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A study of weight transmission through the cervical and upper thoracic regions of the vertebral column in man

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INTRODUCTION

Almost all textbooks of anatomy and many published investigations (Petter, 1933; Davis, 1959, 1961; Taylor & Twomey, 1984) indicate that the vertebral bodies and intervertebral discs sustain all the vertebral compression force, the magnitude of which increases from the axis vertebra to the lumbosacral joint. Thus each vertebra bears the weight of all the part of the body above it and since the lower ones have to bear much more weight than the upper ones, the former are much larger (Rosch & Burke, 1964). In general, this assumption is supported by serial measurements of the vertebral bodies (Brandner, 1970; Taylor & Twomey, 1984). Similarly, Williams & Warwick (1980) are of the opinion that the weight of the head and trunk is supported by a continuous flexible pillar formed by the vertebral bodies and intervertebral discs.

Thus, though the vertebral column is formed by vertebral bodies and neural arches, only the bodies are generally considered to be responsible for weight bearing, the neural arches merely contributing to the formation of the vertebral canal. The articular processes are considered to determine the range and direction of movement between any two vertebrae. However, the work of Davis (1961) has shown that at least in the fifth lumbar vertebra, the pedicles and transverse processes are also involved in transmission of part of the compressive force to the pelvis.

Very recently, Denis (1983) and Louis (1985) have claimed that zygopophyseal joints are also involved in weight bearing. Both have put forward the 'three column spine' concept for spinal stability. However, the three column spinal concept of Louis differs from that of Denis. According to Denis, the anterior spinal column is formed by the anterior half of the vertebral bodies and intervertebral discs, the middle spinal column includes the posterior half of the vertebral bodies and discs and the posterior longitudinal ligament, and finally the posterior column corresponds to the facet joints and posterior ligamentous complex. According to Louis the vertebrae are composed of three pillars; the anterior pillar formed by the vertebral bodies and the other two pillars formed by the articular processes lying posteriorly.

Recently, the authors have developed a hypothesis according to which the vertebral column not only transmits weight through the bodies and intervertebral discs but also through the neural arch. In the cervical region, it is transmitted through three columns; an anterior column formed by the bodies and intervertebral discs and two posterior columns formed by the articular pillars. This hypothesis also suggests that the relative magnitude of compressive forces passing through the bodies and the neural arches should alter with change of curvature at the cervicothoracic junction.

This concept of a three column spine in the cervical region is similar to that of Louis (1985).

Following the ideas of Davis (1961) and on the basis of various mechanical principles, this hypothesis of weight transmission through the neural arch component of the cervical and upper thoracic vertebral column has been tested in the present investigation. An attempt has also been made to find the route and magnitude of compressive forces passing through different pillars of a curvilinear vertebral column.

MATERIAL AND METHODS

Measurements were made on 44 adult columns in the collection of the Government Medical College, Surat. All the columns were male and were free from anomalies, artefacts, senile and pathological change.

Studies at the upper cervical (C_2) *level*

In all 44 columns, naked eye observations were made of either side to observe overlapping of the superior articular surface on the body and inferior articular facets.

The surface areas of both the superior articular surfaces, body and inferior articular facets were measured by tracing their outline on thin tracing paper. The tracing was then transferred to graph paper and the area measured in cm^2 by counting the number of squares covered.

The areas of the two superior articular surfaces were summed and compared with the total area of the inferior articular facets and the inferior surface of the body. Statistical analysis (r) was applied to find the correlation between the areas of the superior and inferior articular surfaces.

Studies at various levels in the cervical and upper thoracic region

For these measurements, C_2, C_4, C_6, C_7, T_1, T_2 and T_5 vertebrae were selected from the cervical and upper thoracic regions of the column. From C_6 to T_2, vertebrae were chosen in series because they form a junctional zone between the cervical and thoracic curvatures, while the others were chosen at intervals because they did not differ greatly from the neighbouring vertebra.

Vertebral body

The area of the inferior surface of the body in each vertebra was measured using the graph paper method. The inferior surface was preferred to the superior surface since the C_2 vertebra could then be included in the comparison. It was also easier to take a tracing of the interior surface since the superior surface had raised lateral margins; this surface was more representative of compressive force transmission at that level.

Neural arch

Pedicle

The pedicle index is the product of the greatest and smallest diameters of a pedicle at its most slender portion (Davis, 1961). This was determined as an indicator of the size of the pedicle. The mean of the indices of the two sides was then calculated to give the *mean pedicle index* for each vertebra.

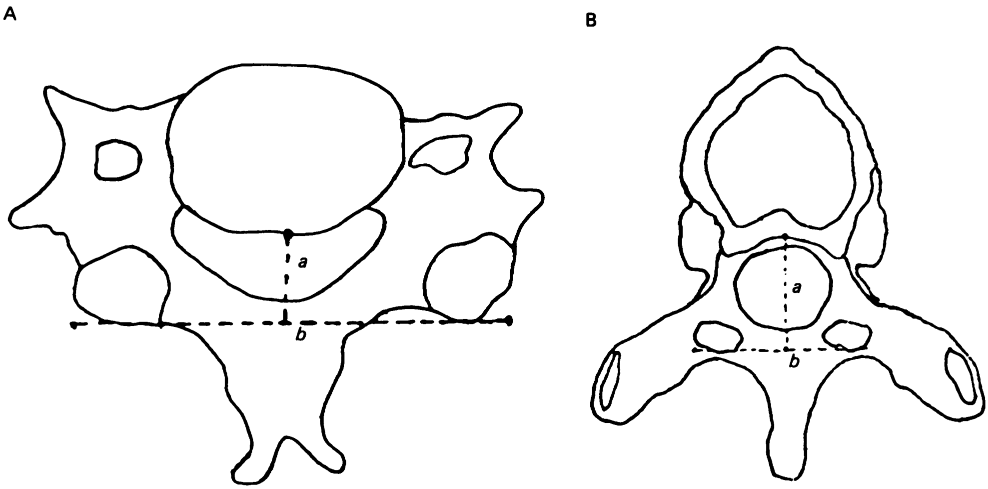

Fig. 1 (A–B). Arch index is obtained by the product of parameters *a* and *b*. (A) Cervical vertebra. (B) Thoracic vertebra.

Inferior articular facets

The surface areas of the inferior articular facets were measured using the graph paper method, and the mean area of the two sides was then calculated to obtain the *mean articular facet area* for each vertebra.

Arch index

This was obtained by the product of *a* and *b* as shown in Figure 1; *b* is the maximum distance between the two articular facets at distance *a* from the posterior margin of the body. A *mean arch index* (± S.D.) for each vertebral level was obtained. The arch index indicates approximately the position of the articular processes in relation to the body.

In the vertebral column, the size of the bodies gradually increases from above downwards. Hence, to compare the magnitudes of the articular facets, pedicles and arch indices at various levels, their ratios to body area were calculated. Thus three ratios, namely pedicle index/body area, articular facet/body area and arch index/body area were obtained.

Body-pedicle angle

This angle was measured by projecting the long axis of the pedicle and the vertical axis of the body on the lateral aspect of the vertebra (Fig. 2). In the cervical region, the long axis of the pedicle was drawn after detaching the transverse process. *Mean body–pedicle angle* ± S.D. for each vertebral level was calculated.

The above measurements and ratios were compared by calculation and graphic means.

RESULTS

Study at C_2 level

Out of the 44 axis vertebrae, in 39 vertebrae (88 %) the superior articular surfaces overlapped the inferior articular facets (Fig. 8). The range of overlapping varied from just marginal to three quarters of the surface of the inferior articular facet.

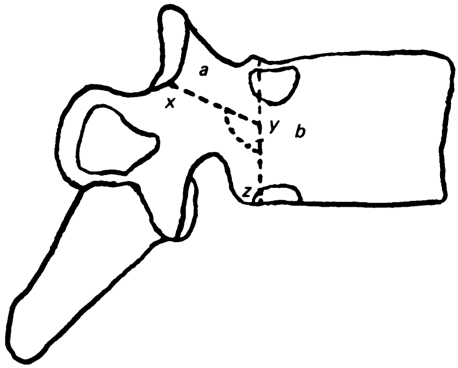

Fig. 2. Body–pedicle angle, *xyz*. *a*, long axis of pedicle; *b*, long axis of body.

Table 1. *Vertebral dimensions at various levels*

Mean value ±S.D. (cm^2).

Vertebral level	Mean body area	Mean inferior articular facet area	Mean pedicle index	Mean arch index
C_2	2·41±0·36	1·02±0·20	0·61±0·03	4·11±0·73
C_4	2·75±0·60	1·05±0·31	0·27±0·05	3·74±0·85
C_6	3·28±0·67	1·16±0·16	0·33±0·05	4·26±1·01
C_7	3·69±0·78	1·19±0·10	0·38±0·06	4·88±0·69
T_1	4·25±0·53	0·98±0·05	0·65±0·09	4·35±0·60
T_2	4·76±0·70	0·90±0·10	0·65±0·13	4·21±0·93
T_5	5·34±0·45	0·83±0·06	0·40±0·07	4·00±0·67

The areas of the two superior articular surfaces were summed for each vertebra, and mean surface area was calculated (mean 4·40 cm^2; range 3·10–5·38 cm^2). This was compared with the mean surface area obtained by summing the area of body and facets (mean 4·45 cm^2; range 3·18–6·0 cm^2). Thus the inferior articular surface area (body ×2 articular facets) was 0·05 cm^2 more than the mean surface area of two superior articular surfaces. A significantly high correlation between superior and inferior articular surface areas was observed ($r = 0{\cdot}72$; $t = 4{\cdot}66$; $P < 0{\cdot}001$).

Studies at various levels in the cervical and upper thoracic regions

Measurements of the area of the inferior surface of the body, mean articular facet area, of the pedicle index and of the arch index are presented in Table 1 and Figures 3 and 4. Mean body surface area showed a gradual increase from above downwards. The area of the inferior surface of T_5 vertebra was more than double that of the body of C_2 vertebra. The mean surface area of the articular facet showed a slow increment from C_2 to C_7 followed by a sharp decline at T_1 level which gradually continued to T_5. Pedicle size was greater at C_2, T_1 and T_2 levels while it was smaller at the emaining levels (Fig. 3). Arch index was maximum at C_7 level (Fig. 4), indicating that at this level the articular processes were placed widest apart in relation to the body.

Comparison at each level of body area with the articular facet area, pedicle size and arch size (as ratios) is presented in Table 2 and by Figures 5, 6 and 7.

Table 2. *Ratios at various levels*

Vertebral level	Articular facet area/body area	Pedicle index/ body area	Arch index/ body area
C_2	0·42	0·25	1·70
C_4	0·38	0·09	1·36
C_6	0·35	0·10	1·29
C_7	0·32	0·10	1·32
T_1	0·23	0·15	1·02
T_2	0·18	0·13	0·88
T_5	0·15	0·07	0·74

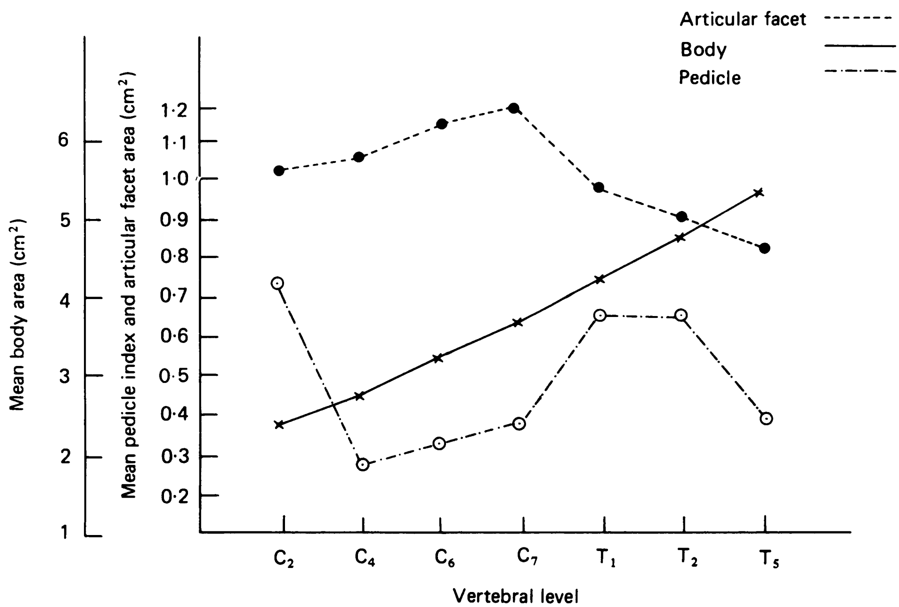

Fig. 3. Mean surface area of body, mean articular facet area and mean pedicle index at various vertebral levels.

Articular facet area/body area ratio

The mean surface area of a single inferior articular facet in relation to body area showed a very slow decline down to C_7 level, but there was then a sharp decline at T_1 level followed by a gradual further decline to T_5 (Fig. 5). This indicated that the area of facet in relation to body area declined considerably in the thoracic part of the column.

Pedicle index/body area ratio

Compared to body area, pedicles were largest at C_2 level and smallest and of equal strength at C_4, C_6 and C_7 levels (Fig. 6). Pedicles became more prominent again at T_1 and T_2 levels but were relatively small, in relation to the body, at T_5.

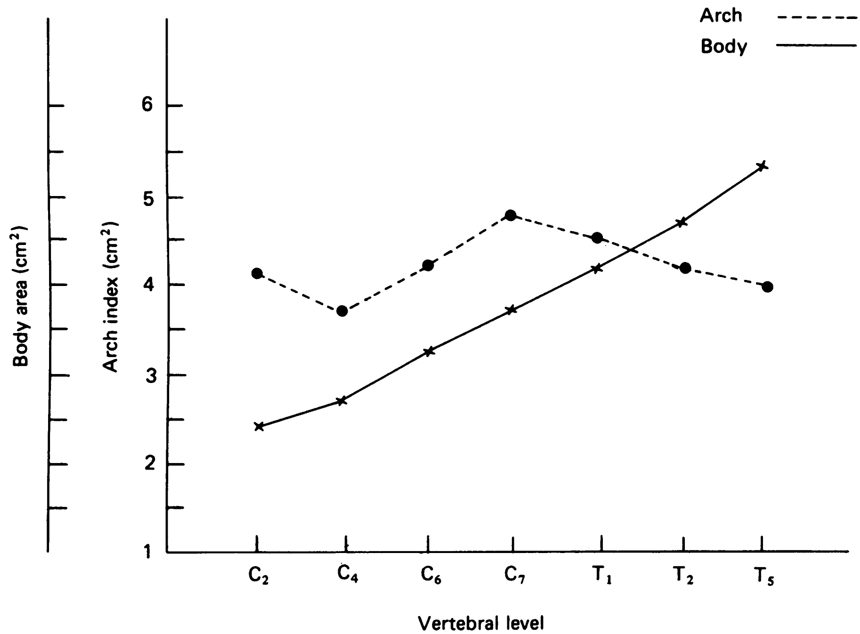

Fig. 4. Graph showing the arch index and the surface area of the body at various vertebral levels.

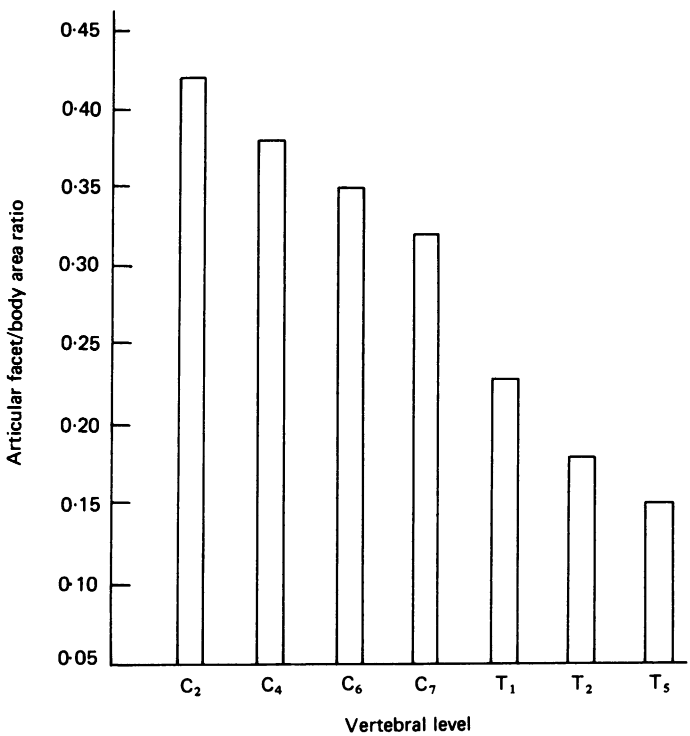

Fig. 5. Articular facet area/body area ratio at various vertebral levels.

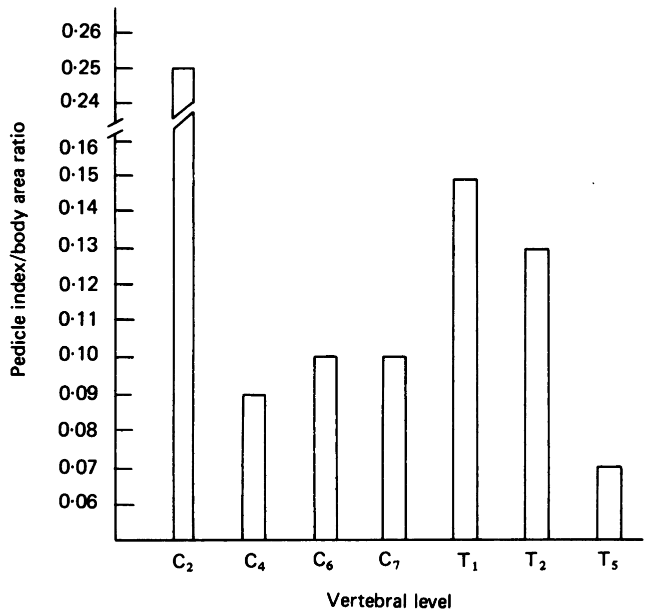

Fig. 6. Pedicle index/body area ratio at various vertebral levels.

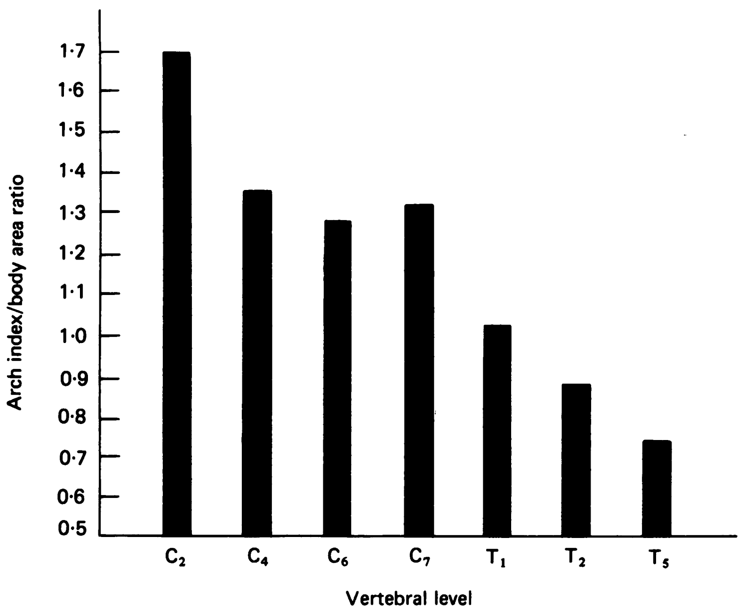

Fig. 7. Arch index/body area ratio at various vertebral levels.

Arch index/body area ratio

This ratio showed a gradual decline from C_2 to T_5 level. Above C_7 level the size of the arch was greater than body area, but at T_1 the two were of almost equal size, below which body area exceeded the arch size (Fig. 7).

Body–pedicle angle. Angles between body and pedicle at various levels are given in Table 4. At C_2 level, in relation to the body, pedicles were directed backwards,

Table 3. *Percentage area of body and articular facets at various vertebral levels*

Vertebral level	Total area (body + facets) (cm^2)	(%)	Body area (cm^2)	(%)	Area of two articular facets (cm^2)	(%)
C_2	4·45	(100)	2·41	(54·1)	2·04	(45·8)
C_4	4·85	(100)	2·75	(56·7)	2·10	(43·2)
C_6	5·60	(100)	3·28	(58·5)	2·32	(41·4)
C_7	6·07	(100)	3·69	(60·7)	2·38	(39·2)
T_1	6·21	(100)	4·25	(68·4)	1·96	(31·5)
T_2	6·56	(100)	4·76	(72·5)	1·80	(27·4)
T_5	7·00	(100)	5·34	(76·3)	1·66	(23·7)

Table 4. *Angle between pedicle and body*

Vertebral level	C_2	C_4	C_6	C_7	T_1	T_2	T_5
Mean angle	64°	82°	104°	105°	111°	111°	111°
Range	50–65°	75–85°	98–110°	100–110°	104–116°	108–117°	103–114°
S.D.	±3·30	±3·31	±3·66	±3·24	±6·23	±7·54	±6·30

downwards and laterally while, at C_4 level, pedicles were almost horizontal. From C_6 level onwards, pedicles changed their direction and became directed upwards and backwards. Their lateral deviation gradually diminished and, at T_5, it was directed completely backwards.

Table 3 presents the percentage areas of the body and the articular facets at different vertebral levels. Percentage area of the two articular facets in the cervical region was little less than the body area and remained almost constant from C_2 to C_7. However, the facet area declined considerably in the thoracic region.

These results can be summarised by saying that the superior articular surfaces of the axis vertebra overlapped the inferior articular facets and body and that the surface areas of superior and inferior articular surfaces were highly correlated. Body surface area gradually increased from above downwards. In relation to the body area, pedicles were largest at C_2, T_1 and T_2 level; articular facet area and arch size diminished considerably in the thoracic region. Pedicles were inclined downwards and backwards above C_6 and upwards and backwards below this level (Fig. 14).

DISCUSSION

Mechanical considerations and related anatomical features

The present investigation is based on the following basic mechanical principles. A review of these principles is helpful in understanding the mechanism of weight transmission through the vertebral column.

Resistance to pressure (load) by a uniform structure and the cross sectional area

By definition, stress p is equal to the load P divided by area a which resists the load or compressive force: $p = P/a$. In the vertebral column, the cross sectional area and load both increase from above downwards. Thus cross sectional area of the

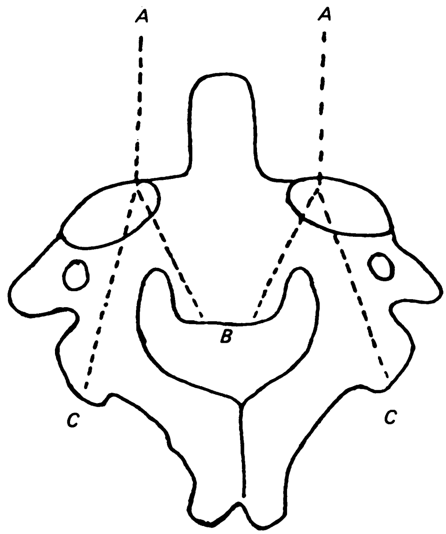

Fig. 8. Line diagram of the axis vertebra showing the distribution of the compressive force (*A*) from the superior articular surface to the body (*B*) and the inferior articular facets (*C*).

column at a particular level is correlated with its ability to resist longitudinal compression.

Geometrical property of columns related to moment of inertia

If we consider that the load p is being transmitted through three columns then the proportion of the load carried through each individual column will depend on its cross sectional area, according to the above principle. However, the position of these columns in relation to each other is also important. The resistance to overturning or bending or buckling increases in cube proportion as the columns are located away from the centre. This also helps to maintain stability. The columns of Figure 12(A) are more stable and efficient for weight bearing than the columns of Figure 12(B).

Beam and column action

Load is transferred basically through column action. A beam is less efficient in carrying load compared to a column of the same dimension. If beam inclination increases towards the vertical the column action becomes progressively more prominent and mechanically the load transfer will be more effective. As the inclination increases towards the horizontal, beam action becomes more dominant and hence load transfer is less efficient.

A number of anatomical features prompted this study and were considered extensively during the investigation.

In most of the subjects, the superior articular surface of the axis vertebra overlaps both a part of the body below and also the inferior articular facet. Hence, it would be expected that the vertical compression force from the superior articular surface on either side would be deflected both to the body and to the two inferior articular facets (Fig. 8). Articular processes in the cervical region are very strong and bar-like (Fig. 9). It would seem reasonable that the strength of these processes is correlated

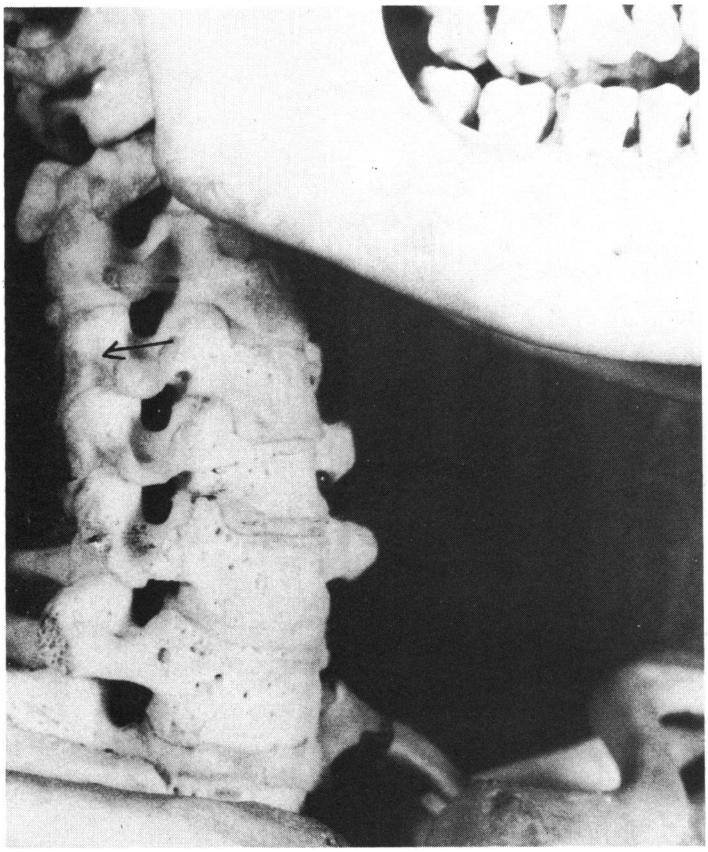

Fig. 9. Lateral view of cervical vertebral column; arrow indicates the pillar formed by the articular processes.

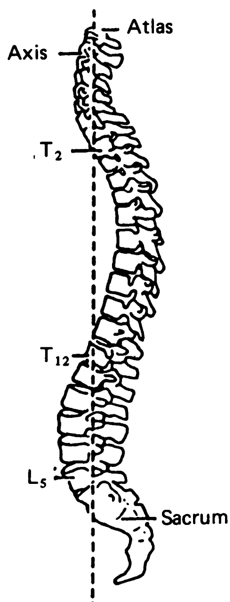

Fig. 10. Line of gravity (vertical pecked line) in relation to the vertebral column curvature.

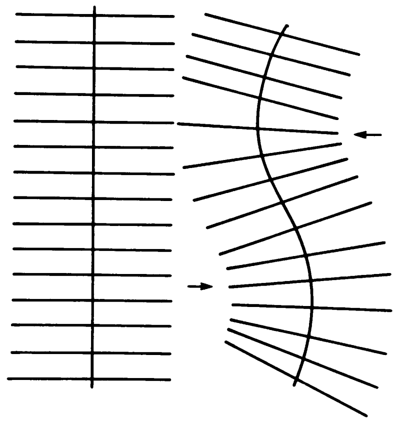

Fig. 11. Diagram to show the sites of increased stress when a straight column becomes curvilinear due to heavy load. On the side of the curvature, closer positions of the spokes (arrows) indicate increased stress.

with the fact that they are responsible for carrying below part of the compressive force diverted to the C_2 articular facets.

The cervical curvature is a posterior curvature and the line of gravity passes posterior to the bodies (Fig. 10). Thus it would be expected that compressive force would tend to be concentrated towards the neural arch, thus involving it in weight transmission. By contrast, in the thoracic curvature, the compressive force will tend to centre on the vertebral bodies (Fig. 11). Similarly a change in the structure and shape of the vertebral column in the cervical and thoracic regions with respect to its two components, body and arch, might be due to change in the magnitude of compressive force distributed between the two components, because of the change in curvature.

The fact that the articular processes, through which it is postulated that weight transmission occurs, are placed at a wide distance from the body in the cervical region but are close to it in the thoracic region, is highly significant in relation to the geometrical property of columns discussed above.

Davis (1961) has noted the role of the neural arch in the transmission of load at L_5 vertebral level. He took measurements of area of the inferior surfaces of the body and pedicle, also took the transverse process index, in L_3, L_4 and L_5 vertebrae, and found that the surface area of L_4 vertebra is more than L_3 and L_5; that the pedicles increase in size from above downwards; and that the transverse process of L_5 is usually much larger than that of L_3 and L_4. This significant inverse relationship between area of body of L_5 and pedicle size and transverse process size, when compared with L_4, supported the view that the neural arch is responsible for transmission of a part of the compressive force from the vertebral column to the pelvis. Both Denis (1983) and Louis (1985) are of the opinion that, throughout the vertebral column, zygopophyseal joints play an important role in weight bearing. Denis (1983) on the basis of his 'three column spine' concept states that the facet joints and posterior ligament complex is involved in conferring stability on the vertebral column. Louis (1985), on the basis of vertebral morphological studies of the dry skeleton, states that descending forces from C_2 to L_5 are transmitted through three columns; an anterior formed by bodies and intervertebral discs and two posterior columns formed by successive articular processes. He opines that this vertical system of columns is reinforced by horizontal struts, namely the pedicles and laminae, which at the level of each vertebra firmly join the columns to each other.

In the present investigation, as in Davis (1961), an attempt has been made to analyse the role of the neural arch in weight transmission in the cervical and upper thoracic region of the vertebral column.

The weight from the atlas vertebra passes to two superior articular surfaces of the axis. This compressive force (A) can be resolved into two components (B and C; Fig. 8). Component B will go downwards and medially to the inferior surface of the body while component C will go downwards, backwards and laterally, through the strong pedicles, to the inferior articular facet. In most cases the superior articular surface overlaps the facet, but even in cases where overlapping is not seen, easy transfer of compressive force from the superior surface to the facet occurs due to the inclined beam action of the pedicle. The inferior surface of the body receives the component B from both sides, after it has passed through the path of least resistance.

The area of the articular surface relates to its ability to resist longitudinal compression force provided its internal structure remains constant (Davis, 1961). Similarly, Dhall (1984) is of the opinion that the size of the articular facets is correlated with the magnitude of stress imposed on them. Gallioes & Japiot (1925) studied the internal structure of vertebral bodies and found that it is unchanged at different levels. It can be assumed that the internal structure of the articular processes would also be like that of the bodies, as both vertebral components consist of spongy bone covered by a thin layer of compact bone. Hence, the equal surface areas of body and articular facet may be compared to the equal compressive forces acting upon them. On the basis of the above mechanical considerations, the transmission of compressive force at the level of the axis vertebra can be analysed.

The significant correlation found between the area of the two superior articular surfaces and the total area of the body and the two inferior articular facets indicates that whatever compressive force is exerted on the superior surface of the axis vertebra is transferred to the inferior surface of the body and the two inferior articular processes. The diversion of compressive force from superior surface to inferior articular facet on either side is aided by the inclination of the pedicle.

If the areas of the two superior articular surfaces (4·40 cm^2) represent the total compressive force applied, then 2·41 cm^2 area of the body would represent 54 % and 2·04 cm^2 area of two inferior articular facets would approximately represent 46 % of the compressive force applied on the superior articular surfaces. The remaining 0·05 cm^2 of excess inferior articular area might be considered as the increment due to the additional weight at this level.

Thus, compressive force from the superior surface of the axis passes to the body and the articular processes. From the inferior surface of the axis vertebra, compressive force is carried through three columns, anteriorly by the bodies and intervertebral discs and posteriorly by the articular processes. It is essential that the columns formed by the articular processes should be strong enough to sustain the 46 % of the compressive force transmitted through the two inferior articular facets (23 % each) at C_2 level. Not surprisingly, then, the articular processes in the cervical region are very strong bar-like structures and their articulations form strong columns posterolateral to the vertebral bodies (Fig. 9).

The conclusion that compressive force from the two superior articular surfaces of the axis vertebra is carried below through three columns is similar to Louis' (1985) concept, but the present study supports his entirely morphological observations with

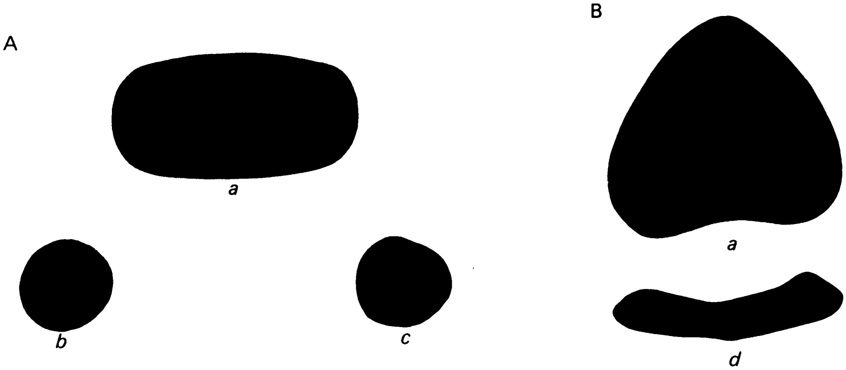

Fig. 12(A–B). Diagrammatic representation of the positions of weight bearing pillars of the vertebral column in the cervical (A) and thoracic (B) regions. *a*, cross section of anterior column formed by bodies; *b* and *c*, cross sections of posterior column formed by articular processes; *d*, cross section of posterior column formed by lamina.

a mathematical analysis and some quantification of the magnitudes of the compressive forces involved.

The three columns which sustain the compressive force below the level of the axis vertebra run parallel, following the cervical curvature (Fig. 9). But below the level of C_7, the two strong bar-like columns formed by the articular processes disappear due to the incorporation of articular facets in the laminae. Hence, in the thoracic region, articular facets do not form a separate bar-like mass as in the cervical region. Thus, in the thoracic region it is expected that compressive forces acting on the superior articular facets will diffuse on to the laminae before passing to the inferior articular facets. Thus the cross sectional area of the laminae will be related to the magnitude of compressive force transmitted through it. In other words, the compressive force transmitted through two inferior articular facets should be the same as that transmitted through the cross sectional area of the laminae. The successive articulation of laminae at zygopophyseal joints in the thoracic region will form a column flattened anteroposteriorly which, in the living state, is strengthened by the posterior ligamentous complex. The change in the structure and shape of the cervical and thoracic vertebrae also supports the view that, at the cervicothoracic junction, the two separate posterior columns of the cervical region become incorporated in the lamina to form a single posterior column.

This idea concerning weight transmission in the thoracic region is similar to the concept of the posterior column of Denis (1983). However, Louis (1985) described a 'three column spine' concept for the thoracic as well as the cervical regions, in spite of the absence of distinctive bar-like articular processes in the thoracic region.

The posterior two columns in the cervical region and the single posterior column in the thoracic region are connected by the pedicles to the anterior column. According to Louis (1985) these pedicles act as struts and reinforce the vertical system of columns. According to the hypothesis presented here, the pedicles play an important role in the transfer of the load from one column to the other and can be considered as mechanical beams. However, the transfer of load is effective only when the pedicles are inclined towards the vertical direction. At C_2 level, the inclination of the pedicles is such that it effectively transfers part of the load from anterior to posterior columns.

Similarly, the position of the columns in relation to one another is also important.

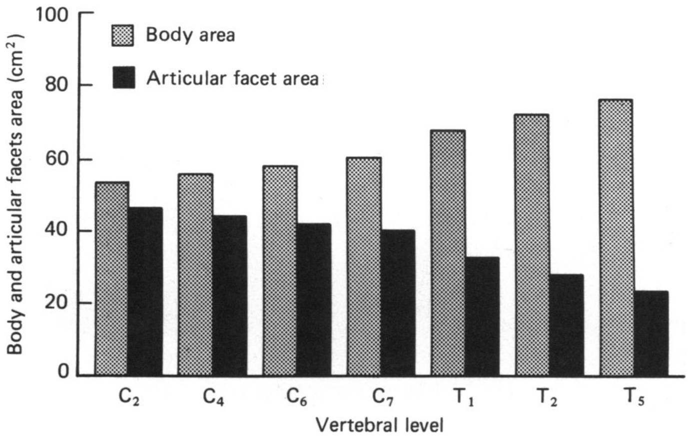

Fig. 13. Bar diagram showing the comparison of mean surface area of the body and mean surface area of the two articular facets at various vertebral levels.

The further the columns are placed away from the centre of load, the more they can resist bending or buckling forces and hence are more stable compared to columns placed closer to each other. The arch index/body area ratio obtained in the present study reveals that the two posterior columns are placed well away (posterolaterally) from the anterior column in the cervical region but that these columns are much closer to each other in the thoracic region (Fig. 12). Possibly this latter disposition contributes to the aetiology of scoliosis in the thoracic region of the vertebral column.

The magnitude of load transmission through the three columns in the cervical region and through the two columns in the upper thoracic region, calculated on the basis of their total relative cross sectional articular area (Table 3; Fig. 13), suggests that transfer of load from one column to the other takes place at the junction of the cervical and thoracic curvatures. Through the most inclined (Table 4) and largest pedicles of the axis vertebra (Table 2), about 46 % of the load is brought on to the two posterior columns (23 % on each). From here downwards to C_7, the surface area of the two articular facets increases very little (Table 1). This suggests that load transmitted through the C_2 vertebra to the posterior columns remains constant and that the addition of extra weight at different levels is minimal. By contrast, the surface area of the anterior column (body area) increases considerably (Table 1), indicating that addition of extra weight at each level is mainly borne by the bodies and little is shared by the two posterior columns. Since the pedicles in the cervical region below the levels of C_2 are close to the horizontal and are of equal strength (Table 2; Fig. 6) it should follow that little or no load passes from anterior to posterior columns. Probably, the two posterior columns in the cervical region are mainly involved in carrying the load passed to them by the C_2 vertebra. But since the slight cervical curvature is directed posteriorly (i.e. towards the neural arch) a little more compressive force on the two posterior columns than on the anterior column might be expected (Figs. 10, 11). The posterior columns, in conditions of increased stress, might carry even more load than that indicated by the surface area of the articular facets. The cervical column is highly mobile and hence, during movement, the distribution of weight transmission between the three columns would be con-

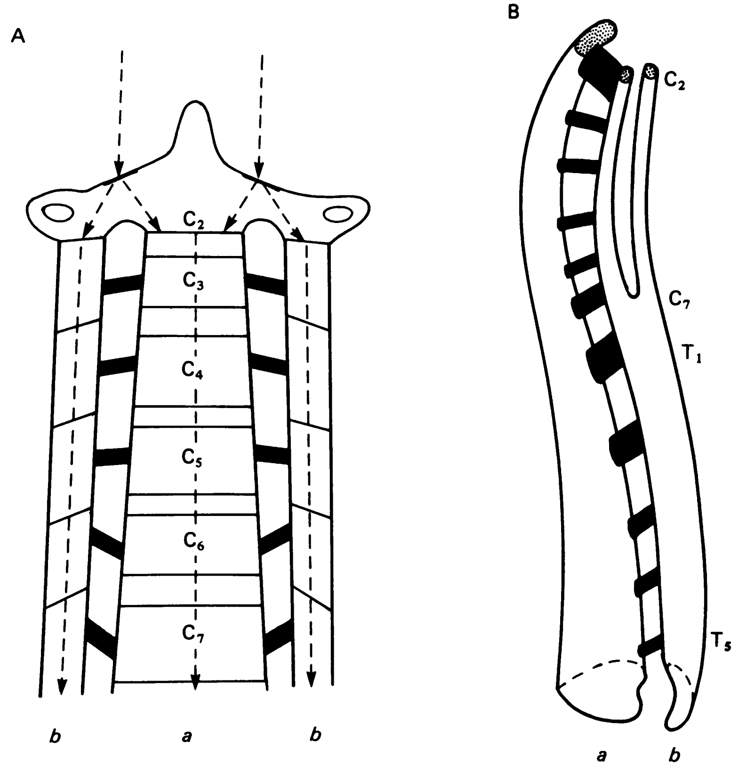

Fig. 14 (A–B). Diagram to indicate weight transmission through the cervical (A) and cervical and upper thoracic regions of the vertebral column (B). *a*, Column formed by bodies and intervertebral discs; *b*, column formed by articular processes in the cervical and by laminae in the thoracic region. Pecked lines and arrows in Figure 14A indicate the path of weight transmission. Thick black bars connecting the columns represent the pedicles. Note the thickness and direction of inclination of the pedicles. In Figure 14B, pedicles are shown on one side only.

stantly changing. Since there is no evidence of increased stress except for the presence of mild curvature (Figs. 10, 11) no further statement can be made.

At the cervicothoracic junction, transfer of part of the weight to the anterior column probably occurs via the pedicles at T_1 and T_2 level, since the pedicles at these levels are strong as compared to their neighbours (Table 2) and are inclined downwards and forwards from the laminae to the bodies (Table 4). At the T_5 level, transfer of weight from the posterior to the anterior column is probably much reduced from that occurring at the T_1 and T_2 level, for pedicle size at this lower level is reduced to a half. The transfer of weight from the posterior to the anterior column at T_1/T_2 is also supported by the fact that at this level there is a sharp decline in articular facet area (Table 3; Fig. 13). However, the bodies at the level of T_1 and T_2 do not show a proportionate increase in area, as might have been expected. This suggests that the vertebral bodies in the thoracic region sustain more load than is suggested by their surface area. This increase in stress is due to anterior curvature (Fig. 10). Hence, in the upper thoracic region, a major proportion (76 %; Table 3) of the compressive force acting on the vertebral column is transmitted through the anterior column formed by the vertebral bodies.

The arch index is maximal at C_7 (Table 1), indicating that the three columns are widest apart at this level. This is necessary because at this level a wide base must be formed against the fixed thoracic column for support, stability and effective movements of the cervical column. The fact that in the upper thoracic region the posterior column becomes weaker and more closely placed to the anterior column (Tables 1, 2) strongly supports the view that load from the posterior column has been transferred to the anterior column. The closer positions of the columns and the increased stress on the anterior column make the thoracic region more susceptible to bending or buckling deformity. Moreover, the fact that the anterior column formed by the bodies is longer and more slender in females at puberty (Taylor & Twomey, 1984) may further reduce its stability.

SUMMARY

The role of the neural arch in weight transmission in the cervical and upper thoracic regions of the vertebral column has been investigated.

Measurements at the levels of C_2, C_4, C_6, C_7, T_1 and T_5 vertebrae were made in 44 adult male vertebral columns. At each level, the area of the inferior surface of the body was compared with the area of the inferior articular facets, the pedicle index and the arch index; inclination of the pedicle in relation to the body was also measured.

On the basis of these studies it was found that at C_2 level the compressive force acting on the superior articular surfaces was transmitted to the inferior surface of the body and to the two inferior articular facets. From C_2 to C_7, compressive force is transmitted through three parallel columns - one anterior, formed by the bodies and intervertebral discs, and two posterior, formed by the articulations of the articular processes on either side. Due to the posterior curvature in the cervical region, the posterior columns here sustain more of the compressive force. From C_7 level downwards, the compressive force is transmitted through two columns, i.e. one anterior formed by the bodies and intervertebral discs and one posterior formed by successive articulations of the laminae. Below C_7 level, compressive force from the posterior column is partly transferred to the anterior column through the pedicles at T_1 and T_2. In the upper thoracic region, due to the anterior curvature, the main part of the compressive force is transmitted through the anterior column, which sustains even greater compressive force than is suggested by body area, with resulting increased stress.

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REFERENCES

BRANDNER, M. E. (1970). Normal values of vertebral body and intervertebral disc index during growth. *American Journal of Roentgenology* **110**, 618–627.

DAVIS, P. R. (1959). The medial inclination of human thoracic intervertebral articular facets. *Journal of Anatomy* **93**, 68–74.

DAVIS, P. R. (1961). Human lower lumbar vertebrae: some mechanical and osteological considerations. *Journal of Anatomy* **95**, 337–344.

DENIS, F. (1983). The three column spine and its significance in the classification of acute thoracolumbar spinal injuries. *Spine* **8**, 817–824.

DHALL, V. (1984). Bilateral asymmetry in the area of the articular surface of human ankle joint. *Journal of the Anatomical Society of India* **33**, 15–18.

GALLIOES, M. & JAPIOT, M. (1925). Architecture intérieure des vertébres. *Revue de chirurgie* **63**, 688–708.

LOUIS, R. (1985). Spinal stability as defined by the three-column spine concept. *Anatomia clinica* **7**, 33–42.

PETTER, C. K. (1933). Method of measuring the pressure of the intervertebral disc. *Journal of Bone and Joint Surgey* **15**, 365–368.

ROSCH, I. J. & BURKE, R. (1964). In *Kinesiology and Applied Anatomy*, 6th ed., pp. 221. Philadelphia: Lea & Febiger.

TAYLOR, J. R. & TWOMEY, L. T. (1984). Sexual dimorphism in human vertebral body shape. *Journal of Anatomy* **138**, 281–286.

WILLIAMS, P. L. & WARWICK, R. (1980). In *Gray's Anatomy*, 36th ed., pp. 271. Edinburgh: Longman.