrally to the mid-point of the 4th lumbar vertebra but a distribution curve of the individual values (fig. 11) indicates that there are two tops on the curve, one representing the negative values (about 50) and one the positive values (about 150). This conforms to the findings that also a certain number of those investigated electromyographically showed activity in the abdominal muscles and not as the majority in the back muscles. Also the 25 pct. of the children presumably must use their abdominal muscles as antigravity muscles in ordinary standing.

A closer analysis of these 25 pct. revealed that they also in other respects deviated from the majority: On an average they had a somewhat more pronounced lumbar lordosis and pelvic inclination than the majority, and as fig. 12 shows they were generally weaker in back, abdominal and finger muscles than the rest. Also, they weighed less in relation to height and were smaller in relation to age than the majority. The "breadth index" (ratio *distance between epicondyles: height*), however, was as in the rest of the children. It would be of great interest to know if these about 25 pct. of the children, who carry their body somewhat more backward using the abdominal muscles as antigravity muscles and apparently are a little less well developed muscularly, later in life have more or less troubles with their backs than the majority.

SUMMARY

The view that the curves of the human spine are evenly distributed on both sides of the line of gravity (cf. fig. 1) has been re-investigated by determining the position of this line in relation to the joints of the lumbar column and by electromyographic studies of the muscles in front and back of the spine in the standing position.

It was found that the common line of gravity for head, arms and trunk on an average lies 1.3 cm. ventrally to the vertical line through the ear-opening in easy standing.

The vertical through the ear-opening runs on an average 1.05 cm.

ventrally to the midpoint of the body of the 4th lumbar vertebra. In 50 out of 200 boys, however, this line passed behind the midpoint, whereas in the majority (150 out of 200) it passed in front of it.

In the majority of the subjects tested the muscles of the lower erectores spinae acted as antigravity muscles in standing, whereas the abdominal muscles were silent. But in 3 out of some 20 subjects the abdominal muscles were antigravity muscles, and the lumbar were silent.

It is concluded, that in the majority the line of gravity passes in front of the spinal column, which is held mainly by the reflex contraction of the muscles of the back. In a minority (less than 25 pct.) the line of gravity passes behind the midpoint of the 4th lumbar vertebra and the abdominal muscles are the active antigravity muscles. This minority appears to be less well developed physically than the majority.

The spine, therefore, does not in general approach the line of gravity, and gravity will not tend to increase all curves of the spine, but will rather tend to diminish the lumbar lordosis.

RESUME

L'idée que les incurvations de la colonne vertébrale sont également réparties des deux côtés de la ligne de gravité (fig. 1) a été reconsidérée en déterminant la position de cette ligne en relation avec les articulations de la colonne lombaire et par des études électro-myographiques des muscles devant et derrière le rachis en position verticale.

Il a été trouvé que la ligne courante de gravité pour la tête, les bras et le tronc est en moyenne de 1,3 cm ventralement par rapport à la ligne verticale qui traverse le trou de l'oreille en position debout.

La verticale à travers le trou de l'oreille se trouve en moyenne à 1,05 cm du côte ventral du point central du corps de la 14ème vertèbre lombaire. Chez 50 des 200 garçons examinés, cette ligne passait derrière le point central, tandis que chez la majorité (150 sur 200) elle passait devant celui-ci.

Chez la majorité des sujets examinés, les muscles de la colonne tendue agissaient comme muscles anti-gravité dans la position debout tandis que les muscles abdominaux étaient au repos. Mais chez trois sur une vingtaine de sujets, les muscles abdominaux étaient les muscles anti-gravité et les muscles lombaires étaient au repos.

Il en est conclu que chez la majorité la *ligne de gravité passe devant* la colonne vertébrale qui est maintenue tendue principalement par le réflexe de contraction des muscles du dos. Chez une minorité (moins de 25 %), la ligne de gravité passe derrière le point central de la 4ème vertèbre lombaire et les muscles abdominaux sont les muscles anti-gravité actifs. Ily appert que cette minorité est moins bien développée physiquement que la majorité.

C'est pourquoi, la colonne vertébrale ne se rapproche pas en général de la ligne de gravité et al gravité ne tend pas à accroître les incurvations du rachis, mais plutôt à diminuer la lordose lombaire.

ZUSAMMENFASSUNG

Die Ansicht, dass die Kurven der menschlichen Wirbelsäule gleichmässig zu beiden Seiten der Schwerlinie (Fig. 1) verteilt sind, wurde neuerdings mittels Bestimmung der Lage dieser Linie im Verhältnis zu den Gelenken der Lendenwirbelsäule und mittels elektromyographischen Untersuchungen der Muskeln vor und hinter der Wirbelsäule in stehender Stellung bestimmt.

Man hat gefunden, dass die gemeinsamme Schwerlinie vom Kopf, den Armen und dem Rumpf im Durchschnitt 1,3 cm ventral von einer Vertikalen durch die Ohröffnung bei bequemer Haltung liegt.

Die Vertikale durch die Ohröffnung liegt im Durchschnitt 1 cm ventral vom Mittelpunkt des Körpers des 4. Lendenwirbels. Bei 50 von 200 Knaben zog diese Linie hinter dem Mittelpunkt vorüber. In der Mehrzahl jedoch (150 von 200) lag sie vor ihm.

In der Mehrzahl der untersuchten Individuen wirkten die Muskeln des unteren Erector trunci als Gegenschwergewichtsmuskeln beim Stehen, während die Bauchmusklen inaktiv waren. Bei dreien aber von 20 Individuen betätigten sich die Bauchmuskeln als Gegenschwergewichtsmuskeln, während die Lendenmuskeln inaktiv waren.

Man schlisst daher, das in der Mehrzahl der Fälle die Schwerlinie vor der Wirbelsäule liegt, und dass diese hauptsächlich durch die Reflexkontraktion der Rückenmuskeln aufrecht erhalten wird. In der Minderzahl (weniger als 25 %) liegt die Schwerlinie hinter dem Mittelpunkt des 4. Lendenwirbels und die Bauchmuskeln sind dann die aktiven Gegenschwergewichtsmuskeln. Diese Minderzahl scheint körperlich weniger gut entwickelt zu sein als die Mehrzahl.

Deshalb erreicht die Wirbelsäule im allgemeinen nicht die Schwerlinie und die Schwerkraft wird nicht die Neigung haben alle Kurven

der Wirbelsäule zu verstärken, sondern wird vielmehr die Lendenlordose zu verringern versuchen.

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