Mechanism of change in the orientation of the articular process of the zygapophyseal joint at the thoracolumbar junction

G. P. PAL AND R. V. ROUTAL

Department of Anatomy, M. P. Shah Medical College, Jamnagar, India

ABSTRACT

The orientation of the superior articular processes in thoracic and lumbar vertebrae differs. The present study was undertaken to investigate the possible mechanism for the change from a posterolaterally facing superior articular surface in the thoracic region to a posteromedially facing curved articular surface in the lumbar region. The material of the study consisted of dry macerated bones of 44 adult human vertebral columns. The orientation of the superior articular process and its relation to the mamillary tubercle (process) was examined between T9 and L5 vertebrae in each column. An abrupt change from the thoracic to lumbar type of articular process was observed in 3 columns (7%). Forty-one (93%) columns showed a gradual change extending over either 2 or 3 successive vertebrae. The present study suggests that the change in the orientation of the superior articular process, from the coronal to the sagittal plane (sagittalisation), occurs due to the change in the direction of weight transmission through zygapophyseal joints at the thoracolumbar junction. It was observed that the gradual sagittalisation of the superior articular process in the transitional zone brought it close to the mamillary tubercle which eventually fused with it. Thus the study suggests that the characteristic posteromedially facing concave superior articular process of lumbar vertebrae may have formed because of the fusion of the articular process and the mamillary tubercle.

Key words: Spine; vertebrae; mamillary tubercle; multifidus muscle; low back pain.

INTRODUCTION

In the thoracic region, the articular surfaces of vertebral superior articular processes are flat and face posterolaterally, whereas in the lumbar region they are curved and face posteromedially. Few textbooks of anatomy (Breathnach, 1965; Williams et al. 1989) mention that the change in the orientation of the articular process from thoracic to lumbar type usually occurs at the 11th thoracic vertebra (T11), but rarely at T12 or T10. Davis (1955) stated that the most frequent site of transition is the 11th thoracic vertebra (zygapophyseal joint between T11 and T12 vertebrae). The above authors described the change as sudden, i.e. at a single zygapophyseal joint where the inferior articular process of the upper and the superior articular process of the lower vertebrae were involved. According to Davis (1955), at the thoracolumbar transitional region one zygapophyseal joint was neither like a typical thoracic nor like a typical lumbar joint. He named this a 'mortice joint' because of its resemblance to a carpenter's mortice.

Singer et al. (1988), using computed tomography, reported a sudden transition in 46% of cases, occurring most often at T12 level. They observed a gradual transition in 54% of cases extending over 2 vertebrae, i.e. at T11 and T12. Similarly, Shinohara (1997) observed that the transition from thoracic to lumbar type was either sudden (66%) or gradual (34%) and when the change was sudden, it occurred most frequently at the 12th vertebra (between T12 and L1 zygapophyseal joints), whereas, when gradual, the change extended over 2 successive zygapophyseal joints.

There is no general agreement among the various authors as to the level and mode of change (sudden or gradual) from the thoracic to the lumbar type of articular process. In addition, none of the previous

Correspondence to Professor G. P. Pal, Department of Anatomy, M. P. Shah Medical College, Jamnagar 361 008, Gujarat, India.
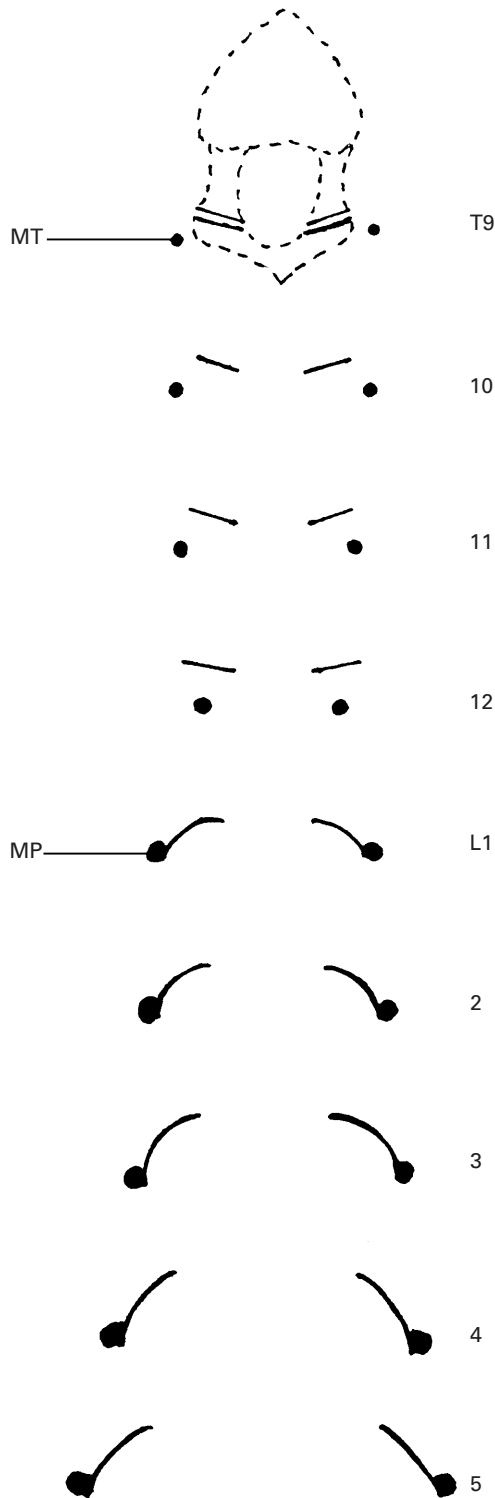
Fig. 1. Drawing to show orientation of superior articular surfaces from T9 to L5 vertebral levels. The articular surfaces are drawn as seen from the superior aspect. The body and pedicle of T9 and inferior articular process of T8 are drawn to give the orientation of the facet joint between T8/T9 and that of anterior and posterior directions. The orientation of the inferior articular processes is not shown at other levels as it reciprocates the orientation of the superior articular surface of the vertebra below. The position of the mamillary tubercle (MT) and mamillary process (MP) in relation to the superior articular process at each vertebral level is indicated. The column shows a sudden change at T12 vertebral level.

investigators has attempted to find the explanation for the change from the thoracic type of articular process to the lumbar type. The present study was undertaken to explore this question.

MATERIALS AND METHODS

The material examined consisted of 44 dry macerated human male vertebral columns from the collection of the M. P. Shah Medical College, Jamnagar, West India. The exact age of individual columns was not known but all were fully ossified (adult). All these columns were free from any congenital anomaly or pathological change.

The direction of orientation of the articular surfaces (facets) was carefully noted in all the superior articular processes from T9 to the 5th lumbar (L5) vertebra.
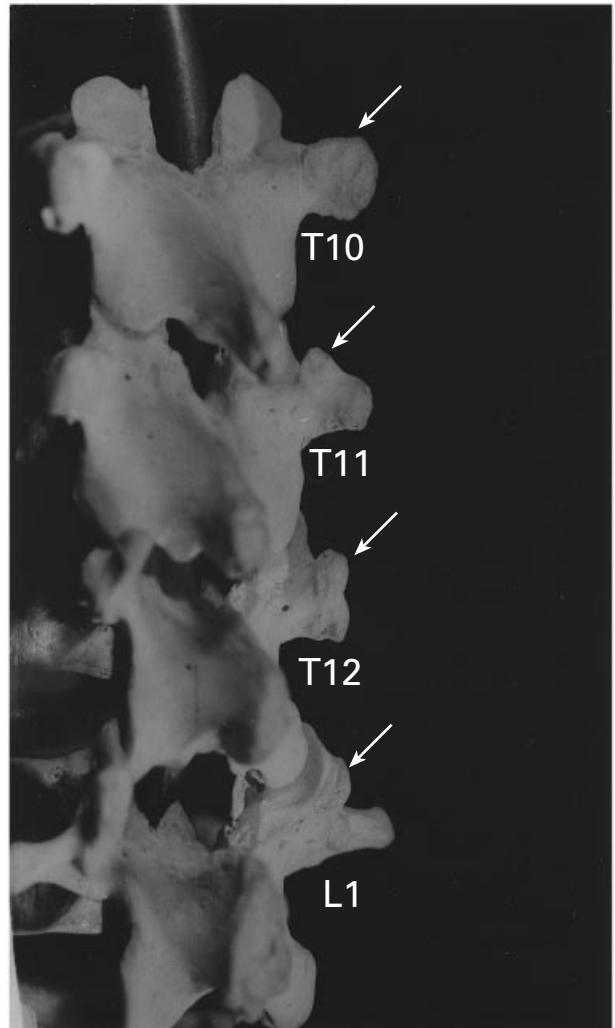

Fig. 2. Vertebral column showing T10 to L1 vertebrae. A sudden change is seen at T12. The mamillary tubercle is seen on the transverse processes of T10–12 vertebrae on the upper 3 vertebrae and a mamillary process is seen on the superior articular process of L1 vertebra (lowest arrow).

Table. *Patterns of change from thoracic to lumbar type of articular surface**

Change observed at 1 vertebra (sudden change)			Change observed over 2 successive vertebrae (gradual change)			Change observed over 3 successive vertebrae (gradual change)		
Vert level (transitional vert)	Zyg jt	Number of columns	Vert levels (transitional vert)	Zyg jts	Number of columns	Vert levels (transitional vert)	Zyg jts	Number of columns
T_{11}	T_{11}–T_{12}	1	T_{10} & T_{11}	T_{10}/T_{11}; T_{11}/T_{12}	2	T_{10}–T_{11} & T_{12}	T_{10}/T_{11}, T_{11}/T_{12} & $T_{12}L_1$	5
T_{12}	T_{12}–L_1	2	T_{11} & T_{12}	T_{11}/T_{12}; T_{12}/L_1	28	T_{11}–T_{12} & L_1	T_{11}/T_{12}, T_{12}/L_1 & L_1/L_2	5
			T_{12} & L_1	T_{12}/L_f; L_1/L_2	1			
Total number of columns		3			31			10
%		7%			70%			23%

Total number of columns observed = 44.
* Zyg jt, zygapophyseal joint; Vert, vertebral; Vert, vertebra(e). The last vertebra of the series, under the heading Zyg jt, was not a transitional vertebra. It showed a typical lumbar type of superior articular process. Thus the superior articular processes of T12 vertebra in the 3 columns were lumbar in type.

The orientation of articular surfaces on both sides, from T9 to L5, was carefully drawn in sequence from above downwards, on paper (Fig. 1). This helped to indicate the changing pattern of orientation of the articular surfaces, at a glance, within a column. The inferior articular surfaces of the upper vertebrae were not drawn as they reciprocate the superior articular surfaces of the vertebrae below.

In the lower thoracic vertebrae (T9 to T12) multifidus takes its origin from a bony tubercle which is situated posterosuperiorly on the transverse process near its root. This tubercle is situated posterolateral to the superior articular process. The mamillary tubercle of T12 is much more prominent, distinct and projects superomedially from the root of the rudimentary transverse process (Fig. 2). Morphologically this tubercle is considered to be an integral part of the transverse process. In the lumbar vertebrae multifidus takes its origin from a bony protuberence (mamillary process) which is situated on the posterior border of the superior articular process (Fig. 2). The relationship of the mamillary tubercle (in thoracic vertebrae) and the mamillary process (in lumbar vertebrae) with that of the superior articular process was also noted and drawn at each vertebral level (Fig. 1).

To identify a transitional vertebra at the thoracolumbar junction, a general rule was formulated and followed, according to which a vertebra in which both the superior articular surfaces were flat and facing posterolaterally and in which the inferior articular surfaces were flat and facing anteromedially was classified as a thoracic vertebra. Similarly, a vertebra in which both superior articular surfaces were curved and facing posteromedially and in which the inferior articular surfaces were curved and facing anterolaterally was classified as a lumbar vertebra. Any vertebra showing articular surface(s) oriented in a different plane (other than just described) was considered to be a transitional vertebra. For example, a vertebra was considered as showing sudden transition when both its superior articular facets were flat and thoracic in nature whilst the inferior facets were curved and lumbar in form. Similarly, a column was considered as showing gradual type of transition when the articular processes of 2 or 3 successive vertebrae showed neither the features of a thoracic nor of a lumbar vertebra.

RESULTS

The change in the orientation of the articular process, from thoracic to lumbar type, followed 2 different patterns, i.e. sudden and gradual.

Sudden change

The sudden type of change was observed in 3 out of 44 columns (7%). This change occurred at a single vertebra. The superior articular processes of transitional vertebrae were thoracic in type and inferior articular surfaces were lumbar in type (Fig. 3A, B). This type of change was observed at T11 vertebra in 2 columns and at T12 vertebra in 1 column (see Table). An important observation, in all 3 columns, was that the lower border of the inferior articular process of the upper vertebra showed an extension of
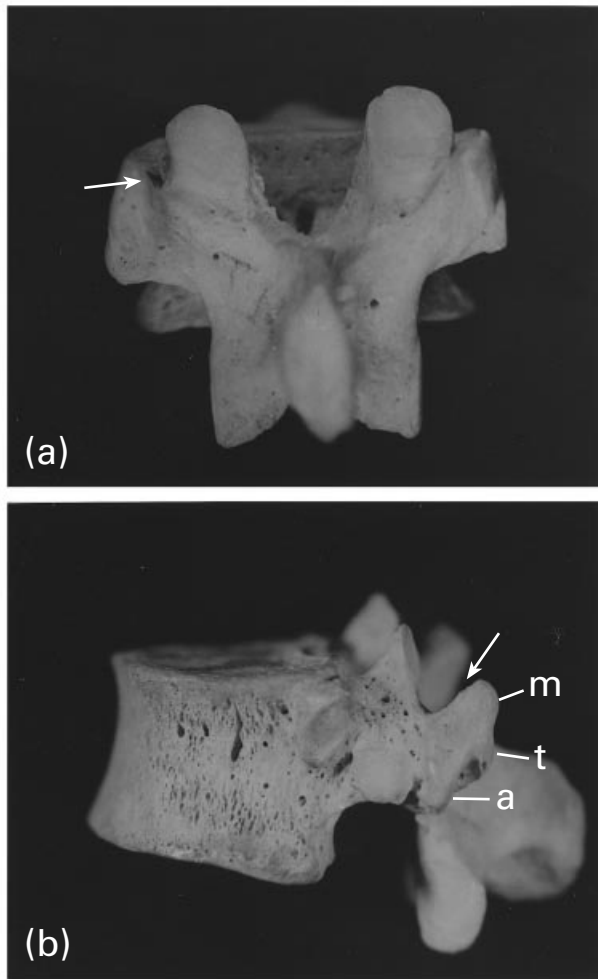
(a)

(b)

Fig. 3. (*A*) Dorsal view of a T12 vertebra showing a sudden transition from thoracic to lumbar. The superior articular processes are thoracic in type (flat and facing posterolaterally). The lamina is narrow (lumbar in type). The mamillary tubercle is prominent and is directed upwards (arrow). (*B*) Left lateral view of the vertebra illustrated in *A* showing a notch between the mamillary tubercle and the superior articular process (arrow). The inferior articular process is lumbar in type (facing anterolaterally) and the transverse process is rudimentary and represented by 3 tubercles, i.e. mamillary (m), transverse (t) and accessory (a).

the articular surface at its lower border. Thus the inferior articular process of the upper vertebra came in contact or rested at the bottom of the notch formed by mamillary tubercle and articular process of the transitional vertebra (Fig. 3*B*). This indicated that at these vertebrae extension movement was limited by bony contact.

Gradual change

This type of change in the orientation of articular processes was observed in 41 out of 44 vertebrae (93 %). Many of these columns (31 out of 44) showed a gradual change extending over 2 successive vertebrae and a few columns (10 out of 44) showed the change over 3 successive vertebrae. The various patterns of orientation are tabulated in the Table and shown in Figure 4.

Four different types of transitional articular surfaces were seen intervening between a typical thoracic and typical lumbar type of articular surface (Fig. 5). The most frequently observed transitional articular surface showed double articular areas (Fig. 5*a*). The medial half of the superior articular surface was oriented coronally (facing backwards) and the lateral half faced posterolaterally (similar to a typical thoracic superior articular surface). Both these areas were separated by a vertical ridge. Panels *b* and *c* of Figure 5 show the rotation of the articular processes towards the sagittal plane. The fourth type of articular surface was most frequently observed at T12 and L1 levels. This articular surface was slightly concave (curved) and faced posteromedially. The mamillary tubercle was situated posterolateral to the lateral margin of the articular process (Fig. 5*d*).

The gap between the mamillary tubercle and the articular process was in the form of a notch of varying
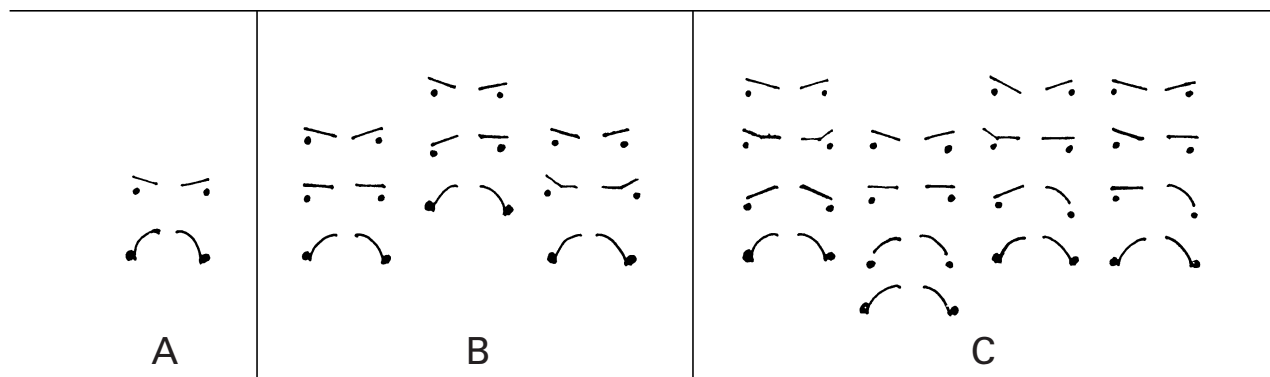

A   B   C

Fig. 4. Diagrammatic representation of various common patterns of change from thoracic to lumbar type of articular surface, i.e. sudden change (*A*), change occurring over 2 successive vertebrae (*B*) and occurring over 3 successive vertebrae (*C*). The uppermost vertebra in *A*, *B* and *C* is transitional because although its superior articular surfaces are thoracic in type, its inferior articular surfaces reciprocate the superior articular surfaces of the vertebra below. The lowermost vertebra in each type of change shows a lumbar type of articular process and hence should not be considered as transitional.

depth (Fig. 6). This was due to fusion between the mamillary tubercle and the articular process. In this type of vertebra the articular surface of the superior articular process potentially extended towards the medial aspect of the mamillary tubercle (Fig. 7). Thus, with the increasing sagittalisation of the superior articular process, its lateral border came closer to the mamillary tubercle (Fig. 5 *a–d*). It was also observed that the change in the orientation of articular processes was always towards the direction of sagittalisation when traced craniocaudally (Fig. 4 *B, C*). From Figure 4 it is also evident that orientations of transitional surfaces are not always identical on the right and the left sides. Similarly, from the Table it is evident that the most frequent vertebrae to show transition were T11 and T12. None of the columns showed the transitional or lumbar type of articular surface at T9. Similarly, none of the columns showed the transitional or thoracic type of articular surface at L2. The transitional zone extended between T10 and L1 segments (Table).

DISCUSSION

The findings of the present study are not in accordance with those of Davis (1955), Singer et al. (1988) or Shinohara (1997). Davis (1955) observed the change, from thoracic to lumbar, as abrupt (occurring at one vertebral level). Singer et al. (1988) found the sudden and gradual transitions almost in equal proportion. Similarly, Shinohara (1997) also found the transition to be both sudden (66 %) and gradual (34 %). The present study observed a gradual transition in 93 % of columns, which is in marked contrast to the above studies. This might be due to the fact that Davis (1955) may have failed to recognise various transitional types of articular surfaces (Fig. 5) and must have considered them to be thoracic. On the other hand, Shinohara (1997) recognised only 2 types of transitional articular surface (similar to the surfaces shown in Fig. 5*b, c*). It is possible that he may have confused the transitional articular surface with double articular areas (Fig. 5*a*) as a typical thoracic vertebra and the slightly curved surface (Fig. 5*d*) as the surface of a typical lumbar vertebra. This might be the reason as to why both Singer et al. (1988) and Shinohara (1997) observed the gradual change extending over only 2 successive vertebrae, while the present study the change was found to extend over up to 3 successive vertebrae.

The present study yielded 2 important facts. First, there was gradual sagittalisation of the superior articular process in the transitional zone (T10 to L1).

Secondly, fusion to a varied extent was observed between the articular process and mamillary tubercle at T12 and L1 levels (Fig. 6). Based on the above observations, in the following discussion an attempt is made to suggest an answer of the question as to why and how the posterolaterally facing flat articular surfaces in the thoracic region change to the posteromedially facing curved surfaces in the lumbar region. However, before understanding the reasons for the change in orientation of the articular processes, it may be helpful to consider the mechanisms of load transmission in the thoracic and lumbar regions of the vertebral column. The mechanism of weight transmission could suggest the possible cause of change in the direction of the articular processes.

The following 3 facts help to explain the mechanism of weight transmission through the vertebral column. First, it is a well known fact that zygapophyseal joints are involved in weight bearing and a considerable proportion of weight is transmitted through the lumbar facet joints (Davis, 1961; Adams & Hutton, 1980; Denis, 1983; Yang & King, 1984; Dietrich & Kurowaski, 1985; Louis, 1985; Pal & Routal, 1986, 1987, 1996; Pal & Sherk 1988; Pal et al. 1988; Pal, 1989; Shinohara, 1997). Secondly, it is a general observation that the forces act at a right angle to the plane of any articular surface. Thirdly, the line of gravity passes anterior to the vertebral bodies in the thoracic region and posterior to them in the lumbar region, crossing the column at T11 and T12 vertebral levels.

Weight transmission through zygapophyseal joints situated at the thoracic and lumbar regions

As the thoracic column is concave anteriorly and the line of gravity passes anterior to the vertebral bodies, there is tendency for accentuation of load on the vertebral bodies. Hence the weight acting at the zygapophyseal joints is also transmitted towards the vertebral body. This is supported by the fact that the superior articular surface faces posterolaterally and thus would transmit the weight anteromedially to the body through its pedicles (Fig. 8 *A*). In the lumbar region the line of gravity passes posterior to the vertebral bodies; there is therefore a tendency for weight to be accentuated on the zygapophyseal joints. The posteromedially facing curved articular surface of the lumber vertebrae is expected to receive the load from the inferior articular process of the upper vertebra and transmit it anterolaterally to its strong wall (Fig. 8 *B*). From the superior articular process this load is expected to be transmitted inferiorly to the
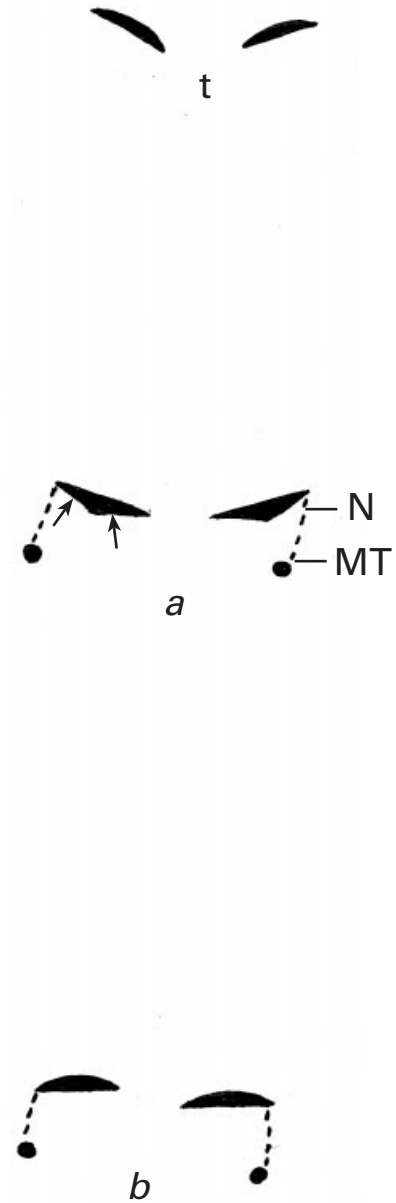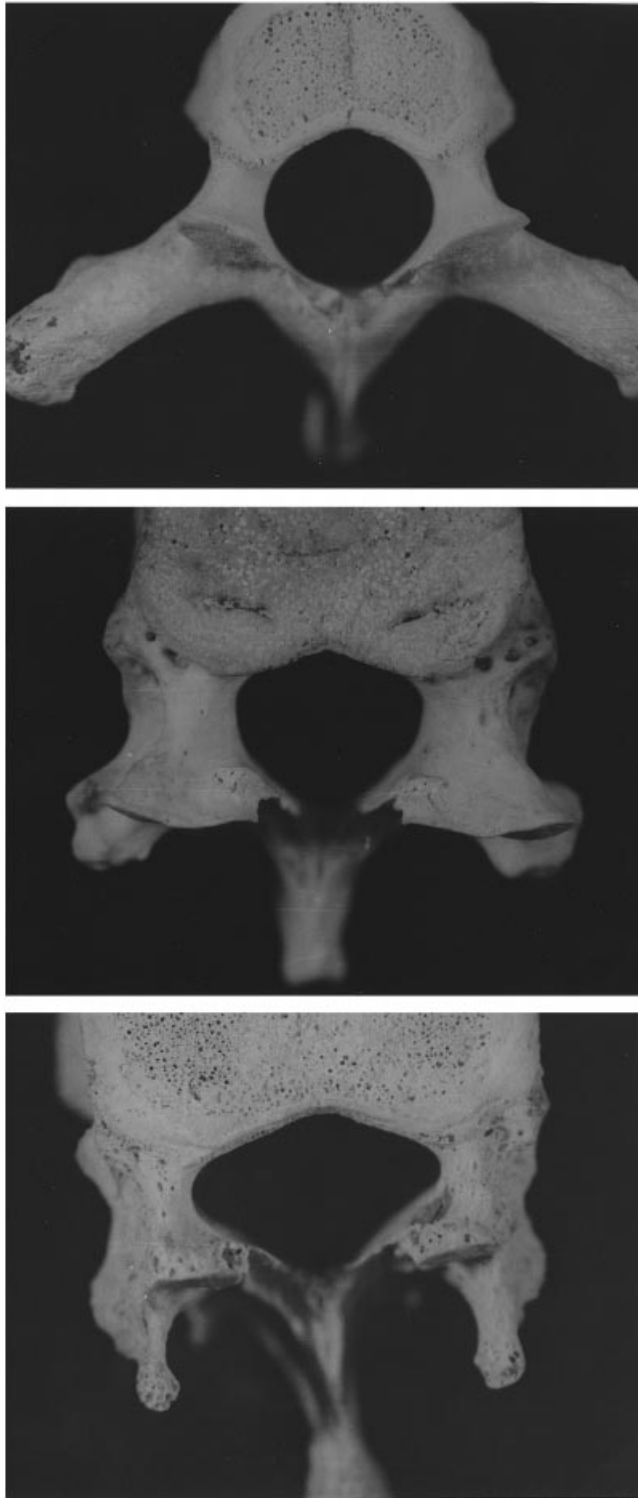
Fig. 5. For legend see opposite.

lamina. This assumption is supported by the fact that the trabecular bone of the superior articular process converges on a strong compact ridge which starts below the superior articular process and runs towards the inferior articular process through the lamina (Fig. 8 C). The superior articular processes in the lumbar region are curved because they have to embrace the inferior articular processes intimately to receive the load and then to transmit it below to the lamina.

The above mechanism of load transmission by the lumbar facet joints is also supported by the findings of Cihak (1970), according to whom the lumbar zygapo-
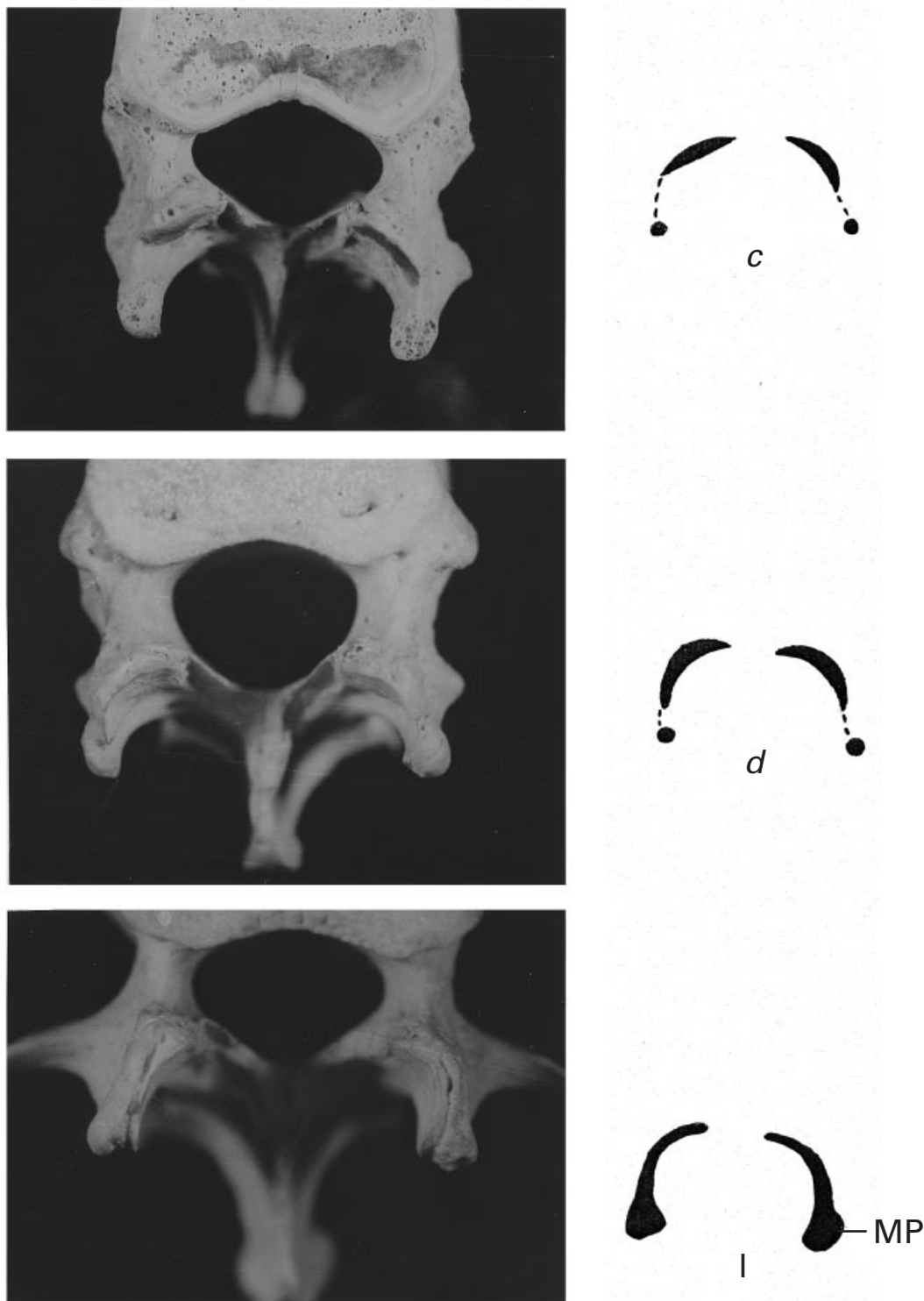
Fig. 5. Photographs and diagrammatic representations of various types of articular surfaces, i.e. typical thoracic (t), transitional articular surface showing double articular areas (*a*), coronally oriented articular surface (*b*), posteromedially facing flat and curved articular surfaces (*c*), posteromedially facing and slightly curved articular surface (*d*), and a typical lumbar articular surface (l). Articular surfaces seen in *a*, *b*, *c* and *d* are transitional in nature hence, they are distinct (away) from mamillary tubercles (MT). A notch (N) is always seen between a transitional articular surface and mamillary tubercle (indicated by stippled line). MP, mamillary process.

physeal joints, at birth, are all oriented in the coronal plane, similar to the joints of the thoracic vertebrae. However, during postnatal growth their orientation starts to change from the coronal to the sagittal plane.

The process of 'sagittalisation' begins at the 6th postnatal month and is completed by the age of 18 months. During this period the articular surface gradually rotates from coronal to sagittal, becoming
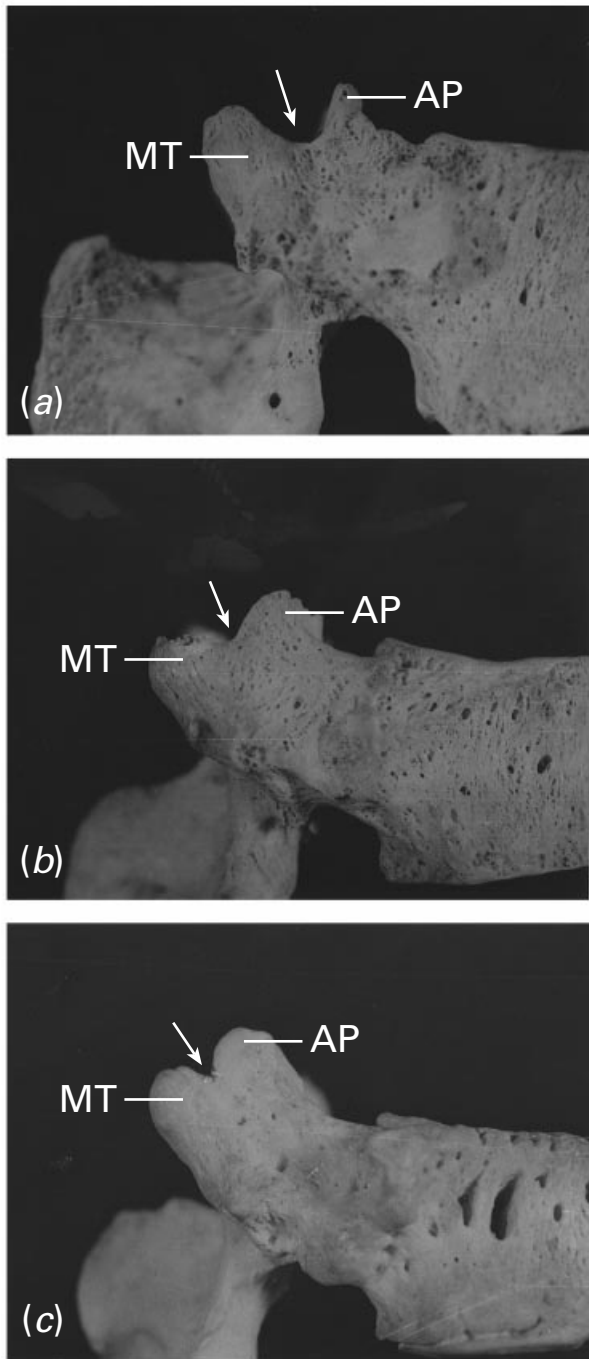
Fig. 6. Lateral view of transitional vertebrae showing the gradual fusion of the superior articular process (AP) and mamillary tubercle (MT). With increasing sagittalisation of the articular process the gap between it and the mamillary tubercle diminishes and eventually the 2 fuse with each other (arrows in *a*, *b*, *c*).
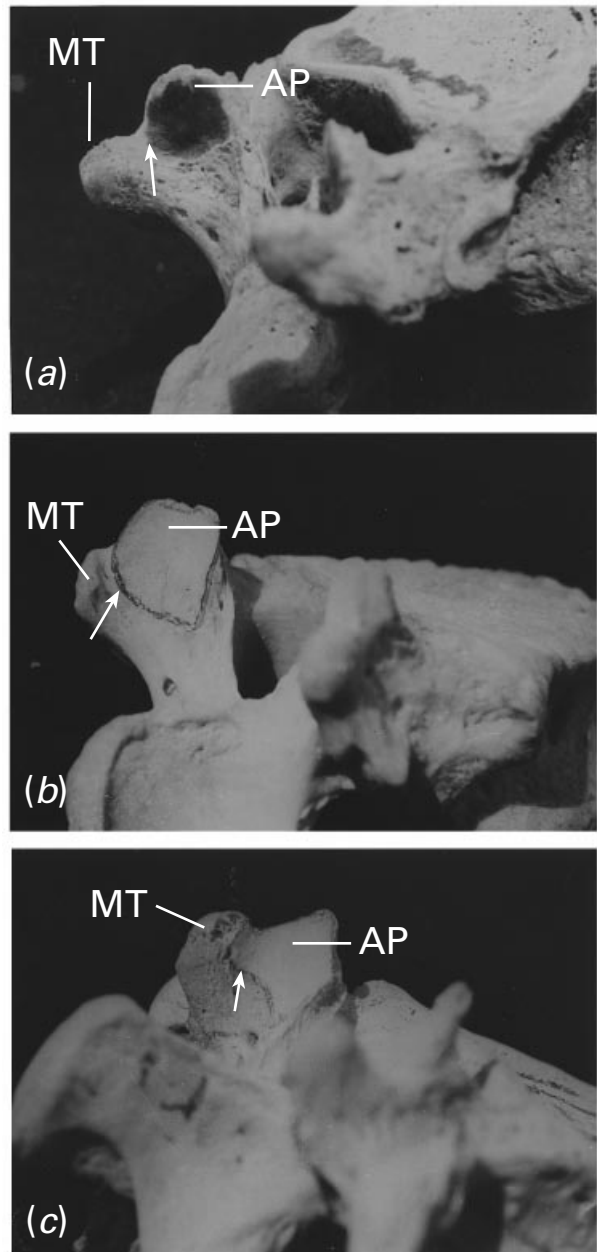

Fig. 7. Superior articular process and mamillary tubercle seen from medial surface. Because of fusion of the mamillary tubercle (MT) with the articular process (AP), the articular surface gradually extends over the medial aspect of the mamillary tubercle (arrows in *a*, *b*, *c*).

characteristically curved at the same time. From the above findings of Cihak, it may be said that the period of sagittalisation corresponds to the development of the lumbar curvature which is associated with the child learning to stand erect and walk. Thus the process of 'sagittalisation' of the articular processes in the lumbar region is associated with loading of the

zygapophyseal joints. The sagittally oriented curved articular processes are well adapted to bear the load acting at the lumbar zygapophyseal joints.

Weight transmission through zygapophyseal joints situated at the thoracolumbar junction

At the thoracolumbar transitional region the orientation of the articular processes differed from that observed at typical thoracic or lumbar vertebrae. This
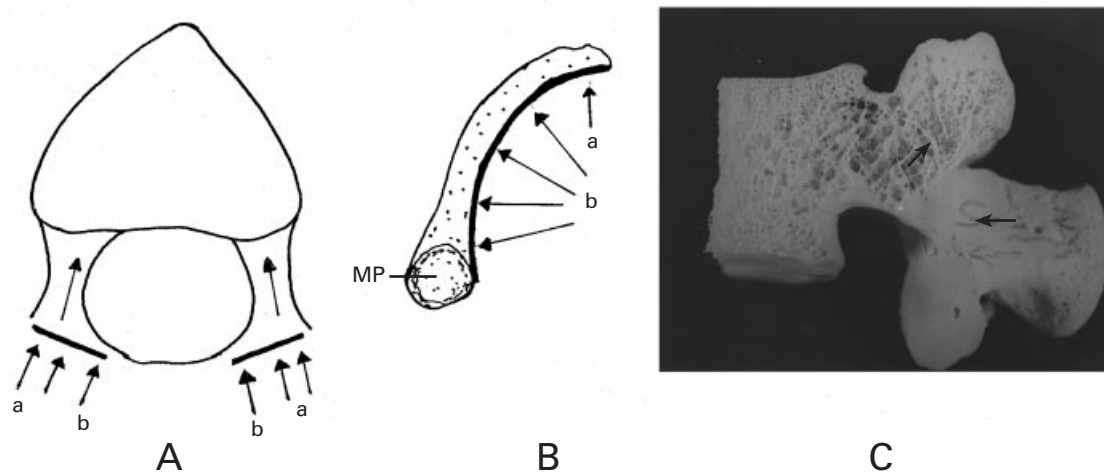
Fig. 8. (*A*) Diagrammatic representation of a typical thoracic vertebra seen from above. From the lateral part of the articular surface forces are transmitted to the pedicle (a), whereas from the medial part forces are transmitted below to the lamina (b). (*B*) Diagrammatic representation of a transverse section passing through a typical lumbar superior articular process. Forces act at a right angle to the articular surface. The articular surface facing dorsally transmits the load to the pedicle (*a*) and a large surface facing medially transmits the forces laterally to the articular process (*b*). MP, mamillary process. (*C*) The trabecular architecture of the superior articular process of a lumbar vertebra (upper arrow) indicates that from the articular process the forces converge to be transmitted to the inferior articular process through a bony ridge on the lamina (lower arrow).

suggests that the mechanism of weight transmission in this region may not be the same as discussed above. As this region is the junction of 2 curvatures, the line of gravity crosses the T11 and T12 vertebrae. Because of this a shift of load from the anterior to the posterior components of the vertebrae (vertebral bodies to facet joints and laminae) is expected (Pal & Routal, 1987). It is suggested that the change in the direction of load might be achieved by the change in the orientation of the articular processes at this region. The present study strongly supports this assumption as the gradual sagittalisation of articular processes was observed in the transitional zone (T10 to L1) (Figs 4*B*, *C*, 5*a–d*). The increasing sagittalisation of the articular processes in the transitional vertebrae is likely to be an adaptation to enable a gradual shift of the load from the anterior to the posterior components of the vertebrae.

From the above discussion it is evident that the rotation of the articular processes at the thoracolumbar junction is associated with the change in the direction of load transmission. Odgers (1933), however, attributed the rotation of the lumbar zygapophyseal joints to the action of multifidus. According to him, by pulling the mamillary process multifidus swings the lateral extremity of the superior articular processes to a more dorsal position, thereby rotating the plane of the joint or by imparting a curvature to it. The present study has suggested a different explanation for the rotation of the articular processes (see above) and considers that multifidus is not responsible for the change in the orientation of the

articular processes. This is supported by the fact that multifidus, in the lower thoracic vertebrae, does not take origin from the lateral extremity of coronally oriented superior articular processes but from the mamillary tubercle which is situated posterolaterally and away from the articular processes (Fig. 2). Similarly, the transitional vertebrae which already show the posteromedially facing flat or curved surface (Fig. 5*c, d*) have a distinct mamillary tubercle, indicating that the rotation of the articular surface has not occurred in relation to the pull of muscle on these vertebrae. Thus multifidus cannot be held responsible for the initiation of sagittalisation as suggested by Odgers (1933). In lumbar region, however, once the fusion between the mamillary tubercle and articular process is completed during infancy, the pull of multifidus may help to deepen the curvature of the superior articular process (see below).

The above assumption that the change in the orientation of the articular processes is associated with a change in the direction of weight transmission at the thoracolumbar junction is also supported by the following. As the line of gravity crosses the T11 and T12 vertebrae, these levels are the most common sites to show transition from the thoracic to the lumbar type of articular process (Table). For the same reason, the gradual sagittalisation of articular processes is also confined between T10 and L1 vertebral levels. In addition, it was observed that the sagittalisation of the articular surface, in the transitional zone always increased with successive vertebrae (craniocaudally). This pattern itself indicates that there is a gradual shift
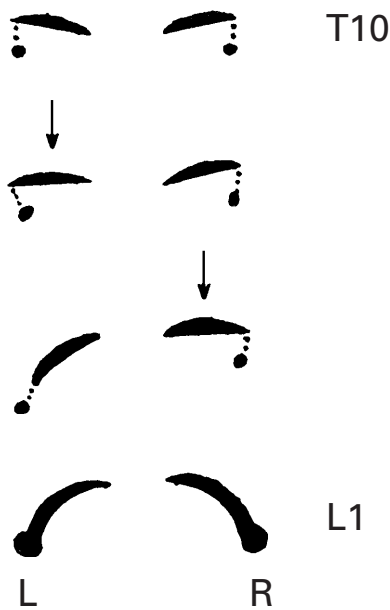
T10

L1

L   R

Fig. 9. Diagrammatic representation of a column showing gradual change and bilateral asymmetry in the orientation of articular surfaces. This indicates that rotation of the articular process is always towards further sagittalisation. This diagram also indicates that until the lamina is no longer loaded (arrow) sagittalisation would not begin.

of load from the anterior to posterior components of vertebrae (from bodies to neural arches). This is also supported by the fact that none of the vertebral columns showed the reverse orientation once sagittalisation is established, i.e. a posteromedial facing (Fig. 5c) or slightly concave (Fig. 5d) surface was never followed by a coronally oriented (Fig. 5b) or posterolateral facing articular surface in the lower vertebrae. Even if there were bilateral asymmetry in the orientation of articular surfaces, the rotation of the articular surface was always towards further sagittalisation (Fig. 9). This figure also strongly supports the assumption that if the lamina was not loaded the articular surface would not start changing to lumbar type. In Figure 9 the articular surface on the left side at T11 was oriented coronally, thus initiating convergence of the load on its hemilamina, while on the right the surface still faced posterolaterally and thus transmitted the load to its body through its pedicle. As the hemilamina of T11 on the left was loaded, the articular surface, in the vertebra below, commenced a gradual change to lumbar type. However, this process on the right only started at T12 after the coronalisation of its superior articular surface. This observation also indicates that the hemilamina and articular process of one side functionally can act independently in relation to their counterparts on the opposite side.

The above discussion indicates that accentuation of load on the lamina is necessary to obtain the lumbar-like articular surface. This is achieved by gradual sagittalisation of articular surfaces when the change is gradual. In the case of abrupt transition, occurring at a single vertebra, the accentuation of load on the facet joint and lamina was achieved (in spite of posterolaterally facing superior articular processes) by bony contact between the inferior articular process of the upper vertebra and the notch of the transitional vertebra below (Fig. 3B).

Fusion of the superior articular process and the mamillary tubercle

The present study has revealed that the gradual rotation of the superior articular process in the thoracolumbar region brings it close to the mamillary tubercle, which ultimately fuses with it to form a lumbar-like articular process. This becomes quite evident if the relationship between the mamillary tubercle and the superior articular process is studied in the transitional zone (Figs 5, 6). The fusion between the 2 processes in the lumbar region is an important functional adaptation to receive the weight from the vertebra above. As the articular process alone cannot intimately embrace the inferior articular process of the vertebra above, it fuses with the mamillary tubercle to achieve the same result.

In the present study many vertebrae in the transitional zone showed incomplete fusion which might be due to incomplete sagittalisation of articular processes. The fusion between the 2 processes seems to start from below and proceed upwards, as a notch of varying depth was observed between the 2 processes in a few vertebrae (Fig. 6). It is speculated that the articular surface must extend on the medial surface of fused a mamillary process soon after fusion (Fig. 7). It is also speculated that after fusion the pull of multifidus may deepen the curvature of the superior articular process as claimed by Odgers (1933). The above discussion suggests that the posterior most part of the lumbar articular process is formed by the fused mamillary tubercle which, morphologically, is an integral part of the transverse process.

Clinical relevance

From the above discussion it may be speculated that the gradual transition may help to protect the spine from fracture at the thoracolumbar junction resulting from sudden vertical impact, i.e. a fall from a height

as in parachuting injuries. This is because, due to the gradual change, the forces are expected to be transmitted gradually between the anterior and posterior components of vertebrae at the junction of the 2 spinal curves. However, where the change is sudden, the single transitional vertebra has to bear the impact of forces, thus making it more liable to fracture. Similarly, a vertebra showing sudden transition is also more susceptible to torsional injuries. As the torsional stress is resisted by the sagittally oriented facet joint, a vertebra showing sudden transition would bear the maximum impact of torsional stress. This study has also supported the finding of Pal et al. (1987) that the lumbar zygapophyseal joints are involved in transmission of substantial loads. These joints may be the site of origin of low back pain because of their vertical orientation which may lead to the stretching of the joint capsule containing a nociceptive type IV receptor system.

REFERENCES

ADAMS MA, HUTTON WC (1980) The effect of posture on the role of the apophyseal joints in resisting intervertebral compressive force. *Journal of Bone and Joint Surgery* **49 A**, 713–720.

BREATHNACH AS (1965) *Frazer's Anatomy of the Human Skeleton*, 6th edn, p. 31. London: J & A Churchill.

CIHAK, R (1970) Variations of lumbosacral joints and their morphogenesis. *Acta Universitaties Carolinae Medica* **16**, 145–165.

DAVIS PR (1955) The thoraco-lumbar mortice joint. *Journal of Anatomy* **89**, 370–377.

DAVIS PR (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.

DIETRICH M, KUROWSKI P (1985) The importance of mechanical factors in the etiology of spondylolysis. *Spine* **10**, 532–542.

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

PAL GP (1989). Weight transmission through the sacrum in man. *Journal of Anatomy* **162**, 9–15.

PAL GP, ROUTAL RV (1986) A study of weight transmission through the cervical and upper thoracic region of the vertebral column in man. *Journal of Anatomy* **148**, 245–261.

PAL GP, ROUTAL RV (1987) Transmission of weight through the lower thoracic and the lumbar region of the vertebral column in man. *Journal of Anatomy* **152**, 93–105.

PAL GP, COSIO L, ROUTAL RV (1988) Trajectory architecture of the trabecular bone between the body and the neural arch in human vertebrae. *Anatomical Record* **222**, 418–425.

PAL GP, SHERK HH (1988) The vertical stability of the cervical spine. *Spine* **13**, 447–449.

PAL GP, ROUTAL RV (1996) The role of vertebral lamina in the stability of cervical spine. *Journal of Anatomy* **188**, 485–489.

SINGER KP, BREIDAHL PD, DAY RE (1988) Variations in zygapophyseal joint orientation and level of transition at the thoracolumbar junction. *Surgical Radiological Anatomy* **10**, 291–295.

SHINOHARA H (1997) Changes in the surface of the superior articular joint from the lower thoracic to the upper lumbar vertebrae. *Journal of Anatomy* **190**, 461–465.

WILLIAMS PL, WARWICK R, DYSON M, BANNISTER LH (1989) *Gray's Anatomy*, 37th edn, pp. 315–317. Edinburgh: Churchill Livingstone.

YANG KH, KING AI (1984) Mechanism of facet load transmission as a hypothesis for low back pain. *Spine* **9**, 557–565.