Journal of Morphological Sciences
J Morphol Sci
Brazilian Society of Anatomy

Short Communication
J Morphol Sci 2022;39:164-169

Transitional Dysmorphisms at the Thoracolumbar and Lumbosacral Junctions: Perspectives on Biomechanical Implications and Etiological Relationships

Niladri Kumar Mahato[1]

[1]Department of Biomedical Sciences Ohio university, Athens, Ohio 45701

Disclose and conflicts of interest: none to be declared by all authors

ABSTRACT
Introduction: the segmented structure of the spinal column serves as an effective mechanism to transmit axial loading while simultaneously allowing stipulated movements in all six degrees of freedom at the spinal joints. The pattern of antero-posterior intra-vertebral loading dynamically shifts at the thoracolumbar (TL) and lumbosacral (LS) junctions where the line of gravity changes its position in the sagittal plane with respect to the spinal curvatures. Recent publications documenting morphological and clinical presentations of thoracolumbar transitional vertebrae (TLTV) and lumbosacral transitional vertebrae (LSTV) anomalies in the spine literature has prompted this perspective article as an attempt to collate probable biomechanical and etiological links between these two transitional anomalies. A summary of these propositions, as documented by clinical studies and hypothetical modelling, has been presented and discussed.
Keywords: Spinal collumn, thoracolumbar junction, lumbossacral junction, transitional anomalies

Introduction

The segmented structure of the spinal column serves as an effective mechanism to transmit axial loading while simultaneously allowing stipulated movements in all six degrees of freedom at the spinal joints[1,2]. Distribution of axial loads in the spine occurs both as intra- (within) and inter- (between) the vertebrae[3]. Typically, intra-vertebral loading entails distribution of the incumbent load on the superior vertebral endplate and the upper facets through the vertebral body, pedicles (anterior elements), lower facets, laminae, spinous process (posterior elements) via the trabecular system[4,5].

Importantly, loading magnitudes at the anterior and posterior vertebral elements are unequal in the sagittal plane and is determined by the position of the line of gravity relative to the spinal curvature[6,7]. Thus, the pattern of intra-vertebral loading depends upon the spine curvatures to which the vertebra belongs to. Cervical and lumbar curves being convex anteriorly, are subjected to greater incumbent loads on the posterior elements (center of gravity passes posterior to curves), whereas the thoracic and sacral segments register greater axial incumbent stress at the anterior elements (center of gravity passes anterior to curve)[7]. Accordingly, the pattern of antero-posterior intra-vertebral loading dynamically shifts at the thoracolumbar (TL) and lumbosacral (LS) junctions where the line of gravity changes its position in the sagittal plane with respect to the spinal curvatures[3]. Consequently, these junctions present distinct and corresponding anatomical changes in vertebral shape, facet joint orientation, pedicular size and laminar dimension facilitating such transition[7,8].

Short Communication

Recent publications documenting morphological and clinical presentations of thoracolumbar transitional vertebrae (TLTV) and lumbosacral transitional vertebrae (LSTV) anomalies in the spine literature has prompted this perspective article as an attempt to collate probable biomechanical and etiological links between these two transitional anomalies[9-17]. A summary of these propositions, as documented by clinical studies and hypothetical modelling, has been presented in Table 1.

Discussion

1. Structural Dysmorphisms:

Numerical variations in the number of vertebrae, asymmetries of zygapophyseal articulating surfaces, costal and transverse process anomalies, and variations in facet angular orientation (tropism) are commonly encountered at the thoracolumbar and lumbosacral areas[18]. Several primary basic science and clinical research articles and reviews have been published in recent years involving morphological alterations, biomechanical implications, and risks of wrong-level spine surgeries in TTLV and LSTV variations. LSTV classifications are available for clinical usage[19,20]. However, although TLTV structural sub-types have been defined, functional implications and mechanisms of loading patterns at these junctional variations have not yet been completely understood[21,22].

DOI: 10.51929/jms.39.164.2022
ISSN 2177-0298

Table 1. TLTV and LSTV anatomy: Biomechanical implications and Clinical Presentations

Structural Presentations	Anatomical Variations	Biomechanical Implications	Clinical Presentations
TLTV	Acute (single level) facet transition from coronal to the sagittal plane	Acute shifts in antero-posterior loading Increased TL junction stress Increased pedicle stress Acute rotatory restriction Musculoskeletal dysfunction	Upper back pain Degenerative disc disease[17] Adjacent segment disorder[14]
	Numerical anomalies Facet tropism	Loading asymmetry Unilateral stress Increased kyphotic curve Scoliosis	Scoliosis Unilateral facet arthropathy Myofascial strain[9]
LSTV	Accessory articulation Unilateral rudimentary facet	Asymmetric loading	Unilateral low back pain[12]
	Incomplete sacralization/ lumbarization	Asymmetric SI joint surface area and loading Sacral and lumbo-pelvic dysfunction	Low back pain SI joint pain Hip pain Nerve root irritation
	Sacralization (L_{1-4})	Increased SI joint surface Decreased lordotic curve Increased obliquity of sacral ala and SI joint loading trajectory Larger SI osseous corridors	Adjacent segment/ LS disc degeneration[15] SI pain and fusion
	Lumbarization (L_{1-6})	Decreased SI joint surface Increased lordotic curve Decreased obliquity of sacral ala and SI joint loading trajectory Increased SI shear stress and LS instability Smaller SI osseous corridors	Lumbar spine Instability[21] LS facet pain and spondylolisthesis[26]

TLTV=thoracolumbar transitional vertebrae; LSTV=lumbosacral transitional vertebrae; LS=lumbosacral; SI=sacroiliac.

a. TLTV: Thoracolumbar transitional vertebrae (TLTV) or transitions have been described in a variety of morphological subsets[21]. Abrupt and inconsistent transition of facet morphology from thoracic to the lumbar orientation has been described as anomalous TL transitions. On the other hand, supernumerary thoracic vertebra, ribs and associated costovertebral articular variations have been proposed to represent TLTV sub-types[21]. Typically, TLTVs have been associated with numerical anomaly of thoracic vertebra (eleven or thirteen thoracic vertebrae)[15]. Unlike LSTVs, very few studies have defined TLTVs as a spectrum of dysmorphisms, as usually observed with LSTV. Rarely, studies have probed the overlap of structural or numerical relationships between TLTVs and LSTVs. Anatomical studies probing morphological, biomechanical, or etiological relationships between two transitional states are even rarer[15-17].

b. LSTV: Morphological data on LS junction and transitional variations is widely available in the literature[10-23,24]. The current LSTV classification system proposed by Castellvi et.al in 1984 is currently used for clinical purposes[19]. Newer classification for sub-type identification have been proposed to integrate biomechanical implications of LSTV variants into such systems[10-20-23]. Mostly, LSTV is considered as a spectrum of dysmorphisms ranging from incomplete fusion of the L5 transverse process/es to the sacral ala on one hand, complete fusion (sacralization) of the terminal L5 vertebra into the sacral mass, to partial-to-complete separation of the S1 vertebra from the sacrum (lumbarization) on the other. Consequently, one end of the LSTV spectrum represents a lumbar spine with four lumbar (six sacral segments) with the other end presenting six vertebrae (four sacral segments)[25].

2. Biomechanical Implications: Since the transitional zones act as junctions for shifts in the line of gravity in the sagittal plane, physiological changes in antero-posterior, intra- and intervertebral loadbearing can be expected at these regions. Since the presence of additional vertebrae in certain TLTV and LSTV situations accentuate corresponding spinal curvatures in the sagittal plane, such changes increase loading stresses in vertebral elements and enhance the risk of tissue damage with repeated flexion-extension motion[12-16-24]. Additionally, clinical, biomechanical, and computational modeling studies, including our groups' work, have demonstrated significant levels of vertebral stress generated on lateral bending in LSTVs[26].

a. TLTVs: Morphologically, acute transition of facet orientation at the TL junction changing from the coronal to the sagittal plane across a single spine segment may result in acute shift of the incumbent load from the anterior to the posterior elements in aa vertebra. This may result in acute increase in pedicles stress and may predispose to its mechanical fatigue and failure, juxta-articular or adjacent segment disc degeneration. Only a few studies have identified three types of facet transitions at this junction in a cranio-caudal direction[3-7]. This involves a one-segment (acute) to a two- or three-segment (gradual) shift in the facet orientation (changing from a coronal to a sagittal orientation), including a gradual assimilation of the mamillary processes into the facet anatomy[7]. In context of TLTV, authors have suggested the presence of accessory ribs and their anomalous costovertebral articulations as the basis for a potential TLTV classification system[21]. Accordingly, clinical studies have etiologically linked reported rotational and sagittal plane movements to disc diseases commonly detected with TLTV segments[9-27]. Facet tropism and loading asymmetries in single-segment TLTV transitions have been hypothesized to result in abnormal conjoint rotation and side-bending restrictions accelerating disc, ligament, muscle strain with flexion-extension, lateral bending tasks[28,29].

On the other hand, numerical TLTV aberrations (mostly reported as additional thoracic vertebrae) may lead to accentuation of the thoracic kyphotic curvature. The consequent increase in the junctional stress may lead to intervertebral disc degeneration. Importantly, recent TLTV studies have also reported associated left-right asymmetry in spine-loading and the presence of idiopathic scoliosis in several patients with such anomalies[30,31]. In agreement to the current biomechanical description of scoliosis, morphological asymmetries resulting in lopsided loadbearing may result in the development of primary and compensatory scoliotic curves caudal to a segmental dysfunction [32].

b. LSTVs: Biomechanical changes associated with LSTVs involve a spectrum of morphological alterations affecting the LS and sacroiliac (SI) junctions[33]. Unilateral or bilateral accessory L5-S1 articulations demonstrate increased articular stress and pain at the accessory joints at the sacral ala (Bertolotti's Syndrome)[20]. Associated dysmorphic facet joints, partial sacralization, asymmetries at the sacral auricular surface present painful joints. On the other end of the LSTV spectrum, separation of the S1 from the sacral corpus (partial or complete lumbarization), also results in SI joint asymmetries and painful arthropathies[14]. Additionally, complete sacralization increases bilateral SI joint areas that present larger peripheries of articular areas and larger ligamentous attachments. Moreover, complete sacralization reduces the number of lumbar vertebrae and the lumbar lordosis by decreasing the LS curve and the intervertebral angles. Also, the trajectory of SI loading areas become more oblique as the osseous corridors connecting the upper sacral transverse elements to the ilium become larger and more angulated due to the bilateral osseous integration of the L5 TP to the sacral ala. Complete lumbarization, conversely, reduces the area of the SI joint with reduction in ligamentous attachment areas. Though the lumbar lordosis angle increases with complete lumbarization of S1, the trajectory of SI loading trajectory becomes competitively horizontal. This results in greater shearing stress at the SI joint as the obliquity of the bilateral osseous corridors connecting the upper sacral transverse elements to the ilium decreases[34]. Complete LSTV variants are also commonly associated with reciprocal changes in pelvic incidence, sacral slope, and pelvic tilt[35]. More common LSTV variants representing unilateral anomalies may be associated with coronal curvature deformities of the lumbar spine[15-21].

3. Etiological Relationships: Recent studies involving whole spine imaging have refocused our attention to segmental variations in the spine and how they relate to wrong-level diagnostic and surgical procedures[24]. Some of these studies have documented the prevalence of symptomatic and asymptomatic TLTV and LSTV variations in large cohorts of studied population. Interestingly, a number of these studies also point to the coexistence of TLTV and LSTV in the same individuals, often being associated with scoliotic changes at the corresponding spinal areas. Curiously, several TLTV cases with additional thoracic vertebrae (usually thirteenth thoracic vertebrae with accessory ribs) have been reported to coexist mostly with complete sacralization (four) or rarely with lumbarization (six lumbar vertebrae)[7-11-15-36].

a. TLTV: Morphological anomalies associated with TLTV and LSTV may have significant impact on biomechanical instability of the associated spine segments. As evidenced by anomalous changes in segmental motor control, muscle dysfunctions and mechanical stress associated with such transitional anomalies, it may be inferred that such changes could developmentally lead to compensatory scoliotic adaptations of the spine[9-1-13]. Disproportionately asymmetrical loading on one side of the spine may result in ipsilateral proliferation of trabecular and cortical osseous tissue thereby resulting in asymmetric size of ipsilateral vertebral components. This, in turn, may cause increased ipsilateral convexity of the spinal curvature in the coronal plane inferior to the affected segment and a contralateral reciprocal compensatory curve, further caudal to the first one[7].

b. LSTV: Despite congenital segmentation anomalies being accepted as the general etiology of transitional vertebrae, evidence in favor of developmental, biomechanical, and mechanistic malformation of these junctions into LSTV zones has considerably increased with experimental and clinical studies[11-14-16-21]. As in incomplete LSTVs with unilateral dysmorphic facet joints, asymmetric SI joint surfaces are susceptible to mechanical instability, and as such, structural modifications like accessory LS articulations, hypertrophied ligamentous attachments and compensatory curvilinear adjustments are very frequently observed with LSTV anomalies. Accordingly, it may be argued that changes in biomechanical stability brought about in the spine due to loading asymmetries (both in the sagittal and coronal planes) at the TL and LS junctions may not only present as stand-alone anomalies. Rather, segmental TLTV or LSTV variations may be mechanistically linked together and may be constituents of a mechanical cascade of structural changes, compensatory mechanisms of bone growth, thereby etiologically connecting TLTV and LSTV malformations in a biomechanical continuum [Fig. 1][6].

Anatomical anomalies defined as transitional vertebrae and the evidence linking adjacent-segment degeneration, musculoskeletal and instrumentation failures to these regions strongly suggests pathological loading at these spine segments. Accordingly, from a developmental perspective, the presence of a transitional anomaly at the thoracolumbar region may mechanistically result in compensatory morphological alterations cascading into the lumbosacral spinal segments. Thus, it could be argued that one kind of transitional anomaly may be etiologically accountable for the development of the other variety of transitional anomaly and vice-versa. Evidence of the presence of accessory ossification centers at segments adjacent to TLTV and LSTV regions further substantiates the compensatory and cascading nature of osseous modifications for reasons of stability[37,38]. Future directions in transitional vertebrae research (clinical or radiological studies with patients, morphological studies on skeletal collections, or from studies using computational modelling) should explore the cranio-caudal continuity of structural changes associated with TL and LS junctional transitions. Such investigation may be helpful to ascertain etiological determinants and biomechanical relationship between TLTV and LSTV variations, and to explain refractivity of low back pain interventions due to involvement of larger areas of interconnected spinal anatomy affected by anomalous spine loading[39,40].

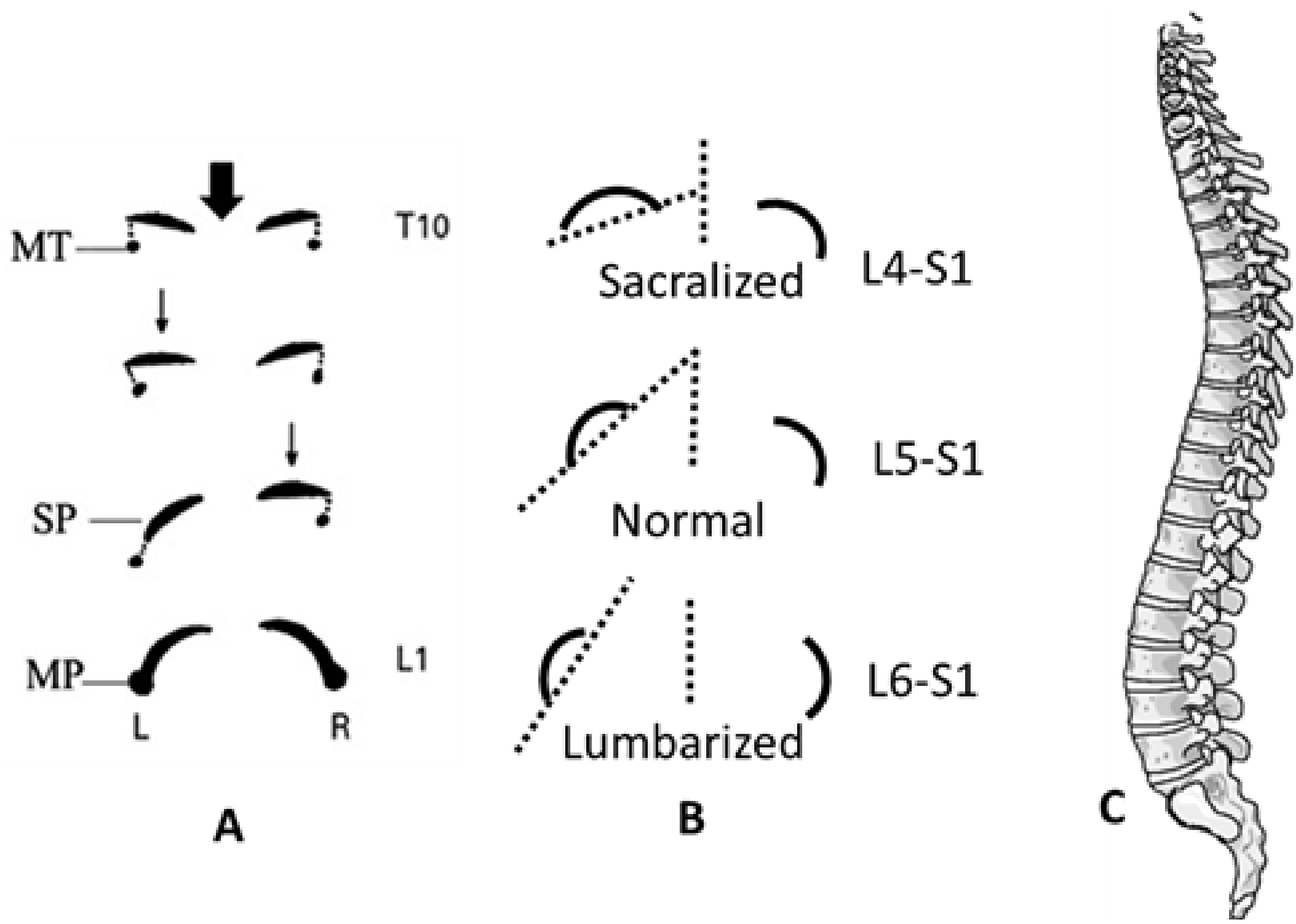

Figure 1. Adapted from Pal & Routal (1999). (A) Superior view of the gradual sagittalization (from top to bottom) of superior facets with progressive fusion of the superior articulating process (SP) with the mamillary process (MP). This fusion results in the change of facet orientation from a postero-lateral to a postero-medial direction. MT, mammillary tubercle; L, left; R, right; T10, L1, thoracic and lumbar vertebral levels. (B) Shows the change in orientation of the lumbosacral facet joint angulation (from coronal to progressively sagittal) with sacralization, a normal L5-S1 articulation and lumbarization. (C) Sagittal view of the distal spinal curvatures, thoracolumbar and lumbosacral boxed in the cranio-caudal direction.

References

1. Panjabi, M.M., The stabilizing system of the spine. Part II. Neutral zone and instability hypothesis. J Spinal Disord, 1992. 5(4): p. 390-6; discussion 397.
2. Panjabi, M.M., The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. J Spinal Disord, 1992. 5(4): p. 383-9; discussion 397.
3. Pal, G.P. and R.V. Routal, Transmission of weight through the lower thoracic and lumbar regions of the vertebral column in man. J Anat, 1987. 152: p. 93-105.
4. Pal, G.P., Weight transmission through the sacrum in man. J Anat, 1989. 162: p. 9-17.
5. Pal, G.P., L. Cosio, and R.V. Routal, Trajectory architecture of the trabecular bone between the body and the neural arch in human vertebrae. Anat Rec, 1988. 222(4): p. 418-25.
6. Mahato, N.K., Thoracolumbar transitional vertebrae: stages of osteological transition, mechanism of changes in zygapophyseal loading and orientation, and assimilation of mammillary processes. J Anat, 2018.
7. Pal, G.P. and R.V. Routal, Mechanism of change in the orientation of the articular process of the zygapophyseal joint at the thoracolumbar junction. J Anat, 1999. 195 (Pt 2): p. 199-209.
8. Pal, G.P., R.V. Routal, and S.K. Saggu, The orientation of the articular facets of the zygapophyseal joints at the cervical and upper thoracic region. J Anat, 2001. 198(Pt 4): p. 431-41.
9. Serafino, F., *et al.*, Understanding regional activation of thoraco-lumbar muscles in chronic low back pain and its relationship to clinically relevant domains. BMC Musculoskelet Disord, 2021. 22(1): p. 432.
10. McGrath, K., *et al.*, Clinical assessment and management of Bertolotti Syndrome: a review of the literature. Spine J, 2021.
11. Li, Y., *et al.*, Percutaneous Vertebroplasty Versus Kyphoplasty for Thoracolumbar Osteoporotic Vertebral Compression Fractures in Patients with Distant Lumbosacral Pain. Pain Physician, 2021. 24(3): p. E349-E356.
12. Garg, B., *et al.*, Variations in the Number of Thoracic and Lumbar Vertebrae in Patients With Adolescent Idiopathic Scoliosis: A Retrospective, Observational Study. Int J Spine Surg, 2021. 15(2): p. 359-367.
13. Becker, L., *et al.*, Musculature adaption in patients with lumbosacral transitional vertebrae: a matched-pair analysis of 46 patients. Skeletal Radiol, 2021. 50(8): p. 1697-1704.
14. Matson, D.M., *et al.*, Sacral Dysmorphism and Lumbosacral Transitional Vertebrae (LSTV) Review. Int J Spine Surg, 2020. 14(Suppl 1): p. 14-19.
15. Doo, A.R., *et al.*, The prevalence and clinical significance of transitional vertebrae: a radiologic investigation using whole spine spiral three-dimensional computed tomographic images. Anesth Pain Med (Seoul), 2020. 15(1): p. 103-110.
16. Abbas, J., *et al.*, Is Lumbosacral Transitional Vertebra Associated with Degenerative Lumbar Spinal Stenosis? Biomed Res Int, 2019. 2019: p. 3871819.
17. Yan, Y.Z., *et al.*, Rate of presence of 11 thoracic vertebrae and 6 lumbar vertebrae in asymptomatic Chinese adult volunteers. J Orthop Surg Res, 2018. 13(1): p. 124.
18. Rai, R.R., *et al.*, A Radiological Study of the Association of Facet Joint Tropism and Facet Angulation With Degenerative Spondylolisthesis. Korean J Spine, 2019. 0(0): p. 0-0.
19. Castellvi, A.E., L.A. Goldstein, and D.P. Chan, Lumbosacral transitional vertebrae and their relationship with lumbar extradural defects. Spine (Phila Pa 1976), 1984. 9(5): p. 493-5.
20. Mahato, N.K., Redefining lumbosacral transitional vertebrae (LSTV) classification: Integrating the full spectrum of morphological alterations in a biomechanical continuum. Medical Hypotheses, 2013. 81(1): p. 76-81.
21. Park, S.K., *et al.*, Thoracolumbar junction: morphologic characteristics, various variants and significance. Br J Radiol, 2016. 89(1064): p. 20150784.
22. Du Plessis, A.M., L.M. Greyling, and B.J. Page, Differentiation and classification of thoracolumbar transitional vertebrae. Journal of Anatomy, 2018. 232(5): p. 850-856.
23. Jancuska, J.M., J.M. Spivak, and J.A. Bendo, A Review of Symptomatic Lumbosacral Transitional Vertebrae: Bertolotti's Syndrome. Int J Spine Surg, 2015. 9: p. 42.
24. Carrino, J.A., *et al.*, Effect of spinal segment variants on numbering vertebral levels at lumbar MR imaging. Radiology, 2011. 259(1): p. 196-202.
25. Mahato, N.K., Implications of structural variations in the human sacrum: why is an anatomical classification crucial? Surg Radiol Anat, 2016. 38(8): p. 947-54.
26. Mahato, N.K., R. Dhason, and D.R. Ram, Quantifying Range of Motion and Stress Patterns at the Transitional Lumbosacral Junction: Pilot Study Using a Computational Model for Load-Bearing at Accessory L5-S1 Articulation. Int J Spine Surg, 2019. 13(1): p. 17-23.
27. Ravikanth, R. and P. Majumdar, Bertolotti's syndrome in low-backache population: Classification and imaging findings. Ci Ji Yi Xue Za Zhi, 2019. 31(2): p. 90-95.
28. Zhu, Q., *et al.*, Biomechanical evaluation of the Total Facet Arthroplasty System: 3-dimensional kinematics. Spine (Phila Pa 1976), 2007. 32(1): p. 55-62.
29. Rai, R.R., *et al.*, A Radiological Study of the Association of Facet Joint Tropism and Facet Angulation With Degenerative Spondylolisthesis. Neurospine, 2019.
30. Pal, G.P., R.H. Bhatt, and V.S. Patel, Mechanism of production of experimental scoliosis in rabbits. Spine (Phila Pa 1976), 1991. 16(2): p. 137-42.
31. Pal, G.P., Mechanism of production of scoliosis. A hypothesis. Spine (Phila Pa 1976), 1991. 16(3): p. 288-92.
32. Szpalski, M., R. Gunzburg, and M. Mayer, Spine arthroplasty: a historical review. Eur Spine J, 2002. 11 Suppl 2: p. S65-84.
33. Mahato, N.K., Variable positions of the sacral auricular surface: classification and importance. Neurosurgical Focus, 2010. 28(3).
34. Mahato, N.K., Re-examining the Spectrum of Lumbosacral Transitional Dysmorphisms: Quantifying Joint Asymmetries and Evaluating the Anatomy of Screw Fixation Corridors. Neurospine, 2020. 17(1): p. 294-303.
35. Tague, R.G., High assimilation of the sacrum in a sample of American skeletons: prevalence, pelvic size, and obstetrical and evolutionary implications. Am J Phys Anthropol, 2009. 138(4): p. 429-38.
36. Masharawi, Y., *et al.*, Facet tropism and interfacet shape in the thoracolumbar vertebrae: characterization and biomechanical interpretation. Spine (Phila Pa 1976), 2005. 30(11): p. E281-92.
37. Belkoff, S.M., *et al.*, The biomechanics of vertebroplasty. The effect of cement volume on mechanical behavior. Spine (Phila Pa 1976), 2001. 26(14): p. 1537-41.
38. Singer, K.P., P.D. Breidahl, and R.E. Day, Variations in zygapophyseal joint orientation and level of transition at the thoracolumbar junction. Preliminary survey using computed tomography. Surg Radiol Anat, 1988. 10(4): p. 291-5.
39. Clark, B.C., *et al.*, A randomized control trial to determine the effectiveness and physiological effects of spinal manipulation and spinal mobilization compared to each other and a sham condition in patients with chronic low back pain: Study protocol for The RELIEF Study. Contemporary Clinical Trials, 2018. 70: p. 41-52.
40. Thomas, J.S., *et al.*, Effect of Spinal Manipulative and Mobilization Therapies in Young Adults With Mild to Moderate Chronic Low Back Pain: A Randomized Clinical Trial. JAMA Network Open, 2020. 3(8): p. e2012589-e2012589.

Mini Curriculum and Author's Contribution

1. Niladri Kumar Mahato MBBS MS DNB Ph.D. Contributions: Transitional Dysmorphisms at the Thoracolumbar and Lumbosacral Junctions: Perspectives on Biomechanical Implications and Etiological Relationships; technical procedures, literature search, interpretation, preparation of draft manuscript, critical review and final approval.
ORCID: 0000-0001-5439-1172

Received: March 9, 2022
Accepted: March 24, 2022

Corresponding author
Niladri Kumar Mahato
E-mail: mahato@ohio.edu