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Original Research Article

The Distribution of Bone Mass in the Cross Section of Human Vertebra and Their Functional Analysis

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Abstract: One hundred two cross sections of thoracic and lumbar spines at the base and at half the length of each (63 male ,74 female) were examined with respect to x-ray density .The distribution of x-ray density was recorded using the computer densitometry .An irregular distribution of density on the sections plane was found. The higher density levels lied at the cranial and caudal edge, between zones of less density. This distribution complies with the stress diagram which would beg to bending stress in sagittal level by evaluating the biomechanical literature, one comes to the conclusion that at least the spines of the thoracic and lumbar are adjusted at a bending stress and in this manner were also stressed in life time. Functional adaptation of the bone on its mechanical stress is reached by several factors of bone materials at the same time.

Keywords: Human thoracic and lumbar spine, functional adaptation, x-ray density, tensile breaking strength.

INTRODUCTION

Since Bourgery [1], Meyer [2], Wolf [3] and Roux [4] many trials were made in an attempt to explain the conformity between the form and the structure of the skeleton related to the functional stress. In general it was agreed that the architecture of the bone is affected by its mechanical stress. But, at that time no sure evident was found for the influence of the bone structure on the stress distribution.

First in 1948, 1950 and 1954 Pauwels showed the way for providing evidences with the observations that the material distribution in the bone was proportional to the stress distribution. When the structure mass of an X-Ray was compared with optical stress model experiment of local stress mass (Isochromats), Pauwels found good conformity between both of them.

Kummer [5-6] confirmed that the bone should be seen as: a body with even strength that’s to say the amount of material at any point of the bone cross section is in the same ratio to the local stress mass. He regarded the adaptation of the bone as a cybernetic control process, according to which the bone deformation is determined by the local stress mass. For this reason, Kummer differentiates between the long term mechanism (the deformation of the organic matrix) and the short term mechanism (deposits or removal of the calcium salts).

This hypothesis shall be based on the function of the structures of the vertebral column. In this case, it shall deal with the investigation of the human vertebra.

Barthez[7] has already mentioned the diagonal position of the vertebra in human beings and animals without giving an explanation for that.

Strasser [8] confirmed that the vertebra form leverages, at which the muscles which are attached very tightly to the vertebral column, are connected to the dorsal wall. Slijper [9] and Kummer [6] share the same opinion.

But on the other hand, the way of the mechanical stress of the vertebra is described in medical literature in so many different ways.

Strasser [8], based on comparisons observed, claimed that the vertebra have the same direction of all resulted muscles attached to them. According to the above mentioned only a clear axial stress can be evident.

After examinations on so many skeletons of different mammals, Slijper [9] came with so complicated rules, according to which, the vertebra is oriented and formed, in a normal situation in the direction of the muscles attached to them have the shortest length possible.

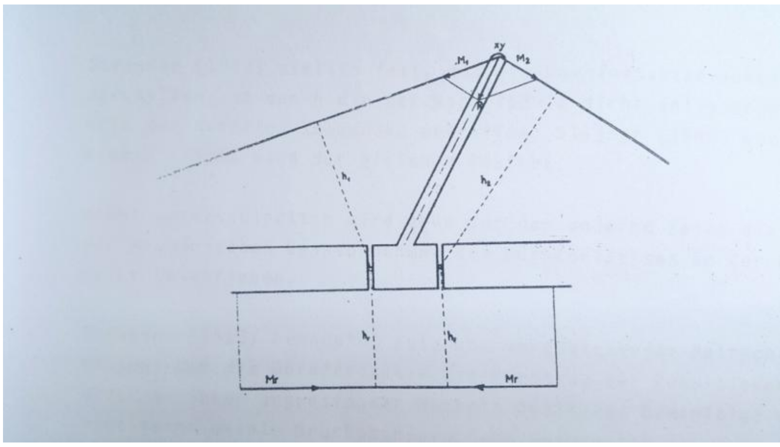

Fig-1: Graphic determination of the position of the resulting strength R in case of an axial stress of the vertebra [6]

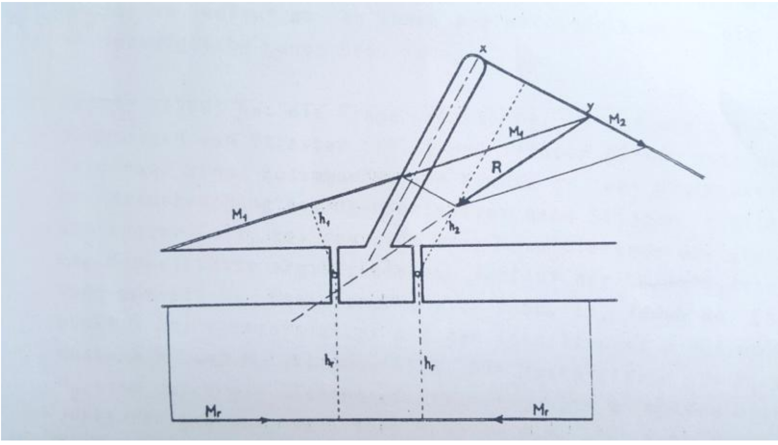

Fig-2: Graphic determination of the position of the resulting strength R in case of a leaning stress of the vertebra [6]

Kummer [6] has investigated the question whether and how the assertions of Strasser [8], Slijper [9] can be compatible. Summarizing this he was able to determine two possibilities of stress of the vertebra according to Slijper. The first case, in which the resultant of the attached muscle power is obtained, has the same direction of the vertebra. This results (as in figure 1) when the end point $_x$ of the vertebra meet at the cross section point $_y$ of both muscles M_1 and M_2The muscle power of M_1 and M_2, due to their equilibrium conditions are given atboth sides of the spinal junction, as their moments M_1 h_1 as well as M_2 h_2 are compensated by the moments of the straight stomach muscles M_r $h_{r.}$ The resulting power Rlies exactly in the axis of the vertebra.

Fig-3 on the left side Stress diagram in cross section of the columns

a) Axial compressive stress
b) Oblique thrust, with its effective direction remaining within the core of the columns.
c) Oblique thrust, with its effective direction remaining outside the core of the columns. Pressure and tensile stress trajectories form now together this type of bendable load of the typical pointed arch.

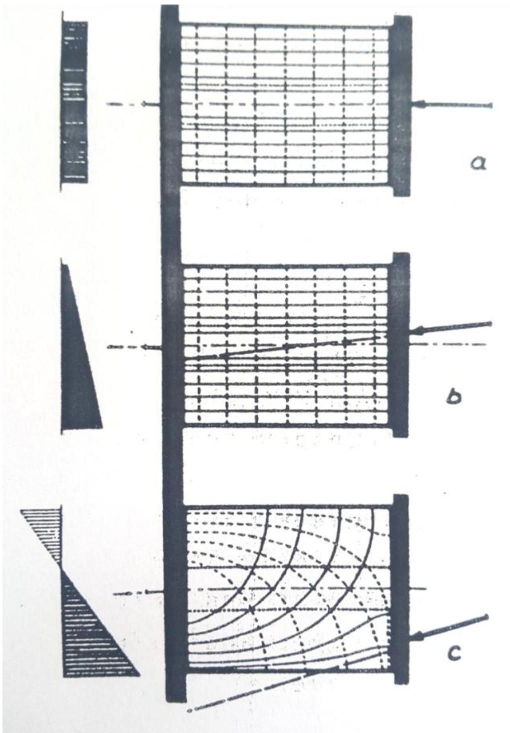

Fig-3: Course of the stress trajectories as well as stress diagram in short and plump columns [6]

The second case chosen by Slipjer as an example of muscle insertion which was supposed by him, was that the end point x of the vertebra does not lie at the section point y of both muscle directions (Figure 2), but the vertebra meets the muscle M_2 at the section point $_x$ at a right angle. In this case the resultant of the muscle M_1 and M_2flow in oblique direction towards the axis of the vertebra, which results in immense bending stress.

Kummer [6] showed the flow of the stress trajectories in a model experiment with the typical pointed arch for bending stress (Figure 3).

As Kummer [6] supposed that the bending stress can be clearly seen in long elements, he examined the third chest spine of a tiger (panther tigris). Just like the case of short vertebra of the Ungulates, he found no bending systems of the cancellous bone, which could have been typical for bending stress. The cancellous bones proceed parallel to each other as well as to the axis of the vertebra. Kummer came to the conclusion from this result, that there are no sure evidence for the existence of vertebra with a bending structure of the spongiosa in the sagittal plane till now.

Gallois and Japiot [10] made sketches for structural flow of the vertebra using x- Ray images in a medial sagittal section and composed bending systems which are considered as bending stress of the vertebra.

Schlüter [11] introduced structural analysis of the vertebra of the lumber spine and the lower thoracic spine. He determined that a complete conformity with the trajectories photogram of a lever which was formed accordingly having a bending stress. He believed that he found therein the evidence for bending stress of the vertebra in the sagittal plane.

Now the question regarding the stress of the vertebra shall be examined using the analysis of material distribution or at least to explain it in a better way.

If the perception of W. Roux [4] regarding the functional adaptation, and the (Formation law of bones) of F. Pauwels [12] is considered, the material distribution of a bone , e.g. is adjusted with the bending stress. This can be seen clearly in a cross section. For this reason, the amount of the bone tissues of the vertebral spine should be examined in this issue to determine under which type of stress do they exert the optimal resistance.

MATERIAL AND METHOD

Material

In the case at issue, all thorax and lumber spines of three dead bodies which were grounded in formalin were examined at the Institute of \Anatomy, University of Colon, were used in gross anatomy course at the Institute of Anatomy., University of Colon. The compounds were macerated and finally degreased.

Its regarding a 74 years old lady (A), a76 yeas old man (B) and a 63 years old man (C). No Changes caused by illness were evident. A cross section. from each vertebra at its base and at half of the length were examined. In this manner, 102 samples were processed.

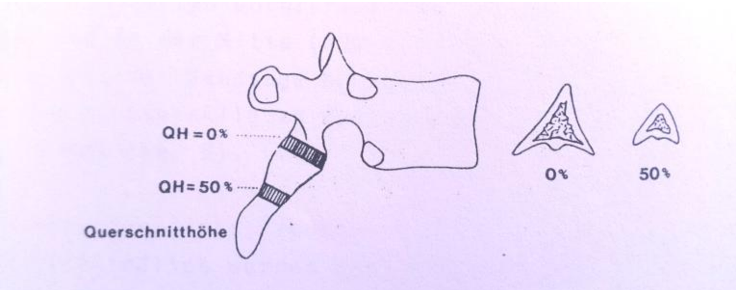

Fig-4: Localization of the cross sections with typical example for the form of the examined thoracic spine – Cross sections of spine

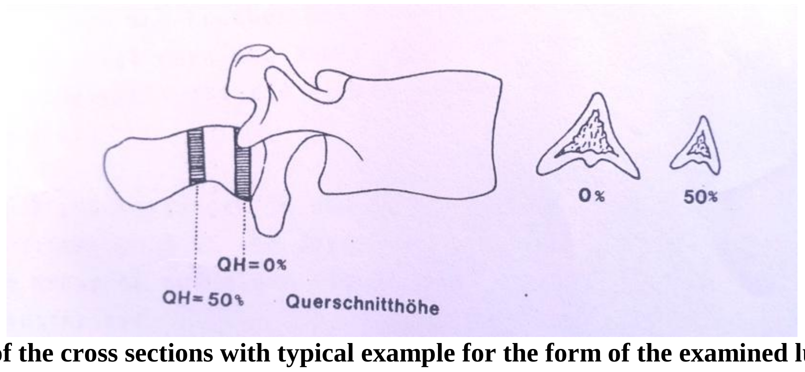

Fig-5: Localization of the cross sections with typical example for the form of the examined lumber spine – Cross sections of spine

Method

Using a saw band, a slice with 5mm thickness was cut from the isolated spines at the base (0% of the length) and at the middle (50% of the length). The cross section distribution lied at right angle to the length axis of the spine (Figure 4 and Figure 5).

The directions to the right, to the left, dorsal and ventral were marked. Finally the cross sections, which were polished within the range of ±5 % exactness to a thickness of 5 mm. The plane parallelism of the intersections was controlled, using the vernier caliper.

X-Ray images were made from the bone slices. For calibration of the density two standardized aluminum step wedges were included in the image [13]. (exposure to light 12 s at 80 cm focal distance.)

In this manner , the different densities in X-Ray images of the bone can be compared with the corresponding layer of the aluminum thickness and can be accordingly quantified. Comparison unit is the layer of the aluminum thickness in millimeters (mm Alu).

The densitometry in the X-Ray images was carried out by the densitometer 3 CS of Joyce Loebel. After that, the measured data was transferred to a desk top (Apple II, Basis 108)

With the help of the program which was developed by the associate professor Dr. R. Breul, the density distribution was displayed in 10 color –and density levels, as a graphical two dimensional image. Individual colors reflect accordingly zones of similar X-Ray absorption. The color arrangement was as follows: black-red-violet- dark yellow-light yellow- dark green-light green- dark blue- light blue-rose, in descending density level, with black being the highest level.

The term density in this study refers always to the X-Ray density of the bone tissue . it is only a term referring to the mineral content, but also a factor that determines the porosity of bone tissue.

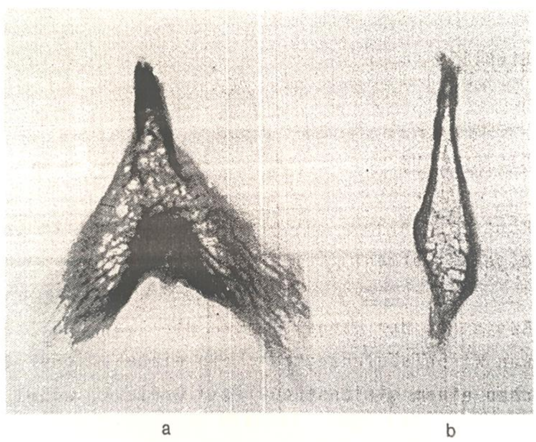

Fig-6: X-Ray image of cross section of the 3. Lumbar spine (A, L_3) a) Base; b) middle (female, 74 years old)

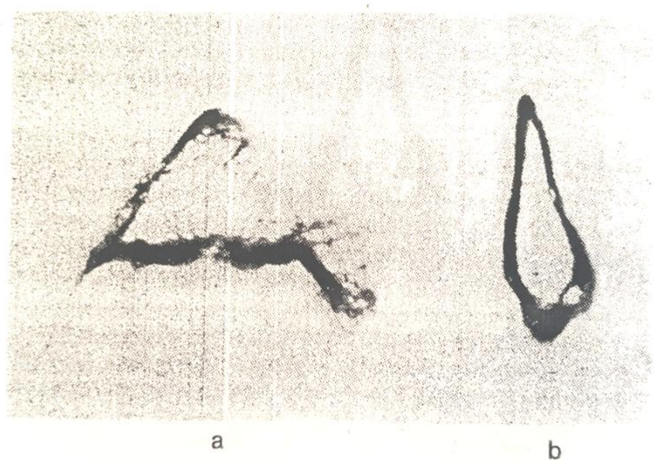

Fig-7: X-Ray image of cross section of the 12. Thoracic spine (C, Th $_{12}$) A) Base; b) middle (male, 63 years old)

THE RESULTS

General form

In the X-Ray images the cross sections showed he following forms:

At the base (0 % of the length) the cross sections of the different spinal column segments showed a uniform image which resembles an isosceles triangle, in which the angle between the two shanks lies cranial (Fig. 6a, 7a, 8a)

The cross sections in the middle of the spine show quite different forms (Tab. 1) 33 from 51 cross sections are triangular (Fig. 8).

In the object A the segments Th_3, L_3, L_4, and in the object C, the segments Th_3, Th $_{8-11}$, as well as L $_2$, L $_3$, are elliptical. Segment Th 2of the object C shows a round cross section,segment A, L3 (Fig.6 b) and segment C, T h 12 (Fig. 7 b) show the form of a rhombus (Tab. 1).

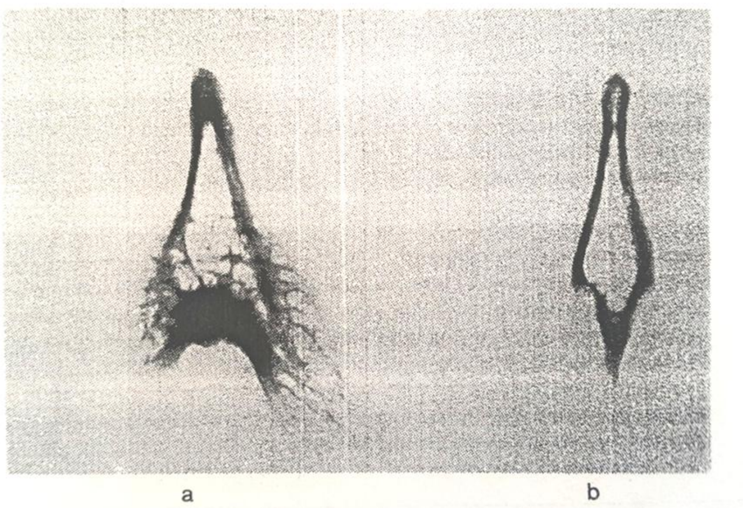

Fig-8: X-Ray image of cross section of the . Lumbar spine (B, L 1) a) Base; b) middle (male, 76 years old)

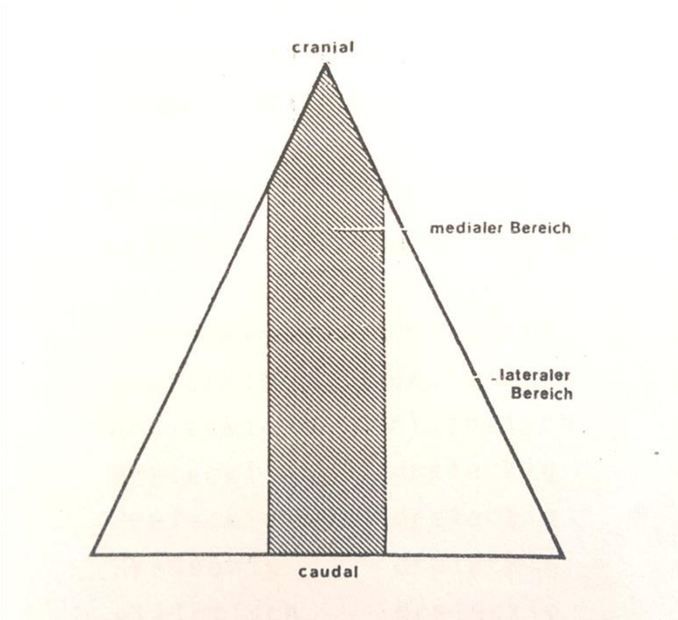

Fig-9: Schematic illustration for orientation at the spinal cross section

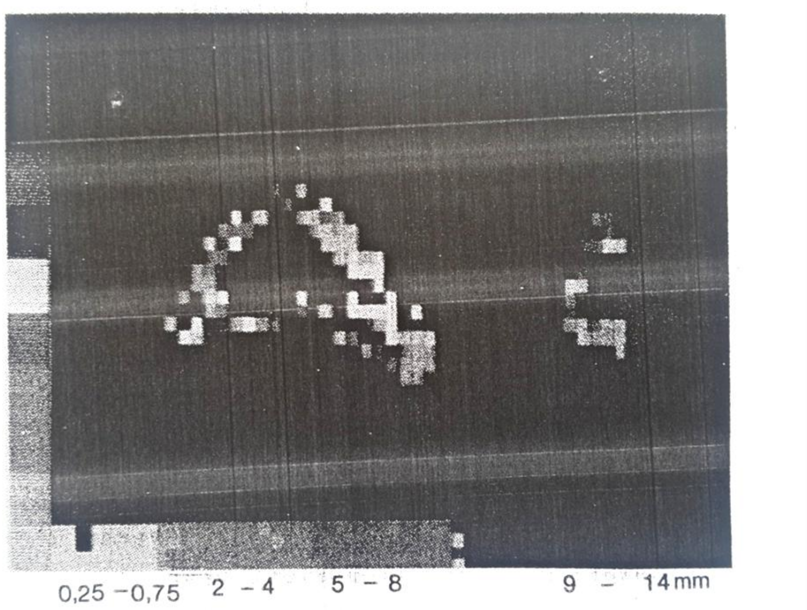

Fig-10: computer densitometry of thecross section of the spinal segment T h 2 a) 0 % of the length; b)50 % of the length (female, 74 years old)

Table 1: Form of the cross sections in the middle of the spine, (50 % of the length); By reference to the X- Ray images

Spine segment	74 years old female (A)	76 years old male (B)	63 years old male (C)
T h_1	triangular	triangular	triangular
T h_2	triangular	triangular	round
T h_3	triangular	elliptical	elliptical
T h_4	triangular	triangular	triangular
T h_5	triangular	triangular	triangular
T h_6	triangular	triangular	triangular
T h_7	elliptical.	triangular	triangular
T h_8	elliptical.	elliptical.	elliptical
T h_9	elliptical.	triangular	elliptical
T h_{10}	elliptical.	triangular	elliptical
T h_{11}	elliptical.	triangular	elliptical
T h_{12}	triangular	triangular	rhombus
L_1	elliptical.	triangular	triangular
L_2	triangular	triangular	elliptical
L_3	rhombus	elliptical.	elliptical
L_4	triangular	elliptical.	triangular
L_5	triangular	triangular	triangular

Distribution of density

A. The cross sections at the base (0 % of the length)

(i) Object A, segments T h_1- L_5 (Tab. 2)

In the cross sections at the base of object A a distribution pattern of the high density level (black and red) was found in the rectangle cranial and caudal around the medial sagittal (Fig. 9, 10 a) higher density levels found in both the cranial and the caudal are concentrated at the top and the lower edge. A zone of very low density or the density level 0 lies between them. Only in three cross sections, lateral high density level were evident.

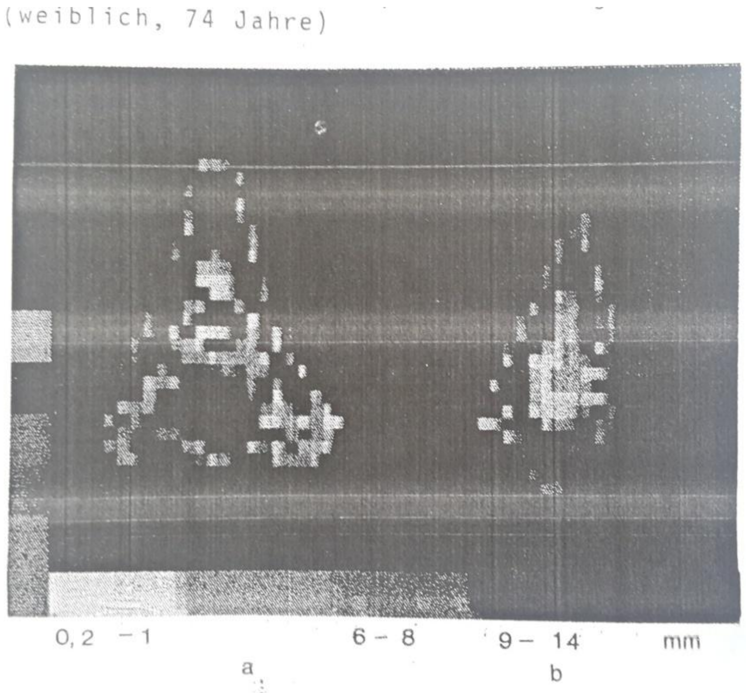

Fig-11: computer densitometry of the cross section of the spinal segment L_1; a) 0 % of the length; b) 50 % of the length; (male, 76 years old)

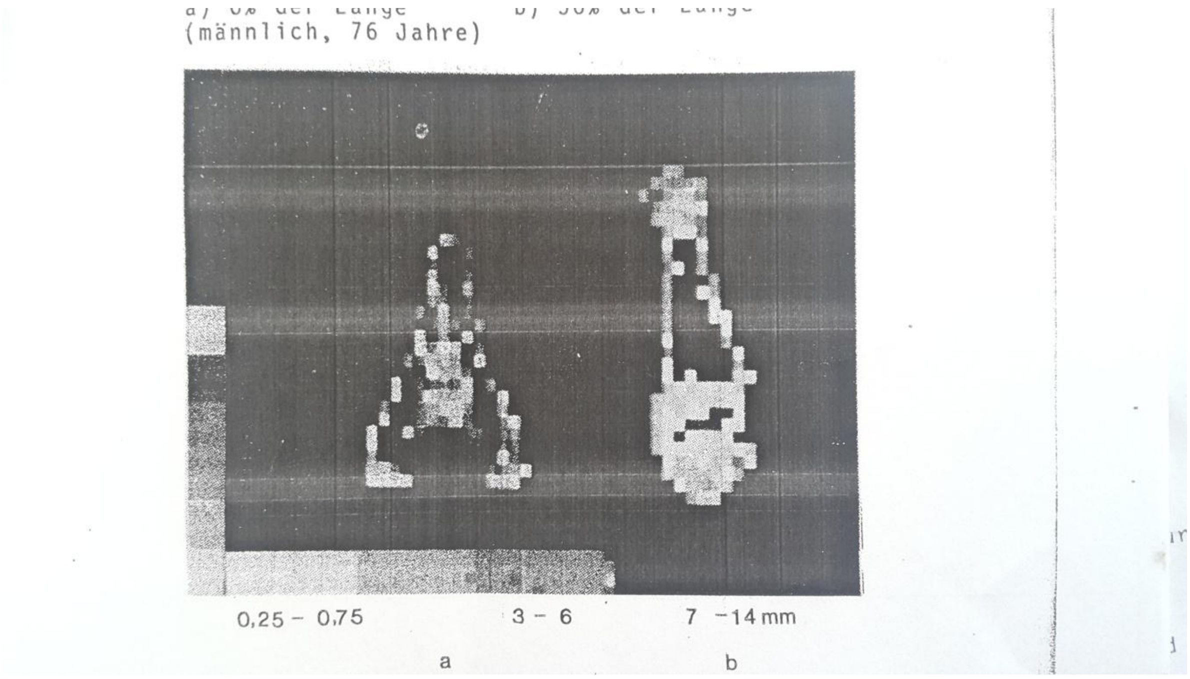

Fig-12: computer densitometry of the cross section of the spinal segment L_5; a) 0 % of the length; b) 50 % of the length; (male, 63 years old

(ii) Object B , segments T h $_1$- L $_5$ (Tab. 3)
Here also resulted a similar density distribution. In 11 segments, the higher density levels (black and red) lied n the triangle cranial and around the median sagittal caudal (Fig. 11 a) The higher density levels which lied cranial as well as caudal are concentrated at the edge and a zone of very low density or the density level 0 lies between them. In 6 segments additional lateral higher density levels were evident.

(iii) Object c , segments T h $_1$- L $_5$ (Tab. 4)
These segments also showed the pattern of density distribution which was already mentioned earlier. In 13 segments, the higher density levels (black and red) lied on the triangle cranial and around the median sagittal caudal (Fig. 12 a) The higher density levels which lied cranial as well as caudal are concentrated at the edge and a zone of very low density or the density level 0 lies between them.

In 3 segments (T h $_7$, T h $_{12}$, and L $_2$) additional isolated lateral higher density levels were evident. In object l $_4$ a pattern of higher density levels were cranial and lateral evident.

Table 3: Distribution of the higher density levels (black, red) by reference to the computer densitometry 76 years old, male (B) T h $_1$ – L $_5$ (Fig. 9)

Spine segment	Cross section at the base of the spine (0 % of the length)	Cross section at the middle of the spine (50 % of the length)
T h $_1$	cranial arch formed and medial	cranial arch formed and medial
T h $_2$	cranial arch formed and medial	cranial arch formed and medial
T h $_3$	cranial arch formed and medial	cranial arch formed and basal
T h $_4$	medial: cranial and caudal	cranial: caudal and isolated lateral
T h $_5$	medial: cranial and caudal	cranial: caudal and isolated lateral
T h $_6$	medial: cranial caudal isolated lateral	Cranial, caudal and isolated lateral
T h $_7$	medial: cranial and caudal	medial: cranial, caudal and isolated lateral
T h $_8$	medial: cranial and caudal	medial: cranial and caudal
T h $_9$	medial: cranial and caudal	medial: cranial and caudal
T h $_{10}$	medial: cranial and caudal	medial: cranial, caudal and isolated lateral
T h $_{11}$	medial: cranial, caudal and isolated lateral	medial: cranial, caudal and isolated lateral
T h $_{12}$	cranial arch formed and medial	medial: cranial, caudal and isolated lateral
L $_1$	medial: cranial, caudal and isolated lateral	medial: cranial, caudal and isolated lateral
L_2	medial: cranial, caudal and isolated lateral	medial: cranial and caudal
L $_3$	medial: cranial, caudal and isolated lateral	cranial: caudal and isolated lateral
L $_4$	medial: cranial caudal and isolated lateral	medial: cranial and caudal
L $_5$	cranial and caudal	Cranial and isolated lateral

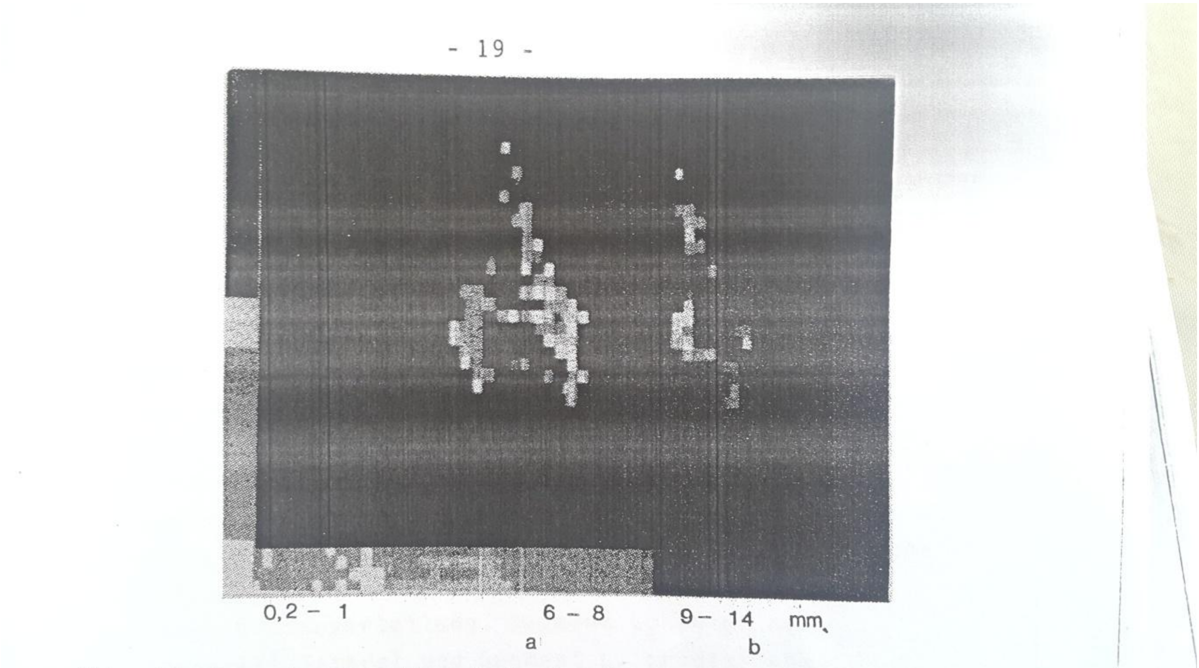

Fig-13: computer densitometry of the cross section of the spinal segment L $_2$; a) 0 % of the length ; b) 50 % of the length; (female, 74 years old)

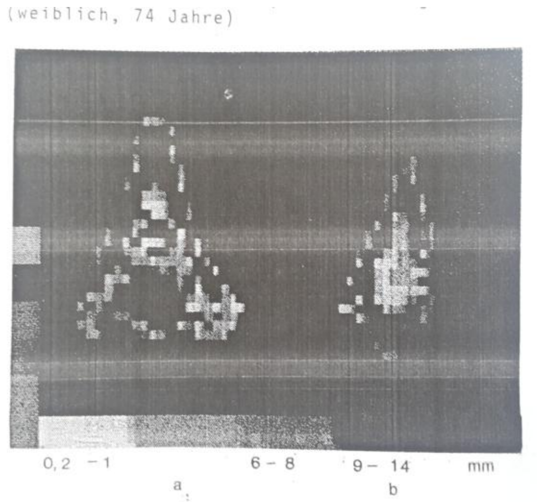

Fig-14: computer densitometry of the cross section of the spinal segment T h $_{12}$; a) 0 % of the length; b) 50 % of the length; (male, 76 years old)

B. The cross sections at the middle (50 % of the length)

(i) Object A, segments T h $_1$- L $_5$ (Tab. 2)

The distribution of the higher density levels (black and red) was also found in the triangle cranial and around the medial sagittal, caudal Higher density levels which were found in both the cranial and the caudal were concentrated at the edge. A zone of very low density or the density level 0 lies between them. In 5 objects (T h $_{1-3}$, T h $_{12}$, and L $_3$) additional isolated lateral higher density levels were evident in cross section (Fig. 13 b). Segment L $_1$ showed all over only low density levels The same spine has at the base also a typical density distribution. Segment L $_4$ showed only isolated lateral and Segment L $_5$ cranial and isolated lateral higher density levels.

(ii) Object B, segments T h $_1$- L $_5$ (Tab. 3)

In these segments, the same distribution pattern of the higher density levels (black and red) was also found cranial and around the medial sagittal, caudal (Fig. 14 b). Higher density levels which were found in both the cranial and the caudal were concentrated at the edge. A zone of very low density or the density level 0 lies between them. In 9 segments additional isolated lateral higher density levels were evident. Not all these segments had a density distribution at the base which was different from the majority of the segments. Segment L $_5$showed only cranial and isolated lateral levels.

Table 4: Distribution of the higher density levels (black, red) by reference to the computer densitometry 63 years old, male (C) T h $_1$ – L $_5$ (Fig. 9)

Spine segment	Cross section at the base of the spine (0 % of the length)	Cross section at the middle of the spine (50 % of the length)
T h $_1$	cranial arch formed and medial	cranial arch formed and medial
T h $_2$	medial: cranial caudal isolated lateral	cranial arch formed and medial
T h $_3$	medial: cranial /caudal	cranial and caudal
T h $_4$	medial: cranial and caudal	cranial and isolated caudal
T h $_5$	medial: cranial, caudal corners	cranial: caudal and isolated lateral
T h $_6$	medial: cranial and caudal	only low density levels
T h $_7$	medial: cranial caudal isolated lateral	cranial, and isolated caudal
T h $_8$	cranial and caudal	cranial, and isolated caudal
T h $_9$	medial: cranial/ caudal	medial: cranial/ caudal
T h $_{10}$	cranial and caudal	cranial and caudal
T h $_{11}$	medial: cranial/caudal	medial: cranial/ caudal
T h $_{12}$	medial: cranial caudal isolated lateral	only low density levels
L $_1$	medial: cranial and caudal	cranial and isolated lateral
L$_2$	medial: cranial caudal isolated lateral	cranial: caudal and isolated lateral
L $_3$	cranial and caudal	isolated cranial and caudal
L $_4$	cranial and caudal	isolated cranial and caudal
L $_5$	medial: cranial and caudal	only low density levels

(iii) Object C, segments T h $_1$- L $_5$ (Tab. 4)

Up to 5 segments, the distribution pattern of the higher density levels (black and red) was found cranial and around the medial sagittal, caudal (Fig. 15 b). Higher density levels which were found in both the cranial and the caudal were concentrated at the edge. A zone of very low density or the density level 0 lies between them. The higher density levels (black and red) equivalent to 9 -14 mm Aluminum were found cranial and around the medial sagittal, caudal.

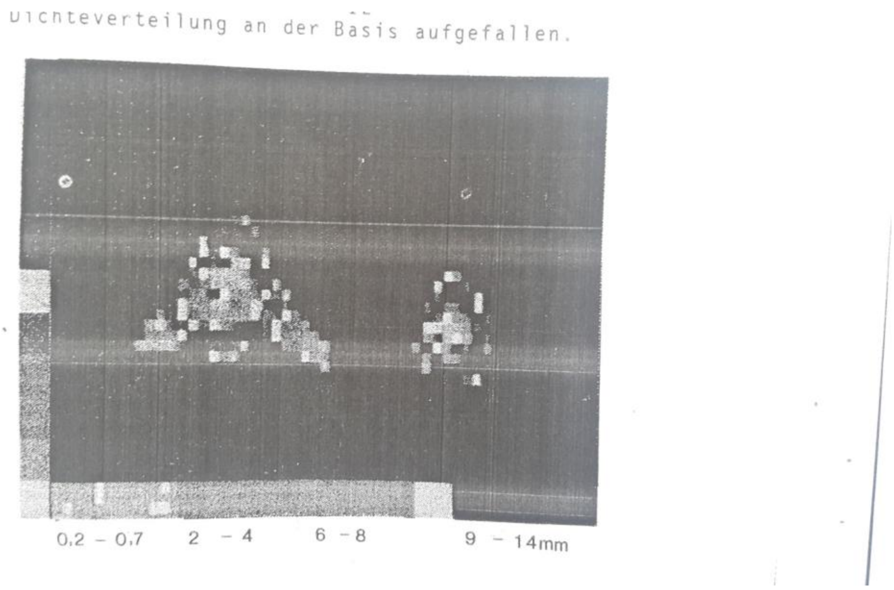

Fig-15: computer densitometry of the cross section of the spinal segment T h $_1$; a) 0 % of the length; b) 50 % of the length (male, 63 years old)

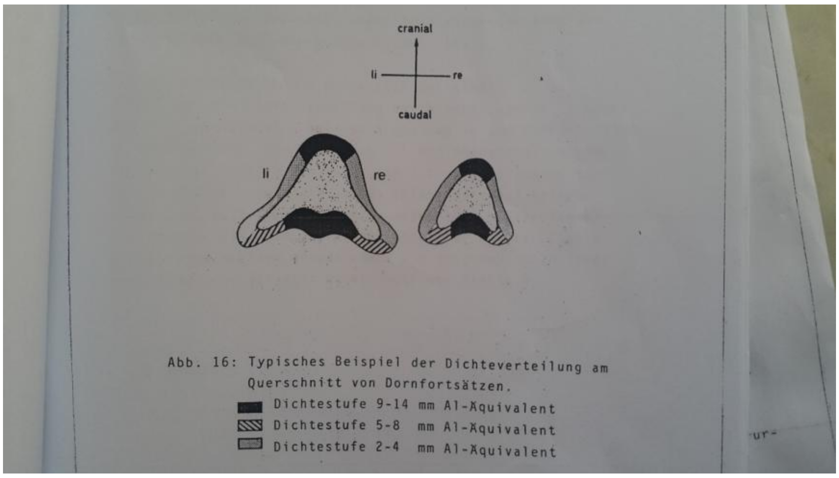

Fig-16: Typical example of distribution of density in a cross section of spine (Density level 9-14 mm Al –equivalent; Density level 5- 8 mm Al –equivalent; Density level 2- 4 mm Al –equivalent)

SUMMARY OF THE RESULTS

a) Cross sections at the base (0 % of the length)

As seen from the above presented examinations results, its regarding the distribution pattern, similar to the distribution of density in these cross sections, with some variations, like the appearance of additional lateral condensations. Higher density levels (black and red) equivalent to 9-14 Aluminum , which were found in both cranial and caudal were concentrated at the edge. A zone of very low density or the density level 0 lies between them. (Fig. 16).

b) The cross sections in the middle (50 % of the length)

Here lies the majority of higher density levels (black and red) equivalent to 9-14 Aluminum in cross section cranial and around the medial sagittal, caudal. But many variations were found, for example the occurrence of exclusively low levels (blue and rosa) equivalent to 0,25 – 0,75 Aluminum. (Fig. 12 b).Higher density levelswhich were found in both cranial as well as caudal were concentrated at the edge. A zone of very low density or the density level 0 lies between them.

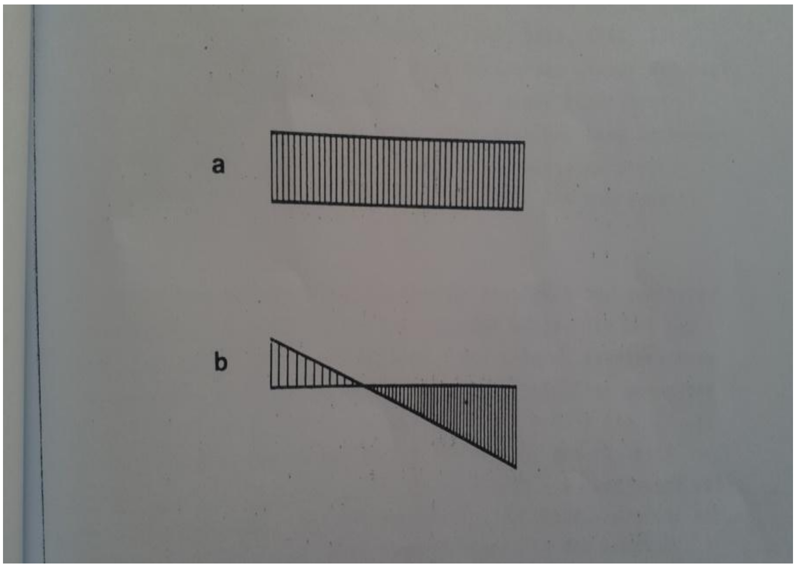

Fig-17: Stress diagram at : a) Axial stress; The stress in cross section showed all over the same value; b) Bending stress. The stress is distributed in the cross section in quite irregular manner. The highest were found at the edge, and fall towards the neutral faser to zero level

DISCUSSION

The cross sections at the base and in the middle of the spines show material concentration in the cranial and caudal edge zones . A zone of very low density lies in between. If this applies, that the bone reflects a body of similar consistence, [12, 14-17]; then, according to this distribution of material, these slices of skeletons as they lived were subjected to bending stress, because an axial stress would have resulted in a uniform distribution of material in the cross section.

Because not even proximate equal distribution of material was found in the examined objects, the supposition of an axial stress of spine is quite unlikely. The real pattern of distribution of material can be compared with the stress diagram presented in Fig. 17., which is valid for bending stress. At the same time, the base material surface stay away from the side facing the load under pressure. In absolute values of compressive stress are always higher than tensile stress.

In the spine the caudal side should be regarded as the compressive side and the cranial as the tensile side. This makes the bending stress towards the caudal in sagittal level.

These findings correspond with the examinations of Gallois and Japiot [10] which were used to describe the stress of spine by the arch systems, and made them assume the bending stress.

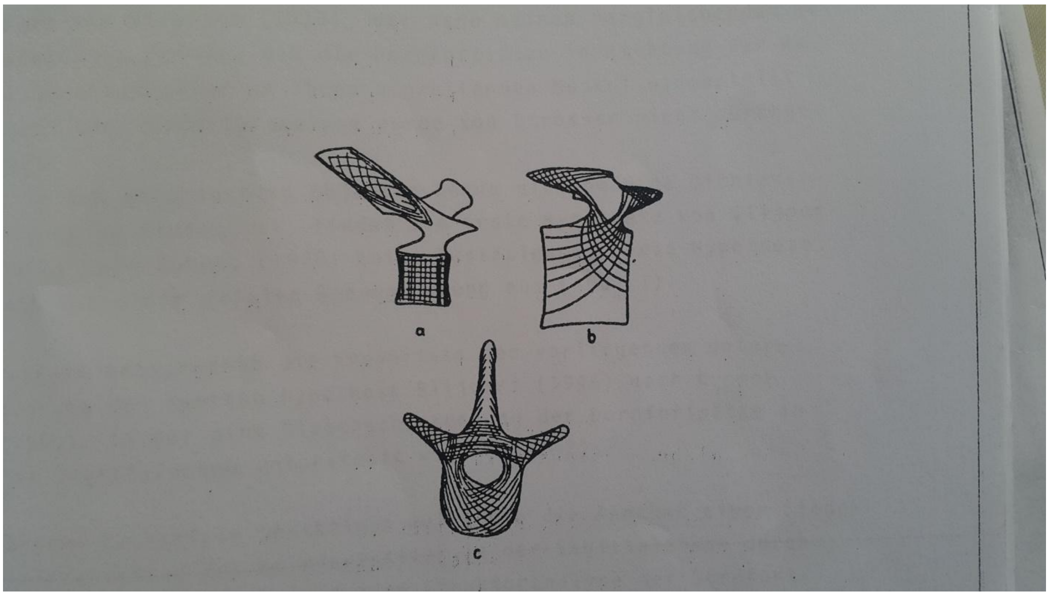

Fig-18: Schematic sketch of a thoracic spine from Slipjer [9] according to Gallios and Japiot [10]. A) Medial section; b) Sagittal section; c) Transversal section

The structure of the courses they sketched in medial sagittal section are very close to the present findings (Fig. 18).

But the these results contradict the suppositions of Strasser [8], who meant according to his compared observations, that the spines in the direction of the resulting are adjusted to all muscles that are taking part in the process. Strasser did not present a structural analysis.

As no even distribution of density was found in the examined objects, the first hypotheses of Slipjer [9] according to Kummer [6] could not be proved. This hypotheses was assumed from an axial stress (Fig. 1).

The results of the present examinations oppose the second hypotheses of Slipjer [9] according to Kummer [6] in which the bending stress of the spine in the sagittal level was assumed (Fig. 2).

Our results confirm further the assumption of bending stress of the spine in the sagittal level through Schlüter [11], which depends on a structural analysis of the spine of the lumbar spine and the lower thoracic spine.

The distribution of density in the cross sections in the middle of the spines showed a less uniform image than the cross sections in the base. So , in object A , in segments T h $_{1\text{-}3}$, T h $_{12}$, L $_{3\text{-}5,}$ and in object B in segments T h $_{4\text{-}7}$, T h $_{10\text{-}12,}$ L $_{5}$, and in object C in segments T h $_{5}$, L $_{2}$ lateral, higher density levels are shown..

Furthermore in 4 cross sections only low levels were found. (Object A, segment L_1, object C segment T h $_{6}$, T h $_{12}$, and L $_{5}$).

As already noticed , some specimens, in which both sections through the base and through the middle of the spine are found, did not comply with the image of a pure bending stress. In the basal sections, additional lateral condensations that deviated from them were evident. The sections in the middle showed a generally uniform distribution, partly with completely low density levels. Therefore in these cases no clear bending stress was evident, but rather more axial stress was found. Two of these streams were found in the transient area of the thoracic spine to the lumbar spine or from the lumbar spine to the 0 s sacrum. Regarding the spines that show only in one of the section levels a typical distribution of density, we would not suppose such an interpretation of the findings.

In total, it can be established that according to the present results, a bending in sagittal direction should be regarded as the significant stress of the spine of the thoracic spine and the lumbar spine of the human being.

SUMMARY

In each 2 cross sections heights (in the base and at the distance of half of the length) of the spine of the thoracic spine and the lumbar spine of the human being. the distribution of X- Ray density was recorded using the computer densitometry.

An irregular distribution of density on the sections plane was found. The higher density levels lied at the cranial and caudal edge, between a zone of fewer density.

This distribution complies with the stress diagram which would belong to bending stress in sagittal level. By evaluating the biomechanical literature [12, 14-17], one comes to the conclusion that at least the spines of the thoracic and lumbar spine are adjusted at a bending stress and in this manner were also stressed in life time.

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