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Trabecular bone structure in lumbosacral transitional vertebrae: distribution and densities across sagittal vertebral body segments

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Abstract

BACKGROUND CONTEXT: Lumbosacral transitional vertebrae (LSTV) are associated with altered articular morphology at the L5–S1 junction. Studies related to lumbo-sacral trabecular architecture in LSTV are few. Altered lumbosacral load bearing at these anomalous junctions possibly results in changes in the number, density, and trajectory of the trabecular bone in transitional lumbosacral vertebral bodies.

PURPOSE: To investigate the pattern, distribution, and density of trabecular bone in the terminal lumbar vertebrae and the first sacral segments in LSTV-affected spines. Measurements were compared with those obtained from normal lumbosacral specimens.

STUDY DESIGN: Observational and descriptive human cadaveric study of vertebral trabecular architecture.

METHODS: Blocks of tissues were obtained from normal (n=20) and LSTV cadaveric specimens (n=16) by sectioning vertically through the fifth lumbar and the first sacral vertebra on either side of the midsagittal plane. Photographs of the cut surfaces were computationally enlarged and mapped for vertical and transverse trabecular numbers and surface areas using the software Image J. All parameters including the trabecular density were computed for anterior, middle, and posterior segments of each of the vertebral elements.

RESULTS: The anterior and the posterior segments showed greater number of trabeculae across all LSTV subtypes in both the terminal lumbar and first sacral vertebrae in comparison with the middle segment. L5 exhibited greater number of vertical trabeculae, whereas the first sacral segments demonstrated greater number and densities of transverse trabeculae. Transition-associated vertebrae showed overall reduced number of the lumbar trabeculae but relatively compact sacral posterior segments with greater number of horizontal trabeculae.

CONCLUSIONS: Findings suggest that some of these variations have overall reduced number of trabeculae across lumbo-sacral vertebrae in LSTV. Screw placements and subsequent pullouts in LSTV may be reviewed in light of different trabecular patterns as reported in this study.

Keywords: Load transmission; Low back pain; Trabeculae

Introduction

The lumbosacral junction is quite unique in terms of its orientation and load distribution [1–4]. Such orientation and resultant trajectories of distribution of weight at the L5–S1 junction facilitates ‘‘wedging’’ of the sacrum within the iliac blades, ‘‘locking’’ of the fifth lumbar vertebra over the sacrum in an inclined slope using the articular facets, and bilateral distribution of load toward the hip joints and thence to the lower limbs [2].

The load that is carried to the sacrum from the axial skeleton is transmitted at three distinct articular interfaces forming the lumbosacral joints. This ‘‘joint complex’’ is constituted by the junction between the body of the fifth lumbar vertebra and the body of the first sacral segment (a secondary cartilaginous joint with the intervertebral disc in between) and a pair of facet or zygapophyseal joints (synovial joint) at the lumbosacral junction. The overall dimensions of the articulating surfaces at this joint complex are larger than the articular surface areas of the preceding joints in having a larger vertebral body,

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pedicle dimensions, and interpedicular distances that not only provide greater support and stability to the incumbent weight but also define the internal trabecular relationship within a given vertebra [5–8]. Lumbosacral transitional vertebrae (LSTV) variations are associated with altered lumbo-sacral articular morphology, weight-bearing dynamics, and clinical implications [9–14]. Transitional anomalies at the lumbosacral junction present as accessory unilateral or bilateral L5–S1 articulations, sacralization (partial or complete fusion) of the fifth lumbar vertebra with the first sacral segment, and lumbarization (partial or complete separation) of the first sacral segment from the sacral mass. In all these transitional variations, the quantum and the trajectory of load passing through the fifth lumbar vertebra probably differ from that in a normal L5 vertebra at a normal lumbosacral junction.

This study takes into account the fact that load transmission through a bone is reflected in its trabecular architecture and bone density patterns [2,15–17]. The arrangement of the trabeculae inside the vertebra imparts the bone its strength to withstand loads from different directions, a fact that is reflected in the orientation and the distribution of the bony trabeculae [4,18]. This fact has been biomechanically well analyzed, verified and established across different vertebral levels including the sacrum [19–23]. It can be anticipated that in transitional L5–S1 states the trabecular architecture and density in the fifth lumbar vertebra would probably vary with each type of lumbosacral transition, reciprocating the dynamics of stress patterns in the bone [8,24–28]. Redistribution of load bearing through L5 vertebrae associated with transitional L5–S1 conditions may thus present different trabecular bony arrangements because of altered biomechanical adjustments in them. This study investigates the characteristics of trabecular arrangement in the midportions of the vertebral bodies in a sagittal perspective. Normal and transitional lumbosacral junctions have been analyzed to demonstrate the differences in the distribution pattern of trabeculae in all LSTV subgroups. One needs to understand the architecture of the vertebral cancellous bone to consider feasibility of screw placements in clinical indications in the context of transitional states at LSTV-affected lumbosacral junctions [29–34].

Materials and methods

Lumbosacral segments were isolated from adult (≥58 years) cadaveric specimens belonging to both the sexes obtained from cadaveric dissection used for undergraduate medical teaching institutions in central and southern regions of India between 2008 and 2011. These specimens were dissected clean for muscular and ligamentous attachments to detect transitional anomalies at the L5–S1 junction. Twenty normal L5–S1 junctions, seven L5–S1 junctions with unilateral or bilateral accessory L5–S1 articulations, six specimens with completely sacralized L5 segment, and three samples with lumbarization of the first sacral segments were observed for the study.

Ten millimeters of midsagittal strips were cut through the L5–S1 junctions including the intervertebral discs from all the specimens with a platinum-edged saw blade of 0.5 mm width. The segments obtained thereof were cleaned to remove all traces of bone marrow from the interstices of the trabecular bone to expose the clear architecture of the finer bony elements at both faces of the cut (Fig. 1).

Photographs were obtained from both sides of the segments. Each surface was divided into three equal segments or areas: anterior, middle, and posterior segments by two imaginary vertical lines. Trabecular elements, both vertical and horizontal, were counted in each of the three areas on each surface of the L5 and S1 segments through photograph magnification. The total areas of the cortical bone present in each of the segments on both the surfaces in a given sample were calculated from the photographs manually by outlining the trabecular areas by using the public domain software Image J (NIH, Bethesda, MD, USA). Cursor tracings were mapped by the computer on the basis of a reference template provided in each photograph (Fig. 1). The results were tabulated as trabecular count (vertical), trabecular count (horizontal), total area of trabeculae (in square centimeters) in each of the segments, and density of trabeculae (as number of vertical and horizontal trabeculae per square centimeter). The data recorded for final analysis were obtained after averaging values of the parameters measured from both the sides of a specimen. All parameters were documented for each of the three types of transitional anomalies studied for the fifth lumbar vertebra (L5)/terminal lumbar vertebra and the first sacral segment (S1) separately (Table and Figs. 2 and 3).

Results

From the results recorded in Table, Fig. 2 (Left and Right), and Fig. 3 (Left and Right), it can be observed that

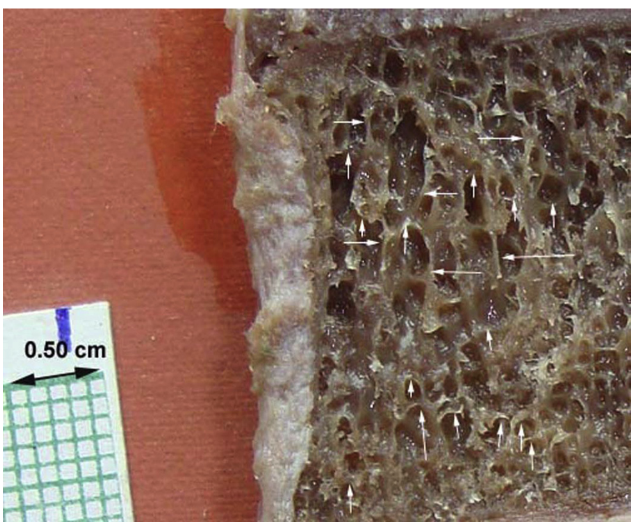


Fig. 1. A section from the fifth lumbar vertebra. The vertical (shown by horizontal arrows) and the transverse (shown by vertical arrows) trabeculae are marked. Note the reference template at the left basal corner of the photograph.

Table
Values of the parameters assessed in the study

Types of lumbo-sacral junctions	Trabecular count (vertical)			Trabecular count (horizontal)			Total trabecular area (in cm^2)			Trabecular density (per cm^2)		
	AS	MS	PS	AS	MS	PS	AS	MS	PS	AS	MS	PS
Normal (n=20)												
L5	26.54	22.00	25.05	21.09	10.72	13.90	1.33	1.01	1.17	13.61	9.35	11.13
S1	22.02	16.00	24.30	28.08	28.02	31.18	1.25	1.02	1.38	14.31	12.58	15.85
Accessory articulation (n=7)												
L5	24.04	18.20	20.12	20.23	15.02	18.11	1.22	0.92	1.04	12.65	9.49	10.92
S1	21.23	22.85	24.73	27.54	20.38	26.32	1.21	1.18	1.33	13.93	12.35	14.59
Sacralization (n=6)												
L5	18.10	12.43	16.98	24.92	20.64	23.55	1.05	0.77	0.99	12.29	9.45	11.58
S1	17.00	11.06	15.33	23.85	18.10	20.61	1.00	0.68	0.89	11.67	8.33	10.27
Lumbarization (n=3)												
L5	26.32	15.85	23.17	18.66	10.74	13.30	1.29	0.77	1.09	12.85	7.60	10.42
S1	19.84	14.55	12.55	27.74	20.78	28.66	1.16	0.86	0.89	13.59	10.09	11.77

AS, anterior segment; MS, middle segment; PS, posterior segment.

Note: Trabecular count represents the total number of vertical trabeculae that measure ≥1 cm each and the number of horizontal trabeculae ≥0.33 cm each. The average area of each segment=3.45 (±1.02) cm^2. All parameters were measured on both the surfaces of a sample.

differences in trabecular patterns and densities exist between the different varieties of lumbosacral junctions investigated in the study. Diverse patterns of trabecular architecture can also be seen in the fifth/terminal lumbar vertebra in contrast to the first sacral segment for the same lumbosacral junction.

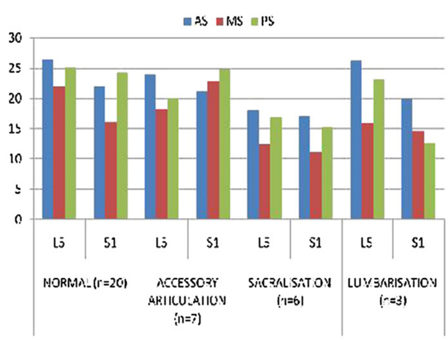
Trabecular count

Normal lumbosacral junction presents greater number of vertical trabecular elements than the horizontal variety across all the segments of the fifth lumbar vertebra. The sacral segment, in contrast, shows increased number of transverse trabeculae across all its segments. The middle segments of both the vertebral elements demonstrate lesser number of trabeculae in comparison with the anterior and the posterior segments. The posterior areas of the sacral segment tend to accommodate greater number of trabeculae. The trabecular concentration in the normal L5 vertebra is greater toward the anterior segment.

The L5 associated with L5–S1 accessory articulation shows lesser number of vertical trabeculae across all the three segments, with the middle segments possessing the least number of trabeculae. Horizontal trabeculae are distributed similar to that observed in the normal L5, with only the number of transverse trabecular elements in the intermediate and the posterior segments showing increased values. The first sacral segment belonging to this type of lumbosacral transition shows gradual increase in the number of vertical trabeculae as one goes from the anterior to the posterior segments. The pattern of distribution of transverse trabeculae is similar to that observed in the normal S1, although the numbers of such trabeculae are fewer than that seen in their normal counterparts.

The last lumbar vertebra in a sacralised specimen (L4 of the spine) bears fewer vertical trabeculae but a large number of horizontally oriented trabecular numeric patterns. The first sacral segment (L5 of the spine) of this fused sacral mass demonstrates less number of vertical trabeculae-like members in the preceding group of lumbosacral spines. The pattern of arrangement of the horizontally directed trabeculae is similar to the other groups, but the number of these trabeculae is reduced.

In the lumbarized specimens, the last vertebra presents trabeculae similar to the normal and the accessory



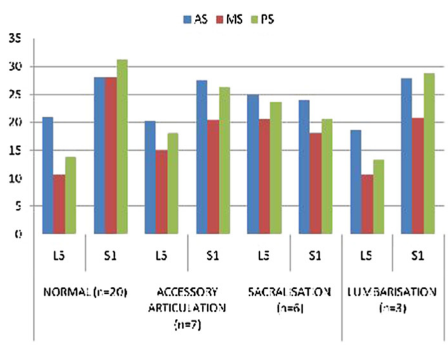


Fig. 2. (Left) The count of vertical trabeculae in the lumboscaral vertebrae. (Right) The number of transverse trabeculae in the vertebral elements at each segment. AS, anterior segment; MS, middle segment; PS, posterior segment.

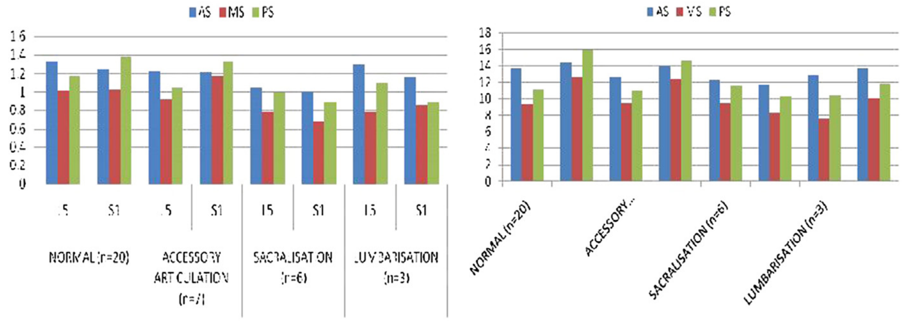


Fig. 3. (Left) The total area of trabecular bone in each of the vertebral segments. (Right) The average density of trabeculae (both vertical and transverse) in all the segments of L1 and S1 elements.

articulation group in number and the distribution. The sacral segment contains fewer vertical and greater numbers of transverse trabeculae in their bodies at the sagittal plane, with a lower number of trabeculae in the middle segment.

Total trabecular area and density per unit area

The total trabecular area in a given segment is proportional to the sum of number of these bony spicules present in that particular segment. Because the surface area of each vertical and transverse trabecula was calculated manually and added up, the distribution of the total area of trabecular bone in a segment reflects the pattern of distribution of the number of trabeculae in the three segments. The area of each segment was calculated approximately to be 3.45 ($\pm$1.02) cm^2. The area of the trabeculae within each of these segmental areas tabulated in the result shows that bone occupies only one-third of the area, whereas two-thirds of area, on an average, is porous. The density of trabeculae in each of the segments shows the total number of trabeculae, both the vertical and horizontal, per square centimeter area across different segments of the vertebra, roughly corresponding with the number of trabeculae distributed within the given segmental areas in the vertebra.

Discussion

It has been documented that trabecular architecture within a bone inherently reflects the distribution of stress traversing the structure. In context of the lumbosacral junction, load within the L5 vertebra is predominantly directed vertically downward through the body of the vertebra. This fact is verified by the greater number of vertically directed trabeculae observed between the end plates of the vertebrae across the sagittal sections. The pattern of arrangement of these trabeculae demonstrates that the anterior segments of the L5 vertebrae at normal L5–S1 junctions are possibly loaded more on their anterior aspects. These vertebrae are subjected to more compressive loads than shear forces. Shear is directed horizontally across the vertebral bodies. The fact is evidenced by lesser number of transversely oriented trabeculae in these vertebrae. The first of the sacral segments in these vertebrae, however, show a diffused array of trabecular pattern with predominantly short, transverse trabeculae. The trajectory of stress experienced within the S1 is more horizontal than vertical as the load transmitted from the first two-and-half segments of the sacrum is dissipated transversely toward the sacroiliac joints. It is to be noticed that the horizontal trabeculae in the posterior segments of the first sacral segment is denser than those seen in the other segments probably because of the fact that it absorbs greater shearing stress coming from the L5–S1 facet joints located posterosuperior to the S1 vertebral body.

The scenario is found to be different in the samples with L5–S1 accessory articulations. The L5 vertical trabeculae are comparatively fewer in number but with similar distribution pattern seen in normal L5. Interestingly, the transversely oriented trabeculae in these L5 are greater in number compared with normal middle and posterior segments. This probably indicates transverse forces active inside these vertebrae that carry load obliquely through the transverse processes in these L5 to the sacral ala. These transverse processes carry a fair amount of load eventually delivered to the ala of the sacrum through the L5–S1 accessory articulation. The first sacral segments associated with these accessory articulations demonstrate similar number and orientation of trabeculae as the normal ones, indicating the usual transverse trajectory of load toward the sacroiliac joint.

Sacralization of L5 incorporates the L5 within the sacral mass. The inclusion of the lumbar vertebrae into the sacral mass imparts the sacrum with different dimensions and traits. The L5 now actually behaves as the first sacral segment. True to this fact, observation in the study detects lesser number of vertically oriented trabeculae in the sacralized L5. Although this bone is subjected to axial load from above, the tubercular architecture of the L5 segment facilitates dissipation of load transversely along the greater number of horizontal trabeculae seen to be present in the bone. It is, however, to be remembered that a portion of stress is also carried by the cortical shell of all vertebrae. The first sacral segment designated in sacralized L5 lumbosacral samples in the study basically represents the second segment of the fused sacral mass. Functionally, this segment bears less stress compared with the first sacral segment (the fused L5) because a good magnitude of load stands transferred already from the first segment on to the sacroiliac joint.

Lumbarization is complete when the first sacral segment is detached from the sacrum and presents as an additional lumbar vertebra. The bones defined as L5 in the lumbarized specimen in this study actually represent the additional lumbar vertebra involved in the formation of the lumbosacral articulation. These L5 elements possess greater number of vertically oriented trabeculae to absorb axial loading. The number of these trabeculae is comparable with those seen in the other groups of L5 vertebrae. Transverse trabeculae are, however, lesser in number in these bones. With lumbarization of the first sacral segment, the mass of the remaining sacrum is reduced and a significant amount of load is possibly dissipated toward the ilium through the strong ligaments such as the iliolumbar, the lumbosacral, and the sacroiliac ligaments. Lumbarization is often associated with the development of these strong ligamentous attachments, and at times, with accessory L5–S1 accessory articulations [35,36]. Thus, a substantial chunk of load is already transferred to the sacraoiliac joint instead being axially loaded on to the first sacral segment of the same lumbosacral junction. Probably as a result, the S1 in this situation shows lesser number of vertical trabeculae. On the contrary, greater number of transversely oriented trabeculae are visible in these segments. This possibly indicates the increased magnitude of shear stress directed to the sacral segment from the rear through the facet joints [2,12,19,23,37]. These joints are highly loaded structures, especially in situations that tend to increase the lordotic curvature. Lumbarization possibly accentuates the incline of the lumbosacral angulation in the sagittal plane, thereby increasing the lumbar lordotic curve and creating a platform for low back pain situation.

It is also interesting to note that the posterior segments of the first sacral segments in transitional variations with accessory L5–S1 articulations and lumbarization demonstrate the presence of greater number of transverse trabeculae possibly indicating a greater share of shear stress subjected to them. It is quite possible that these areas in the sacrum were probably subjected to enhanced direct load from more coronally oriented L5–S1 facets involved with these two transitional variations, as previously reported [28].

The total trabecular areas (calculated as the area covered by the vertical and transverse trabeculae together) reflect the distribution of these two populations of trabeculae in each individual segment in each of the two bones (L5 and S1) constituting the lumbosacral junction. It has been observed that a large area within these segments, actually, does not contain any bony element and is porous. One reason for the uniform reduction in trabecular number in the middle segments across all vertebrae may be because of the presence of venous network with the bones at these areas in the sagittal plane.

The trabecular densities observed in the study depict the distribution of trabeculae in each of the segments per unit area (square centimeters) [38]. It gives an approximate estimate of the magnitude of stress subjected to the segment of the bone. Transitional anomalies are documented to be associated with pathologies at the lumbosacral intervertebral disc, the facet joints, nerve roots, or altered load-bearing biomechanics leading to low back pain. Surgical modalities that have been evaluated to treat such situations often include fusion of the lumbosacral joints [31,37]. Instrumentation at the L5–S1 junction necessitates the need to understand the arrangement of the cancellous bone within the affected vertebrae. This study gives a general idea about the trabecular arrangement found at lumbosacral junction in transitional anomalies that may be helpful to appreciate any probable implication on screwing in nails at these junctions or anticipating the time of a pullout [38,39].

Conclusions

Altered lumbosacral load bearing associated with LSTV results in change in density and trajectories of the trabecular bone within the vertebral corpus at the sagittal areas. Findings from this study suggest that some of these variations are probably associated with greater shear at the sacral elements and also have overall rarified lumbar body interiors. These observations may help in planning screw placements in these situations.

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