



A vertebral shape-based classification for labeling the thoracolumbar junction on CT imaging

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Abstract

Purpose The correct identification of the thoracolumbar junction is mandatory for labeling of the lumbar spine, particularly if visualized incompletely. The current state-of-the-art relies on a continuous counting-based (CCBC), a rib-length-based (RLBC), or rib-based classification (RBC) of the spine enumeration. However, the CCBC and RBC often lead to inconsistent labels depending on the visualized spine segments.

Methods In this retrospective study, three classifications for assessing the thoracolumbar junction were evaluated in CT scans from 2005 to 2018, covering the complete thoracolumbar spine: (1) CCBC, (2) RLBC/RBC, and (3) a vertebra-shape-based classification (VSBC). The classifications were compared regarding consistent labels depending on the visualized spine segments, agreement with nerve morphology, and inter-rater reliability.

Results CT-imaging data from 1,242 subjects (mean age, 63 years $\pm$ 12; 771 women) were included. The VSBC led to more consistent labels than all other classifications. Only the VSBC perfectly complied with the nerve morphology (VSBC, 100%; RBC, 97.2%, RLBC, 96.3%; CCBC, 92.6%). The VSBC had slightly superior inter-rater reliability than the RBC (0.61 vs. 0.59).

Conclusion The VSBC performs more reliably and consistently than other classifications in labeling the thoracolumbar junction, even for anatomical variants or incompletely visualized spines. Compared with rib-based classifications, the VSBC demonstrated modest but clear advantages in consistency and agreement with nerve morphology.

Key points

- Several classifications identify the thoracolumbar vertebral junction, causing spine enumeration inconsistencies.
- Shape-based classification uses several vertebral features to identify the thoracolumbar junction.
- Vertebral shape-based classification perfectly aligns with nerve morphology.
- Vertebral shape-based classification is more reliable than other methods.

Keywords Thoracolumbar transitional vertebrae · Spine · Spine aberration · Vertebra labeling · Thoracolumbar junction · Computed tomography

Abbreviations

d1, d2, d3	The different datasets. d1 is the publicly available VerSe dataset.
CCBC	Continuous counting-based classification
CT	Computed Tomography
RBC	Rib-based classification
RLBC	Rib-length-based classification
SFJ	Superior facet joint

TLTV	Thoracolumbar Transitional Vertebrae
TJ	Thoracolumbar junction
VSBC	Vertebral shape-based classification

Extended author information available on the last page of the article

Introduction

The spine's anatomy is highly variable, with numerical aberrations seen in about 8% of the population [1–3]. At the thoracolumbar junction (TJ) – the transition zone between the thoracic and lumbar spine (T11–L2) – some vertebrae frequently exhibit both thoracic and lumbar characteristics, thus labeled as thoracolumbar transitional vertebrae (TLTV) [4].

Correct identification of vertebrae is an important task, especially in TLTV. This ensures correct labeling for pre-operative planning of spinal surgery or interventions and prevents operating on unintended levels [5, 6]. The current clinical standard for labeling is counting the vertebrae in a cranial-to-caudal manner with the assumption of seven cervical and twelve thoracic vertebrae [7, 8]. However, in patients with anatomical variations or when the spine is incompletely imaged, this may lead to discrepancies. Furthermore, surgeons often identify vertebral levels by the ribs, which a simple vertebral counting does not address. Some ribs may be underdeveloped, i.e., stump ribs, or confused with additional ossification centers arising from the transverse processes [3]. To address this, a widely adopted nomenclature [9] classifies the TJ based on rib length and morphology. Vertebrae with at least one rib longer than 38 mm are considered *true* thoracic. Those with ribs shorter than 38 mm but with a rib-vertebra-joint are labeled as TLTV and included in the thoracic spine. Alternative methods focus on other features such as rib shape, ossification centers, vertebral morphology, or nerve pathways [3, 10, 11]. However, these approaches may conflict in TLTV, for instance, when one side has a rib and the other an accessory ossification center or lumbar transverse process [4, 12].

Recently, morphologic features were described that help differentiate thoracic and lumbar vertebrae. These include vertebral body shape, shape of transverse processes, and orientation of superior facet joint (SFJ) [4, 12, 13]. However, there is no comparison of the reliability and accuracy of the different classification systems, especially for cases involving TLTV.

Therefore, this study aims to evaluate different classification systems for the TJ on CT imaging, including a newly

proposed vertebra-shape-based classification (VSBC). To validate the results, we evaluated agreement with nerve morphology using MRI [11]. We hypothesized that the VSBC performs more reliably regardless of the imaged spine segments, conforms greater with the nerve morphology, and results in less enumeration shifts.

Methods

The retrospective study, using public and in-house CT-datasets, was approved by the local ethics committee that waived the need for informed consent.

We hypothesized, that the VSBC performs more reliably regardless of the imaged spine segments, conforms greater with the nerve morphology, and results in less enumeration shifts.

Participants

The public dataset (*d1*) [12, 14] and two in-house CT datasets (*d2-d3*) from 2005–2018 were included (Fig. 1). Dataset *d1* has been specifically collected to represent subjects with spine anatomical variants, such as stump ribs, cervical ribs, TLTV, and lumbosacral transitional vertebrae. Datasets *d2* and *d3* represent a non-preselected cohort of routine CT scans. Inclusion criteria involved subject age older than 18 years; a minimum spatial resolution of 2.0 mm (cranio-caudal and anterior–posterior direction), and 5.0 mm (left–right direction), and a fully imaged thoracic and lumbar spine. As numeric aberrations of the cervical spine are rare a correct identification of the first thoracic vertebra can be achieved by assessing the first true rib even in incompletely imaged cervical spines [12, 15].

Methodological approaches for labeling the spine

Three methods (Table 1) were used for labeling the vertebrae:

Method 1 (continuous counting-based classification, CCBC): Common clinical practice and gold standard of counting from the first thoracic vertebra in cranial-to-caudal

Fig. 1 Flow diagram of the investigated study cohort. Flow diagram for subject inclusion and exclusion from top to bottom. We used the public VerSe dataset (*d1*; <https://osf.io/b2wxj/>) and two in-house acquired datasets (*d2* and *d3*) with a total of 2,076 subjects (*n*). Only subjects with completely imaged thoracic and lumbar spines were included

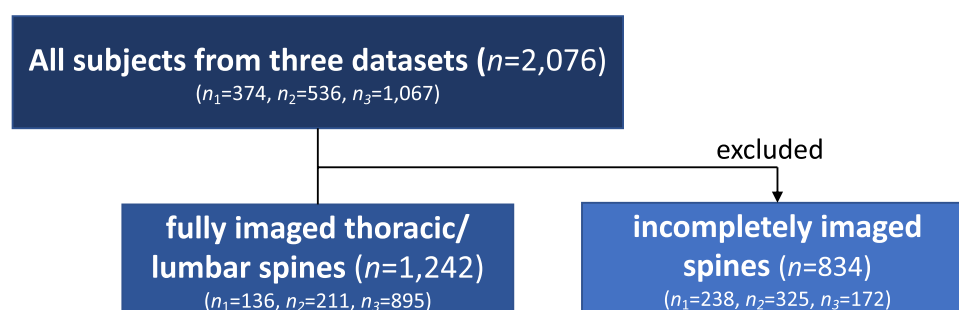


Table 1 Comparison of classifications for labeling the thoracolumbar junction

Classification	Approach	Advantages	Disadvantages
Continuous counting-based classification (CCBC)	• Clinical gold standard [7] • Counting in either cranial-to-caudal direction from the first thoracic vertebra or in caudal-to-cranial direction from the first free pre-sacral vertebra	• Easy to apply • Widely used	• Only possible in fully imaged spines • Discrepant annotations depending on direction of counting in numerically aberrant cases (e.g., 22, 23 or 25 free pre-sacral vertebrae)
Rib-based classification (RBC)	• Identifies thoracic vertebrae by a <i>true</i> rib-vertebra-articulation independent of rib length [8] • TLTV have true rib-vertebra-articulation but rib length below 38 mm [8]	• Without fully imaged spines possible • Widely adopted	• Borderline cases are not addressed, e.g., unilateral ribs or accessory ossification centers • Several rib-based nomenclatures are often mixed (see RLBC)
Rib-length-based classification (RLBC)	• Same approach as RBC but a rib length below 38 mm is termed a stump rib and counted towards the lumbar spine [9]	• Without fully imaged spines possible	• Rib length measurement is not standardized and prone to errors depending on used slice orientation and thickness
Nerve Morphology	• Assesses the fourth and fifth lumbar level by the morphology of the lumbosacral plexus [10]	• Gold standard for assessing functional anatomy of the spine • Great value for pre-operative planning	• Reader training necessary • Only possible on MRI (including sagittal and axial slice orientations)
Vertebral-shape-based classification (VSBC)	• Assesses individual morphology of subregions of each vertebra	• Without fully imaged spines possible • Possible in CT and MRI	• Reader training necessary • Not possible on plain radiographs

CCBC, continuous counting-based classification; RBC, rib-based classification; RLBC, rib-length-based classification; TLTV, thoracolumbar transitional vertebrae; VSBC, vertebral-shape-based classification

direction, assuming 12 thoracic vertebrae, or from the first free pre-sacral vertebra in caudal-to-cranial direction, assuming 5 lumbar vertebrae. May lead to discrepant labels when annotating from top-to-bottom or vice versa.

Method 2 (Rib-based nomenclature): Divided into (2.1) rib-based classification (RBC) following Wigh et al.'s nomenclature [9], and (2.2) rib-length-based classification (RLBC). RBC labels a vertebra with *true* rib-vertebra-articulation but a rib-length below 38 mm as TLTV and includes it in the thoracic spine, while RLBC labels a vertebra with *true* rib-vertebra-articulation but both rib lengths below 38 mm as a lumbar vertebra with stump ribs. As these nomenclatures often get mixed-up in clinical practice, this may lead to discrepant annotations between both rib-based classification systems.

Method 3 (VSBC): Assesses vertebral morphology at the TJ based on three anatomical key aspects: (I) Shape and orientation of the SFJ, (II) shape and position of the transverse and costal processes relative to the SFJ, and (III) presence of a costal fovea (Fig. 2).

- I) In the thoracic spine, the plane of the SFJ is approximately co-planar with the coronal plane, whereas in the lumbar spine the plane of the SFJ is curved but more co-planar with the sagittal plane [12]. In some cases, the SFJ may exhibit an intermediate shape, transitioning from a thoracic angle to a lumbar angle in cranial-to-caudal direction.
- II) In thoracic vertebrae, the transverse process originates at the same level as the SFJ and extends posteriorly, forming an overriding facet alignment visible in sagittal view. In contrast, lumbar vertebrae show the SFJ dorsal to a laterally oriented costal process, without a visible inferior facet in sagittal view (free facet). In TLTV, both transverse and costal processes may be present simultaneously, typically with a smaller laterally oriented costal process and a larger posterior transverse process.

Each thoracic-type feature scores one point. After scoring all three features (range 0-3), rib-vertebra articulation is evaluated: a true rib joint with rib length >38mm confirms thoracic status in vertebrae scoring ≥ 2 . Vertebrae scoring ≤ 1 without a rib joint or with ribs ≤ 38 mm are classified as lumbar. Vertebrae with mixed feature scores, ambiguous SFJ shapes, or partial ribs are labeled TLTV and further subdivided based on the dominant morphological score.

Figure 2 illustrates a comparison of these segmental differences in spine anatomy and Fig. 3 features of TLTV. Supplementary figures S1 and S2 visualize the vertebral morphology of the TJ as 3D-model and a step-by-step approach of the VSBC. Supplementary figure S3 is an image atlas showcasing a variety of TLTV with stump ribs, additional ossification centers and mixed anatomy.

Thoracic | Lumbar Thoracic | Lumbar

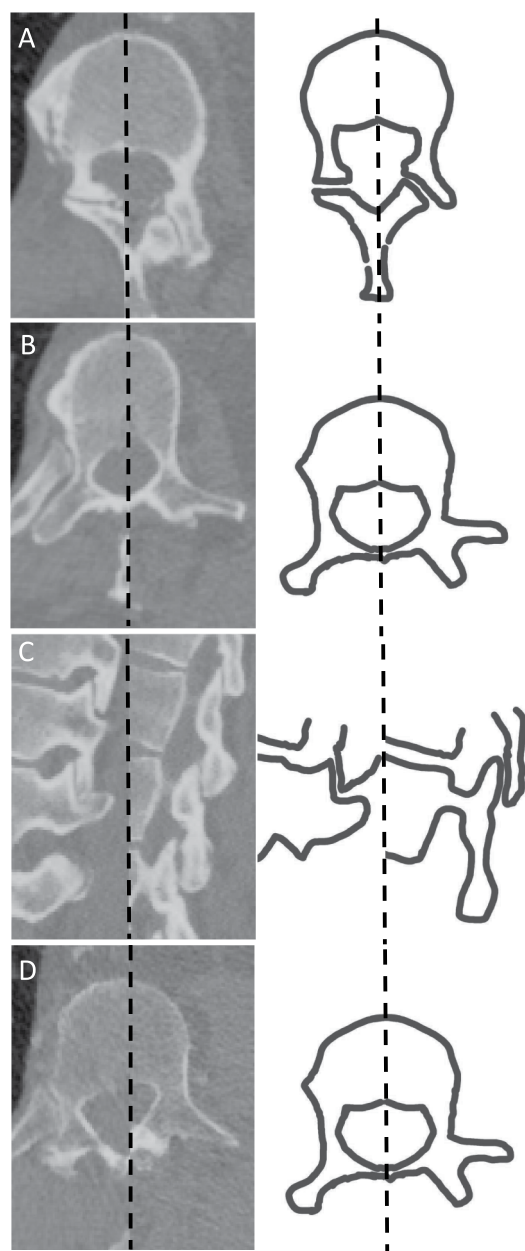
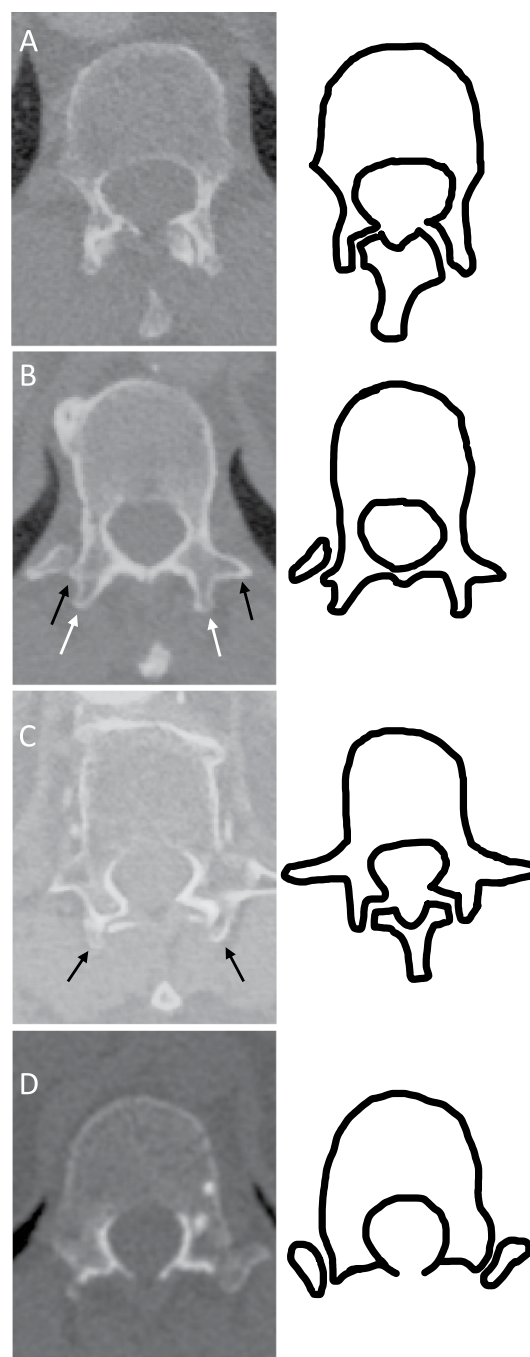


Fig. 2 Classification criteria of thoracic and lumbar shapes of vertebrae. Left column shows normal thoracic and lumbar vertebral features. Right column shows respective features as pictograms. **A)** Example of the difference in orientation of the SFJ. Left half represents a thoracic angulation in medial–lateral direction and the right half a curved angulation in almost anterior–posterior direction typical for the lumbar spine. **B)** Left half shows backward orientation of the transverse process at the same level as the SFJ typical in a thoracic vertebra and right half shows a lumbar vertebra with a costal process with a sideways orientation anteriorly positioned to the SFJ. **C)** Sagittal view of the SFJ in the thoracic spine (left half) shows an *overriding facet* that sits directly on top of the transverse process and a *free facet* (right half) that has no inferior osseous boundary, i.e., absence of the transverse process, in lumbar spine. **D)** Thoracic vertebrae have a costal fovea at the side of the vertebral body (left half), while lumbar vertebrae have a clear, almost 90° angle from the side of the vertebral body to the costal process (right half). SFJ, superior facet joint

Thoracolumbar Transitional Vertebrae



Labeling schematic

All labelings were performed and reviewed by two radiologists (rater 1 and 3) with five and 20 years of experience in spine research. Additionally, 46 spines with challenging TLTV with transitional features, e.g., stump ribs, ossification centers, absent ribs/transverse processes, were assessed by a spine annotation researcher with one year of experience (rater 2), and three radiologists with two, five, and 20 years

Fig. 3 Shapes of Thoracolumbar Transitional Vertebrae. Left column shows borderline TLTV features and right columns respective pictograms for visualization. **A)** TLTV with an intermediate SFJ shape. Right side shows a thoracic direction of SFJ and left side shows a lumbar orientation. **B)** TLTV with both a backward oriented transverse process (white arrow) at the level of the SFJ and a sideways oriented costal process (black arrow) anteriorly to the SFJ. Applying the VSBC labels this as a lumbar vertebra with aberrant costal processes. RBC labels this as a lumbar vertebra as there is a lack of a true rib-vertebra-articulation. **C)** Shows a TLTV with long bilateral costal processes that insert right into the vertebral arch and the posterior vertebral body. The costal processes have no articulation with the vertebral body. Following the RBC this vertebra is counted towards the lumbar spine. However, the SFJ has a thoracic shape and posterior to the costal processes is a pair of transverse processes (black arrows) that have a thoracic shape. Applying the RBC leads to an enumeration shift with 11 thoracic and 6 lumbar vertebrae. Applying the VSBC leads to a normal enumeration of 12 thoracic and 5 lumbar vertebrae. **D)** Shows a TLTV without ribs, thus being labeled as lumbar according to the RBC. However, both the SFJ and transverse processes have a thoracic shape. Applying the RBC leads to an enumeration shift with 11 thoracic and 6 lumbar vertebrae. Applying the VSBC leads to a normal enumeration of 12 thoracic and 5 lumbar vertebrae. RBC, rib-based classification; SFJ, superior facet joint; TLTV, thoracolumbar transitional vertebrae; VSBC, vertebral shape-based classification

of experience (rater 4, 1 and 3) without a previous training session. For this reading test, cut-outs containing only three vertebrae, including ribs and surrounding soft tissues at the TJ were visible to the readers without information on the enumeration of the whole spine. All readers had a background in spine research and were blinded toward the results of their peers.

Control analysis using nerve morphology in MRI

In 110 cases from dataset *d3*, additional MRI of the lumbar spine were available to assess the nerve morphology as proposed by Peckham et al. [11]. In brief, the L4, L5, and S1 nerves were identified by their morphology. The L4 nerve was identified by its proximal split into the peroneal branch, which joins the lateral aspect of the L5 nerve and its smaller caliber of <50% of the caliber of the L5 nerve. The L5 nerve was identified by its great caliber and its non-splitting proximal course. The S1 nerve was identified as the consecutive nerve caudally to the L5 nerve and its slightly smaller caliber in comparison with the L5 nerve.

Statistical analysis

Deviation from normal enumeration of the different methods was assessed by comparing the rate of enumeration shifts, i.e., when the classification system leads to a discrepancy in the expected number of thoracic (i.e., 12) or lumbar (i.e., 5) vertebrae, despite a normal total count of presacral vertebrae (i.e., 24), e.g., a spine with 13 thoracic and 4 lumbar

vertebrae. Cohen's kappa was evaluated for both, the full dataset and for the 46 transitional cases only.

Overlap

All of 136 patients of *d1* have been made open-access and previously reported [12, 14]. All of 211 patients of *d2* have been previously reported [16]. This prior article dealt with the differentiation of benign and malignant vertebral fractures. 718 of 895 patients of *d3* have been previously reported [17]. This prior article dealt with the epidemiology of osteoporotic vertebral fractures whereas in this manuscript we report on TLTV.

Results

Participants

Out of the total 2,076 subjects from all datasets, 1,242 had fully imaged thoracic and lumbar vertebrae. Table 2 presents the baseline demographic and clinical characteristics of the subjects.

Performance comparison of the methodological approaches

The CCBC resulted in discrepant labels in 13.3% of cases (38.2% in *d1*, 10.0% in *d2*, and 10.3% in *d3*). RBC and RLBC led to discrepant labels in 4.3% of cases (9.6% in *d1*, 1.9% in *d2*, and 4.0% in *d3*; Table 3).

The CCBC led to enumeration shifts in 1 case with 26 free presacral vertebrae (0.1%), RBC and RLBC in 17 cases (1.4%) and 40 cases (3.2%), respectively, and VSBC in 18 cases (1.4%; Table 4).

Comparison with nerve morphology on MRI

Out of the 110 subjects with MRI, L5 nerve identification on sagittal and axial slices was possible in 108 cases. Applying nerve morphology led to the enumeration of one 11 T/5L, four 11 T/6L, 94 12 T/5L, seven 12 T/6L, and two 13 T/5L cases. The agreement with the different labeling methods was as follows: CCBC, 100/108 (92.6%); RBC, 105/108 (97.2%); RLBC, 104/108 (96.3%); and VSBC, 108/108 (100%). An example for the assessment of the nerve morphology is presented in Fig. 4.

Inter-rater reliability

As the inter-rater-reproducibility was excellent for all scoring methods when considering the complete dataset

Table 2 Study cohort demographics

	<i>d1</i>		<i>d2</i>		<i>d3</i>
Subjects (<i>n</i>)	136		211		895
Sex (male/female)	71/65		95/116		305/590
Mean age (years)±SD	60 ± 15		55 ± 16		64 ± 10

d1-3, dataset 1–3; *n*, number; SD, standard deviation

Table 3 Discrepancies of labeling methods

Methods	<i>d1</i>	<i>d2</i>	<i>d3</i>	Overall
CCBC (count from top vs. bottom)	52 (38.2%)	21 (10.0%)	92 (10.3%)	165 (13.3%)
RBC vs. RLBC	13 (9.6%)	4 (1.9%)	36 (4.0%)	53 (4.3%)

VSBC N/A

CCBC, continuous counting-based classification; *d1*-3, dataset 1-3; RBC, rib-based classification; RLBC, rib-length-based classification; SD, standard deviation; VSBC, vertebral-shape-based classification

Table 4 Enumeration variants and shifted labels (*) per labeling method

Thoracolumbar enumeration	CCBC	RBC	RLBC	VSBC
11 T/5L	0 (0.0%)	2 (0.2%)	9 (0.7%)	6 (0.5%)
11 T/6L*	0 (0.0%)	13 (1.0%)	37 (3.0%)	15 (1.2%)
12 T/4L	19 (1.5%)	17 (1.4%)	10 (0.8%)	13 (1.0%)
12 T/5L	1,087 (87.5%)	1,068 (86.0%)	1,046 (84.2%)	1,067 (85.9%)
12 T/6L	135 (10.9%)	93 (7.5%)	112 (9.0%)	112 (9.0%)
12 T/7L*	1 (0.1%)	0 (0.0%)	1 (0.1%)	0 (0.0%)
13 T/4L*	0 (0.0%)	4 (0.3%)	2 (0.2%)	3 (0.2%)
13 T/5L	0 (0.0%)	44 (3.5%)	25 (2.0%)	25 (2.0%)
13 T/6L	0 (0.0%)	1 (0.1%)	0 (0.0%)	1 (0.1%)
No. of ambiguous cases	1 (0.0%)	17 (1.4%)	40 (3.2%)	18 (1.4%)

*, shifted labels

CCBC, continuous counting-based classification; RBC, rib-based classification; RLBC, rib-length-based classification; VSBC, vertebral-shape-based classification

($k > 0.9$), we focused our evaluation on the transitional cases only. For the 46 vertebrae with a thoracolumbar transitional anomaly, the average Cohen's kappa for the RBC was 0.59 (range 0.44–0.83) and 0.61 for the VSBC (range 0.45–0.94, Table 5). All kappa scores were determined as statistically significant.

Discussion

When comparing three classification systems for labeling the TJ, the VSBC showed the most consistent and reliable results. It produced fewer enumeration shifts and no

discrepancies, independent of the imaged spinal segments. Importantly, the VSBC perfectly aligned with functional parameters assessed on MRI, namely nerve morphology.

Accurate labeling of vertebrae is critical for communication between clinicians and for safe treatment planning. This is particularly challenging in TLTV, which combine features of both thoracic and lumbar levels [4]. Our study confirmed these challenges, as discrepant annotations frequently occurred depending on which classification systems (CCBC or RBC) was applied, with some authors suggesting whole spine imaging to determine correct spine enumeration [18]. The VSBC, in contrast, applies distinct morphological features – such as SFJ orientation or configuration of transverse processes – which allows consistent labeling. Unlike rib-based methods, the VSBC is not restricted by assumptions about rib length [9]. Remarkably, the VSBC achieved perfect agreement with nerve-morphology-based labeling, reinforcing its validity. Interestingly, a previous publication proposing a nerve-morphology-based classification *only* reached a near-perfect agreement of 92.15% (106/108 cases) [11]. The two failed cases were TLTV with supernumerary ribs (T13 vertebrae), which the VSBC successfully accounts for.

We observed moderate inter-rater reliability for both the RBC and VSBC. Although Wigh et al. provided a definition for TLTV by rib length measurement, our findings showed that interpretations among readers still varied, particularly in cases with stump ribs, additional ossification centers, or intermediate morphology. This likely reflects different interpretations of a "true" rib and varying levels of reader familiarity with TLTV.

The RBC, originally proposed for standard radiographs, is inconsistently applied in CT-imaging, and some authors have already introduced shape-based aspects accompanying the standard rib-based methods [12]. According to the original RBC, a vertebra with a stump rib is counted as TLTV, included in the thoracic spine [9], which however, excludes the possibility of a lumbar vertebra with a stump rib – an issue resolved by the VSBC.

Therefore, the VSBC offers practical advantages. It provides accurate and reliable annotations even in incompletely imaged spines, consistent with functional anatomy, i.e., functional innervation of the lower extremity and anatomy of the lumbosacral plexus. Because it is independent of rib

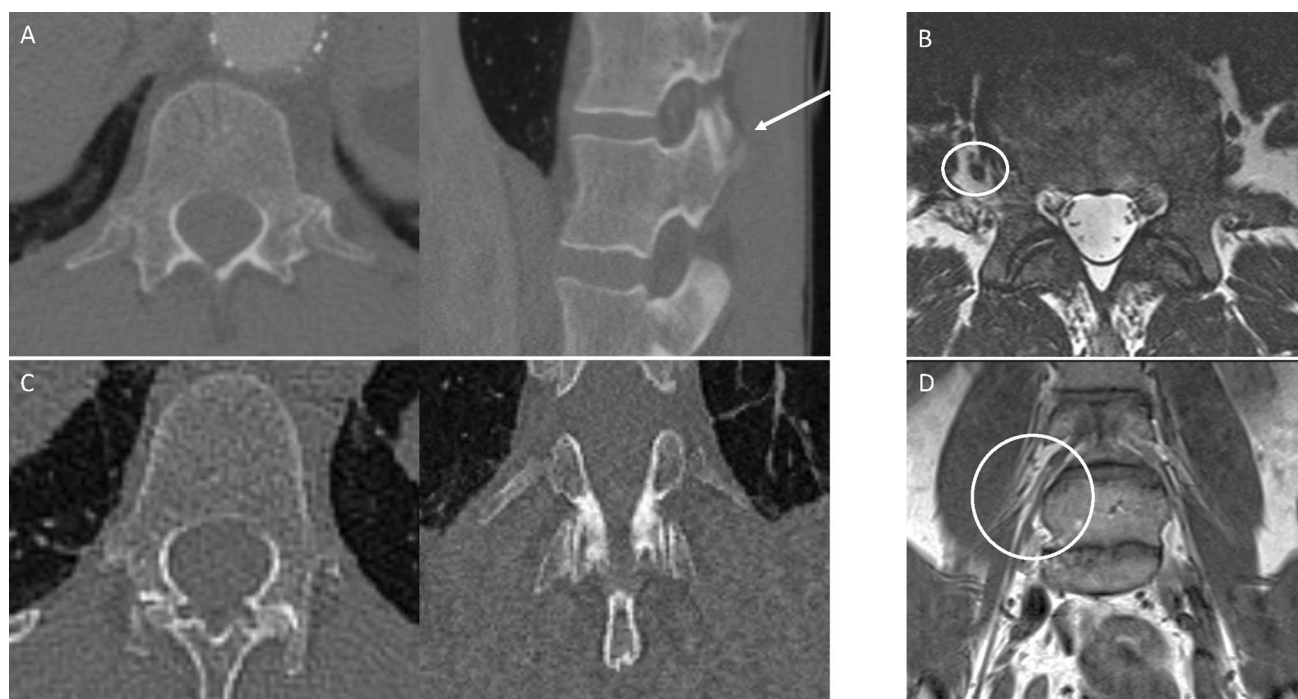


Fig. 4 Enumeration validation by MRI assessment of nerve morphology. **A)** Case 1 CT: Axial CT (left) of the thoracolumbar junction shows a borderline TLTV with short stump ribs on both sides, backwards oriented transverse processes and smaller sideways oriented costal processes on both sides. Sagittal plane (right) shows an *overriding facet* typical in thoracic spine (arrow). According to the VSBC this vertebra is annotated as thoracic, resulting in a *normal* enumeration of 12 thoracic and 5 lumbar vertebrae. According to the RLBC this vertebra is annotated as lumbar, resulting in an enumeration shift of 11 thoracic and 6 lumbar vertebrae. **B)** Case 1 MRI: Complementary MRI of the lumbar spine in axial plane identifies the split course of the L4 nerve root (circle) in line with the annotation of the VSBC of 12 thoracic and 5 lumbar vertebrae. **C)** Case 2 CT: Axial (left) and

coronal (right) CT of the thoracolumbar junction shows a borderline TLTV with short stump ribs on both sides and thoracic angulation of SFJ in medial–lateral direction. According to the VSBC this vertebra is annotated as thoracic, resulting in an enumeration of 13 thoracic and 5 lumbar vertebrae. According to the RLBC this vertebra is annotated as lumbar, resulting in an enumeration of 12 thoracic and 6 lumbar vertebrae. **D)** Case 2 MRI: Complementary MRI of the lumbar spine in coronal plane identifies the split course of the L4 nerve root (circle) in line with the annotation of the VSBC of 13 thoracic and 5 lumbar vertebrae. RLBC, rib-length-based classification; SFJ, superior facet joint; TLTV, thoracolumbar transitional vertebrae; VSBC, vertebral shape-based classification

Table 5 Interrater reliability as measured by Cohen's kappa for the different classification systems for a subset of 46 TLTV

Rater	Rater 2	Rater 3	Rater 4
RBC			
Rater 1	0.55	0.59	0.44
Rater 2		0.64	0.48
Rater 3			0.83
VSBC			
Rater 1	0.59	0.94	0.60
Rater 2		0.52	0.45
Rater 3			0.54

The average Cohen's kappa score for the rib-based classification was 0.59 and for the vertebral shape-based classification 0.61. (n=46; TLTV only)

RBC, rib-based classification; VSBC, vertebral-shape-based classification

morphology, the VSBC can also be applied to MRI, which usually does not fully visualize ribs.

However, this study has several limitations. First, it exclusively focuses on the thoracolumbar junction and did

not assess other anomalies, e.g., lumbosacral transitional vertebrae. Further studies are needed to evaluate altered anatomy across the entire spine. Second, the control analysis using nerve morphology was based on a consensus reading. While the nerve morphology assessment showed excellent inter-rater reliability [11], different ratings might have led to a lower agreement between nerve morphology and the VSBC. Third, the VSBC requires training, and in some cases with altered anatomy, e.g., implants, fractures, or metastases, assessment may be difficult or impossible. Inter-rater agreement for TLTV was only moderate overall, though experienced raters showed higher consistency. This suggests that structured training could further improve reliability.

In conclusion, the VSBC provides a morphology-based approach for identifying thoracic, lumbar, and TLTV. While its improvements over rib-based classifications in TLTV are modest, it consistently resolves difficult cases and shows perfect alignment with nerve morphology. Accurate detection

of spine anomalies such as TLTV remains essential in clinical practice, and the VSBC offers a useful complementary tool that can be applied alongside existing methods, particularly in ambiguous or incomplete imaged cases.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00586-025-09364-0>.

Author contributions DS and JSK analyzed and interpreted the imaging data. HM, CR, PP, analyzed the imaging data. RG, AS, MEH, MM, MU and CZ contributed to study design and writing the manuscript. All authors read and approved the final manuscript.

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