LUMBOSACRAL TRANSITIONAL VERTEBRAE: CLASSIFICATION OF VARIATION AND ASSOCIATION WITH LOW BACK PAIN

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by
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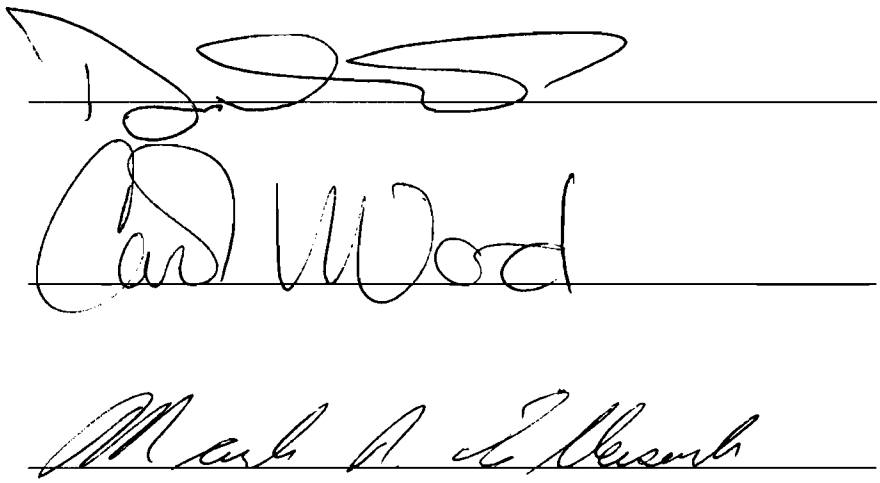
The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled:

LUMBOSACRAL TRANSITIONAL VERTEBRAE: CLASSIFICATION OF VARIATION AND ASSOCIATION WITH LOW BACK PAIN

Presented by Chet Savage

A candidate for the degree of Master of Arts

And hereby certify that in their opinion it is worthy of acceptance.



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LUMBOSACRAL TRANSITIONAL VERTEBRAE: CLASSIFICATION OF VARIATION AND ASSOCIATION WITH LOW BACK PAIN

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ABSTRACT

The association of lumbosacral transitional vertebrae (LSTV) and low back pain, commonly referred to as Bertolotti's syndrome (Bertolotti, 1917), has a controversial history. LSTV are caused by the overlap or shift of developmental fields, and result in vertebrae with abnormal morphology. Current classification systems are inadequate for assessing LSTV both morphologically and clinically. Thus, I have created a classification system based on my analysis of over 2800 individuals in the Hamann-Todd collection. Also, I have analyzed the metric variation among those individuals as well as a control group of 100 individuals. I then analyzed a clinical sample using my classification system. Analysis shows that LSTV have a definite affect on vertebral dimensions ($p<0.0001$), even after separation by sex. In the clinical setting, LSTV were nearly twice as prevalent (13.5% vs. 7% in Hamann-Todd), with unilateral types occurring twice as often; however, LSTV did not cause more intense LBP.

INTRODUCTION

The association of lumbosacral transitional vertebrae and low back pain, commonly referred to as Bertolotti's syndrome (Bertolotti, 1917), has a controversial history. Developmental defects occurring at the lumbosacral border can result in transitional vertebrae that have a mixture of lumbar and sacral characteristics. That is, the morphology of the affected vertebra is intermediary or transitional with a combination of lumbar and sacral anatomical structures. The resulting combination of characteristics producs a variety of morphological configurations collectively referred to as lumbosacral transitional vertebrae (LSTV). The developmental defects that result in LSTV are thought to be caused by a delay in the timing threshold events occurring at the lumbosacral junction (Barnes, 1994). Disruption of developmental timing, with resultant defects, can only occur during the vulnerable time when developmental thresholds are reached. This causes developmental fields to overlap or expand beyond normal parameters, resulting in boundary shifts at the transitional areas of the vertebral column. Boundary shifts at the lumbosacral junction can occur caudally (lumbarization) or cranially (sacralization).

Lumbarization refers to a caudal shift where the first sacral segment assumes some characteristics of the lumbar vertebra. Sacralization refers to a cranial shift where the last lumbar vertebra assumes sacral characteristics and frequently becomes incorporated into the sacrum. Depending on the direction of the shift, an individual may end up with either an extra lumbar segment or one fewer segment, which can have significant biomechanical and clinical implications.

The presence of LSTV is thought by many researchers to be associated with low back pain (LBP). There are many valid reasons to assume that the presence of a transitional vertebra could cause low back pain. Suspected causes of low back pain include disc degeneration, disc prolapse, spinal stenosis, olisthesis, muscle strain or sprain, sacroiliac joint pain, chemical irritation, and nerve impingement; and the presence of a LSTV could potentially cause any of these. However, while numerous studies have found no significant correlation between transitional vertebrae and low back pain (Nachemson, 1974; van Tulder et al., 1997; Adams et al., 2002; Luoma, 2004), many other studies (Keim, 1980; Castellvi et al., 1984; Abe et al., 1997; Dai, 1999; Scheuer and Black, 2000 and sources therein; Brault et al., 2001) have found a significant correlation. A great deal of the controversy surrounding the association of LSTV and LBP is the result of an incomplete understanding of the variation present at the lumbosacral junction and the lack of a comprehensive classification scheme that can be used to differentiate lumbosacral variation according to morphological, developmental, and clinical variants. Therefore, a comprehensive understanding of normal and abnormal variation at the lumbosacral junction and a precise classification system are needed to more thoroughly investigate the association between LSTV and LBP.

The current study has three primary goals. The first is to qualitatively assess the variation present at the lumbosacral junction in order to create a comprehensive classification system. The second goal is to quantitatively (by using measurements of specific vertebral dimensions) assess the variation present at the lumbosacral junction in individuals with and without LSTV. This is done in order to gain a better understanding of how LSTV affect the size and shape of the lumbosacral junction and biomechanically

compromise it. Finally, the classification system created earlier is applied to a clinical sample to discover if the clinical sample differs in the frequency of LSTV types and if there is an association between LSTV and LBP.

Since the etiology of LSTV is developmental but LBP is probably due to the biomechanical consequences of a LSTV, I use both morphogenetic and biomechanical approaches to help understand the association between LSTV and LBP. A morphogenetic approach, which examines embryonic development to determine when and how lumbosacral border defects are initiated, is necessary to understand the etiology of LSTV (Barnes, 1994; Usher and Christensen, 2000). To understand the genetic origins of LSTV we must examine not only the manufacture or absence of proteins necessary for normal development, but the genetic controls that govern the timing of events during skeletal development. The morphogenetic approach, however, cannot tell us much about the causes of low back pain, or if LSTV are the cause. In order to understand LBP and how LSTV can cause it, a biomechanical approach is the most useful.

This study seeks to clarify the relation between lumbosacral transitional vertebrae and low back pain in two phases. In the first phase, I use a morphogenetic approach to develop a classification system to describe the segmental variation at the lumbosacral junction by conducting a survey of a well documented (known age, sex, ancestry, weight, and stature) osteological collection, which is assumed to be representative of White and Black populations within the United States, and recording both the metric and non-metric variation present. These data are then used to assess the frequencies of lumbosacral transitional vertebrae present in the skeletal sample.

The second phase of this study uses a biomechanical approach to explore correlations between the LSTV variants identified in the first phase and low back pain. I present results from a retrospective analysis of over 500 radiographs of patients who have visited a local orthopedic surgeon, Jeffrey W. Parker MD, FAAOS, in Columbia, Missouri and reported low back pain. The clinical sample comes from a region populated predominately by people of European descent, so I can only assess the association between LSTV variation and back pain among US Whites.

During the second phase, the clinical sample was assessed for the presence or absence of the lumbosacral defect variants identified in the first phase. Classification of the clinical sample serves to properly differentiate among the types of variation present among people seeking medical intervention, and elucidate any significant correlation between lumbosacral variants and LBP by examining the correlation between defect types and levels of pain. The occurrence and intensity of pain was assessed using a visual analogue scale (VAS). Intensity and frequency of pain in patients exhibiting LSTV variants are compared to those with normal lumbosacral junctions. In order to illuminate possible confounding factors, the clinical sample was also tested to see if the individuals' height, weight, sex, or ancestry had any effect on the frequency or intensity of pain.

In summary, this study uses a combination of morphgenetic and biomechanical approaches to help understand normal and abnormal variation at the lumbosacral junction and provides valuable information on LSTV frequencies in both the general population and clinical samples. Using this knowledge, the results of this study stand to identify possible associations between morphological LSTV types and the presence and intensity of pain.

BACKGROUND

In order to properly develop a classification system for lumbosacral variation, it is necessary to understand the anatomy of the lumbar spine, as well as the embryological development of the human spine and the factors that can lead to developmental variation. Further, it is necessary to review the ossification process in order to identify possible defects that can arise at that stage. The clinical literature as well as the biomechanics of the lumbar spine is reviewed in order to understand the importance of this study and guide both the current discussion as well as possible future research.

Anatomy

In order to understand LSTV variation it is necessary to first understand the normal anatomy of lumbar and sacral vertebrae. Lumbar vertebrae (Fig. 2-1) are characterized by a large, kidney-shaped body, slender transverse processes; stout pedicles and lamina; short, thick, square spinous processes; transversely curved articular facets; and lack of foramina transversaria and costal articular facets. All of these features reflect the unique suite of stresses the lumbar spine is subjected to, requiring it to be both strong enough to support the upper body and yet flexible enough to allow the needed mobility (Scheuer and Black, 2000). The fifth lumbar vertebra has a distinct appearance from the rest of the lumbar vertebrae, with very wide inferior articular processes, a wedge-shaped body (thicker anteriorly), large, angled pedicles with transverse processes projecting from the entire length of the pedicle, and the largest vertebral body of all the presacral vertebrae.

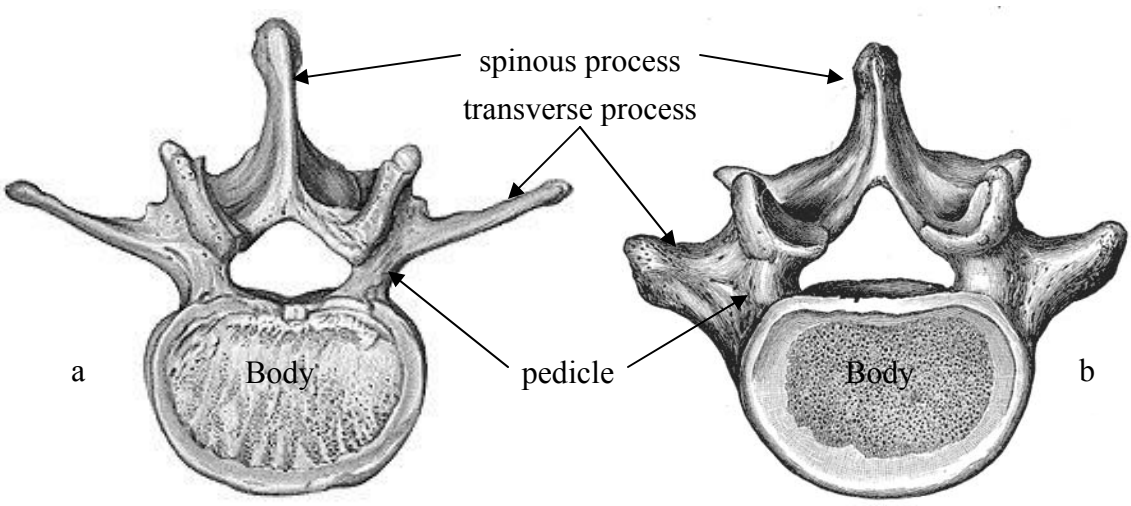


Fig. 2-1. Superior view of the fourth (a) and fifth (b) lumbar vertebrae illustrating normal anatomical features and differences in L5 morphology. Modified from Fysioweb (2005) and Clemente. (1985).

The sacrum (Fig. 2-2) is a bony mass composed of five or six vertebral segments with wide lateral masses, called alae, which articulate with the ilium. The sacro-iliac joint incorporates the first two sacral vertebrae, as reflected by the presence of the auricular surface on the lateral edge of the alae.

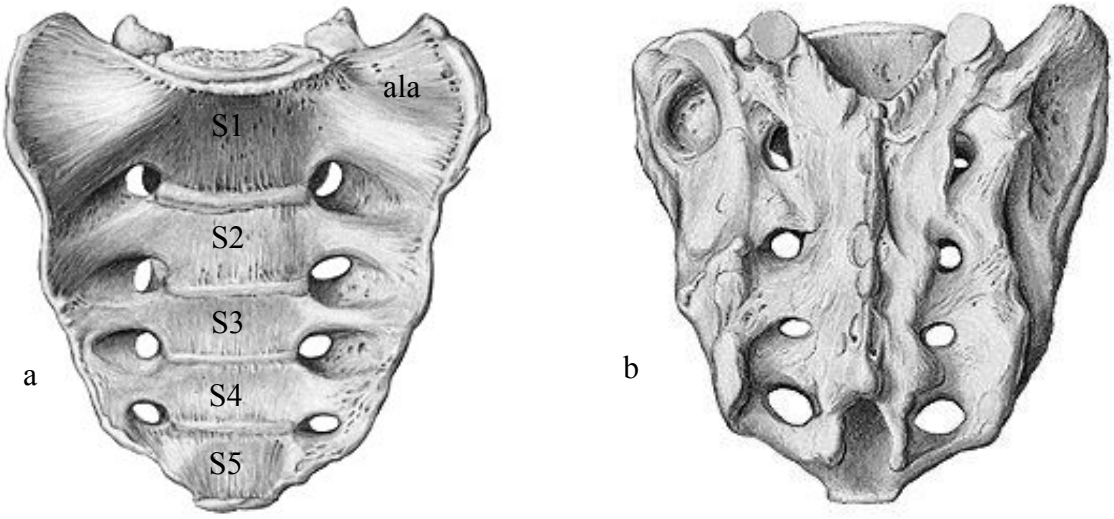


Fig. 2-2. Anterior (a) and posterior (b) views of a normal sa/crum. Modified from Fysioweb (2005).

Between all presacral vertebrae and between L5 and the sacrum lie intervertebral discs (Fig. 2-3). These discs are composed of an inner nucleus pulposus, and an outer annulus fibrosus. The nucleus pulposus is a gelatinous semi-fluid material, initially comprised of notochord cells which are eventually replaced by cells from the inner annulus fibrosus (Scheuer and Black, 2000; An, 2004). The outer annulus fibrosus is primarily composed of collagen fibrils arranged in oblique layers, while the inner annulus fibrosus is fibrocartilaginous (An, 2004). The primary type of collagen in the annulus fibrosus is type I, while type II predominates in the nucleus pulposus.

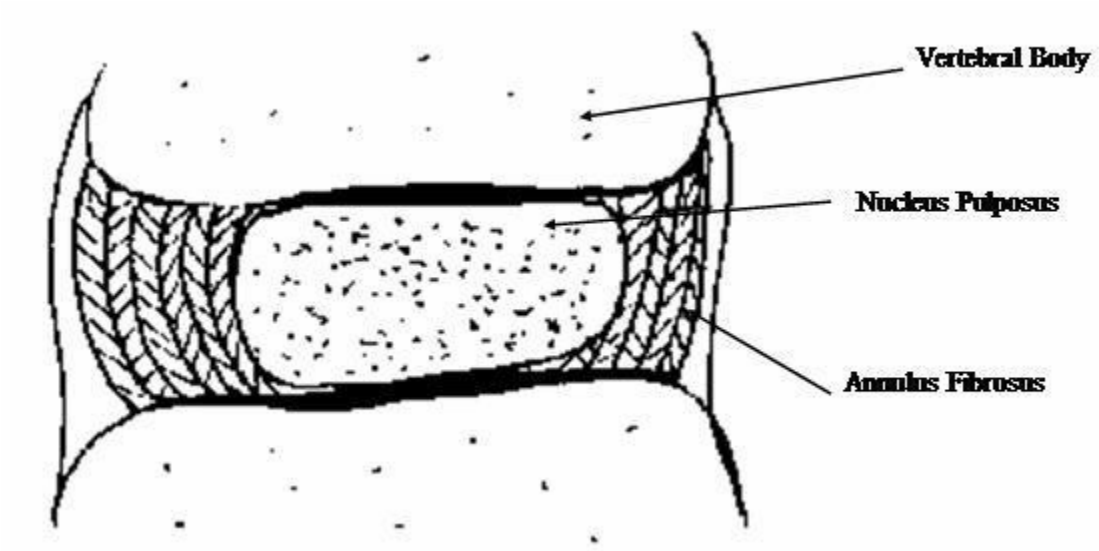


Fig. 2-3. Intervertebral Disc Diagram. Modified from McKay Osteopaedic Research Laboratory (2005).

Biomechanics and Function

To understand why defects in the lumbosacral region can lead to problems, and sometimes intense pain, it is necessary to understand the biomechanics of a normal lumbar spine, namely the functions it serves and the stresses it is subjected to. The

primary functions of the lumbar spine are to support the upper body, transfer weight from the upper body to the legs and to provide mobility in the lower back (Adams et al., 2002). To accomplish all of these functions, the lumbar spine is composed of both rigid bone and flexible intervertebral discs, as well as associated muscles, ligaments, and tendons. All of these features are necessary for support and proper range of motion, but all are subject to failure, which may cause low back pain.

The lumbar spine is subjected to five basic types of force: compressive, tensile, bending, shear, and torsion. Often these forces are applied in various combinations, reinforcing the need for the lumbar spine to be both strong and flexible. Thus, the lumbar spine has large blocky vertebrae; pliable yet resilient annulus fibrosus composed of cross-oriented sheets of collagen; supporting, hydrated, gel-like nucleus pulposus; curved zygapophyseal joints to accommodate torsion and resist forward sliding; and solid attachment sites for muscles (Adams et al., 2002).

While all of these forces act upon the lumbar spine, the range of motion that the lumbar spine is capable of varies by the direction of motion. During axial rotation (twisting from side to side) the lumbar spine only accommodates 5° of motion (Kapandji, 1974). This is due to the angle of the articular processes and the rigidity of the lumbar discs. During flexion and extension, the lumbar spine accommodates maximums of 60° and 35° respectively; and during lateral flexion 20° of motion is accommodated by the lumbar region (Kapandji, 1974).

The lumbar vertebral column is supported by many large muscle groups and spinal ligaments that act to stabilize movement and maintain upright posture (Adams et al. 2002). The muscles belong to three groups, intertransverse, anterolateral, and

posterior, each with many individual muscles with varying functions (Table 2-1). Additionally, abdominal muscles function to flex the spine, increase intraabdominal pressure, and support the internal organs. The spinal ligaments function to prevent excessive flexion of the lumbar spine, and for this purpose are primarily arranged posterior to the center of sagittal plane rotation (Adams et al. 2002). The major ligaments are shown in Fig. 2-4.

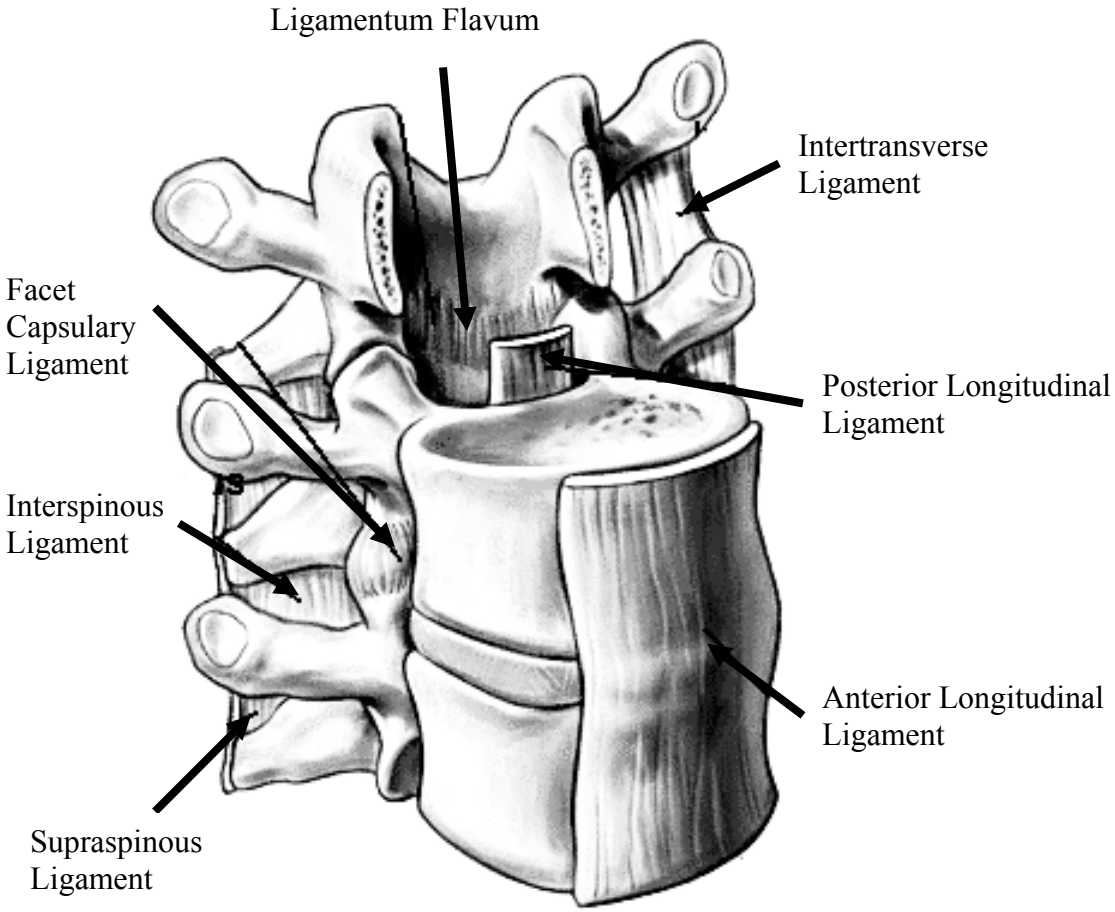


Fig. 2-4. Ligaments of the lumbar spine. Modified from spineuniverse.com (2005)

Table 2-1

Lumbar muscle groups and functions[1]

Group	Muscle	Function
Intertransverse		
	Intertransversarii mediales	Proprioception
	Intertransversarii laterales dorsales	Proprioception
	Intertransversarii laterales ventrales	Proprioception
Anterolateral		
	Psoas major	Flexes hip
	Quadratus lumborum	Brace 12th rib as a base for the lower thoracic fibers of the diaphragm. May also stabilize lateral motion of the spine.
Posterior		
	Interspinales	Proprioception
	Multifidus	Extension of spine, and control of flexion.
	Longissimus thoracis pars lumborum	Extension of spine, and control of lateral bending.
	Iliocostalis lumborum pars lumborum	Extension of spine, and control of lateral bending.
	Longissimus thoracis pars thoracis	Form medial half of erector spinae aponeurosis, extend the thorax in relation to the pelvis, and control flexion.
	Iliocostalis lumborum pars thoracis	Form lateral half of erector spinae aponeurosis, extend the thorax on the pelvis, and control forward or lateral flexion.

[1] Summarized from Adams et al. (2002)

In addition to providing support, the lumbar spine acts to protect the spinal cord and nerve roots from damage. The intervertebral discs are innervated by multiple sources, but primarily from the sympathetic trunk, and the sinuvertebral nerves (Adams et al., 2002). Herniations of the intervertebral discs can put pressure on the spinal cord or cauda equina (the nerve roots that exit the spinal column inferior to the spinal cord), and tears in the annulus fibrosus can damage the nerve plexus (derived from the lateral plexus and sympathetic trunks anteriorly, and the sinuvertebral nerves posteriorly) that innervates it. Both conditions potentially cause low back pain. Thus, disc degeneration, and its association with back pain, has been a source of much discussion in the literature (MacGibbon and Farfan, 1979; Abe et al., 1997; Vergauwen et al., 1997; Brault et al., 2001; Luoma et al, 2004).

The sacrum also has many features related to support and weight-transfer. Because the sacrum is locked in place by the pelvis, it is subjected to different intensities of the five forces previously listed, and thus has different structural requirements. While the need for flexibility is reduced, the sacrum must be rigid to support the body and facilitate weight-transfer, which is primarily done by the associated ligaments (Scheuer and Black, 2000). The five fused segments of the sacrum articulate with the pelvis at the sacro-iliac joint. This stress-relieving joint, with its strong associated ligaments, prevents structural failure of the pelvis by absorbing the stresses applied to the pelvic girdle during locomotion and other activities. However, the sacro-iliac joint may become compromised by fusion of the sacrum and ilium, resulting in fracture of the pelvis, usually parallel to the sacro-iliac joint (Adams et al., 2002).

The intervertebral discs function to evenly transfer compressive forces between the vertebral bodies and allow for small intervertebral movements in many directions (Kapandji, 1974). Disc structures responsible for these functions are the inner nucleus pulposus and the outer annulus fibrosus. The nucleus pulposus deforms easily to transfer compressive forces evenly and provides support to the outer annulus to prevent it from buckling inward from the pressure. The nucleus pulposes does this by binding water inside a collagen and proteoglycan matrix. The proteoglycans bind together the collagen fibrils and act to retain water within the disc, an important function when dealing with the forces acting on the spinal column (Adams et al., 2002), specifically compression (An, 2004). With degeneration, the activity of proteoglycans decreases, thus decreasing disc height and resistance to compressive forces (Adams et al., 2002). The ability of the nucleus pulposus to bind and retain water has important internal mechanical effects. With high water content the pressure within the disc is increased, reducing disc bulge, increasing disc height, and increasing resistance to bending (Adams et al. 2002). The outer annulus fibrosus is composed of alternating sheets of collagen, called lamellae, which serve to limit intervertebral movement and resist compression.

Disc prolapse, or herniation, is the result of mechanical failure of the intervertebral disc. There are three basic types of herniation: protrusion, extrusion, and sequestration. Protrusion is the condition where the annulus bulges but has not ruptured nucleus material; extrusion is where part of the nucleus has been expelled but is still attached to the rest of the nucleus; and sequestration is where nucleus material has ruptured and is no longer attached to the rest of the nucleus (Adams et al. 2002). This condition can result in pain, possibly due to chemical irritation caused by the release of

nitrous oxide into the spinal canal (Adams et al. 2002), by compromising a spinal nerve, or by tearing the nerve plexus that surrounds the annulus. However, herniation does not always cause pain, and is present in a modest degree of asymptomatic patients (Boden et al. 1990; Boos et al. 1995).

Genetics

The genetic origins of vertebral segmentation and vertebra identity are not entirely understood at this time. There are a number of identified genes (with more yet to be identified) involved with somitogenesis and segmentation. The *Notch/Delta* pathway genes are important both in somite production and as upstream links to *Hox* genes; *FGF8* is also "important in determining segment boundaries as well as axial identity" (Pilbeam, 2004:244). Recent research has provided convincing support for the *Hox* gene complex as a primary (though not sole) contributor to final vertebra identity (Fromental-Ramain, 1996; Scheuer and Black, 2000; Usher and Christensen, 2000; Burke, 2001; Pilbeam, 2004). *Hox* genes are expressed with both spatial and temporal colinearity, meaning that the 3' genes (trailing end) are expressed sooner and more cranially than 5' genes (leading end). The 5' end of the DNA strand has a phosphate group, while the 3' end of the DNA strand has an OH (hydroxyl) group attached. Additionally, there are a number of other genes that act upstream and downstream of the *Hox* complex that serve to regulate expression of *Hox* genes and ultimately the identity of each vertebra (Pilbeam, 2004 and references therein).

The *Hox* genes responsible for determining lumbar and sacral vertebrae are *Hoxa-9* (L1-L3) and *Hoxd-9* (L3-Ca1) (Fromental-Ramain et al., 1996) as well as other *Hox* genes expressed in the sacrum and coccyx regions (Burke, 2001). However, *Hox* genes

are not the only requirement for normal sacral development; the presence of the ilium is required for the sacral tranverse processes to develop. *Hox* genes are not expressed in the developing ilium, instead, homeobox containing *Emx2* is expressed. The different gene complexes necessary for sacral and ilium development therefore must be carefully coordinated (Pilbeam, 2004). The improper coordination of these two complexes may be the cause of some vertebral variation, though it seems unlikely to be the only source. Further, though the expression of *Hox* gene patterns seems to be highly conserved among vertebrates, Galis (1999) warns that vertebrae identity is not so highly correlated with *Hox* gene expression that vertebral regions are identifiable by *Hox* gene expression alone.

In addition to the products of *Hox* genes, there are regulatory genes that affect the timing of development. The genetic sensitivity of individuals, and populations, to timing disruptions may explain why some researchers have discovered that certain defects are more common in some families and populations (Schmorl, 1971 and references therein; Barnes, 1994). These genetic findings may have bioarcheological implications and may also be useful in forensic settings when trying to determine the identity or ancestry of an individual.

Embryology

All vertebrae originate from somites that form along the cranial-caudal axis, on either side of the notochord, from presomitic mesoderm. These somites differentiate further into dermomyotome (future inner dermis and muscle) and sclerotome. At the fourth week of development, the sclerotome becomes filled with diffuse core cells. The sclerotome then ruptures and these cells, along with cells from the ventromedial wall, migrate anteriorly towards the notochord and posteriorly towards the neural tube (Fig. 2-

5). The notochord becomes surrounded by mesenchyme by the end of the fourth week, which will later develop into the vertebral centrum. The cells that surround the neural tube will become the neural arch (Scheuer and Black, 2000; Usher and Christensen, 2000; Pilbeam, 2004).

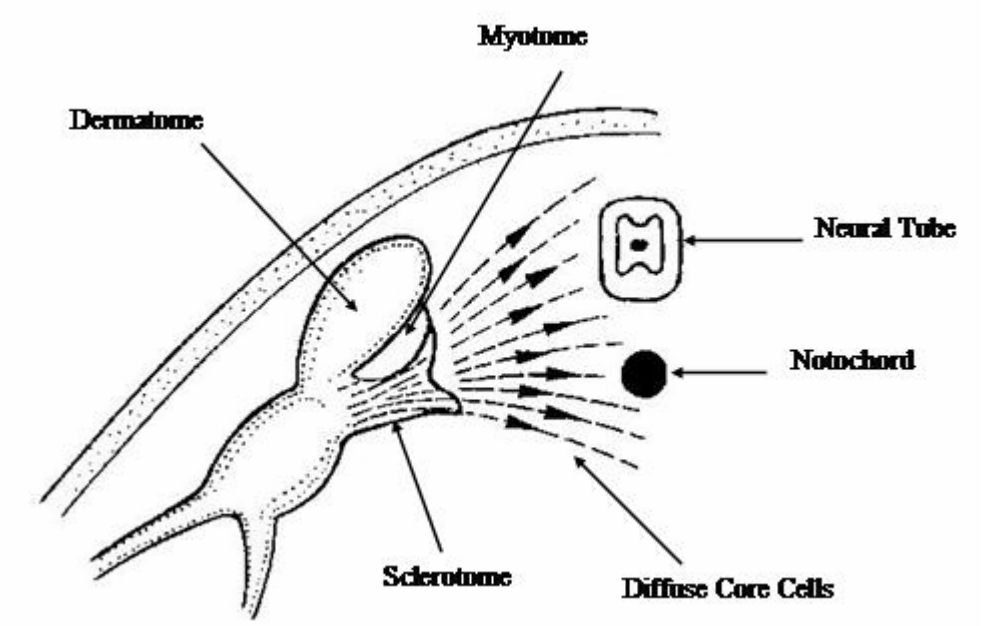


Fig. 2-5. Diagram showing the migration of the diffuse core cells from the sclerotome to the neural tube and notochord. Modofied from Scheuer & Black (2000).

There are multiple competing hypotheses regarding the formation of the vertebral column (Scheuer and Black, 2000 and references therein) but the resegmentation hypothesis has gained the widest acceptance. According to the resegmentation hypothesis, the segmental sclerotome undergoes resegmentation where the dense caudal half of the superior somite unites with the more diffuse cranial half of the inferior somite (Fig. 2-6), forming the future vertebral bodies and ribs. The neural arch, pedicles, and costal elements develop almost entirely from the dense caudal half of each somite and thus attach to the upper end of the vertebral body (Scheuer and Black, 2000; Usher and Christensen, 2000). The first four-and-a-half somites are incorporated into the occipital

region of the skull; the caudal half of the fifth somite forms the body of the atlas along with the cranial half of the sixth somite (Pilbeam, 2004). The process proceeds cranial to caudal with normal development of somites 5-6 through 11-12 forming cervical vertebrae, 12-13 through 23-24 forming thoracic vertebrae, 24-25 through 28-29 forming lumbar vertebrae, 29-30 through 33-34 forming the sacrum, and 34-35 through approximately 39-40 forming the coccyx (though the number of coccyx segments varies) (Schmorl, 1971).

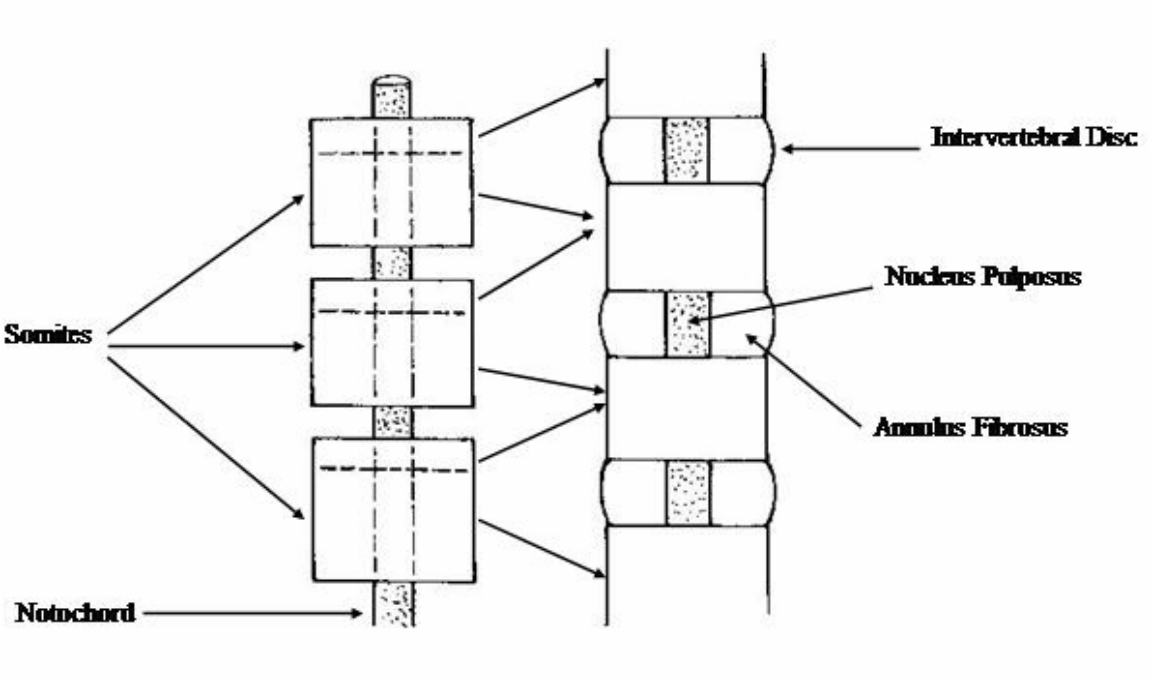


Fig. 2-6. Schematic representation of the resegmentation hypothesis showing the cranial half of the lower somite joining with the caudal half of the upper somite forming the vertebral body and the notochord becoming the nucleus pulposus. Modified from Scheuer & Black (2000).

At six to seven weeks of embryonic development, four to six chondrification centers appear (two in the body, one in each half of the neural arch, and one for each rib), spreading out to form the cartilaginous anlagen (Usher and Christensen, 2000). With

fusion at the spinous process, at the fourth fetal month, the cartilaginous vertebral units are complete. The final tally is thus 24 true vertebrae (being the cervical, thoracic, and lumbar regions) and nine false vertebrae (sacrum and coccyx regions) accounting for two-fifths of adult standing height with the addition of the intervertebral discs (Scheuer and Black, 2000).

Intervertebral discs are formed between the cranial and caudal halves of each somite by the involution of the corda dorsalis during the cartilaginous and ossification stages. By the end of the sixth week of development, the notochord has retrogressed from the vertebral body space and has become condensed within the intervertebral space and becomes the nucleus pulposus (Schmorl, 1971). These notochord cells are eventually completely replaced by inner annulus fibrosus cells by about 20 years of age (Scheuer and Black, 2000; An, 2004).

Ossification

After somite formation, the vertebral bodies are composed of cartilaginous anlagen. Before birth, these cartilaginous anlagen begin to be replaced with bone. The first demonstrable ossification occurs in the lower thoracic and upper lumbar vertebrae (T10-L1) at the third month of embryonic development; proceeding rapidly cranially and more slowly caudally, reaching L5 by the end of the third month and C2 by the end of the fourth month of fetal growth (Schmorl, 1971; Scheuer and Black, 2000).

The early stages of ossification of the vertebral centrum are characterized by the presence of a cartilaginous rim, which persists until about the age of seven. It is from this ring of cartilage, as well as the layer of cartilage below the centrum, that the vertebrae grow vertically. It is also within this layer of cartilage that the secondary epiphyseal ring

develops. Union of the secondary epiphyseal ring and the vertebral body starts at about age 14 or 15, although union does not occur simultaneously in all vertebral segments, and the lumbar vertebrae are the last to unite (Schmorl, 1971), with L5 fusing before L1 (Scheuer and Black, 2000). At about the age of seven, the vertebral end-plates are also present, with many perforations along the edges. The development of grooves in the end-plates along the anterior and posterior margins, and extending into the center of the body, are formed in the newborn but become most prevalent between the ages of eight and ten and do not disappear until the end of growth (approximately 21 to 25 years of age) (Schmorl, 1971). This billowed appearance of the vertebrae is caused by the invasion of the anterior and posterior central perforating arteries (Scheuer and Black, 2000).

The development of the vertebral arches, and their associated processes, occurs independently from the centrum. The vertebral arches begin to chondrify at six weeks of embryonic development, and ossify shortly thereafter (Schmorl, 1971; Clemente, 1985; Maat et al., 1996; Scheuer and Black, 2000). There are competing hypotheses for the order and progression of neural arch ossification, with some proposing multiple centers. The traditional theory is that ossification of the neural arches is intermembranous and initiates on the inner surface at around week 12, spreading to the outer surface within a week and thereafter spreading centripetally. The ossification centers first appear in the cervical region at the second fetal month, thereafter spreading craniocaudally, with L5 being the last to develop at four fetal months (Schmorl, 1971; Scheuer and Black, 2000). When compared to the ossification of the centra, it is clear that the two do not develop in tandem, and seem to have separate initiating factors. In the lumbar region, the centra develop before the arches. Bagnell et al. (1977) suggest that the contraction of muscles

associated with fetal reflexes are responsible for neural arch ossification patterns. Regardless, the centrum seems to develop in line with the notochord, while the neural arch develops in line with the somites, paralleling the peripheral nervous system (Scheuer and Black, 2000). In the mature vertebrae, the body is composed of both the centrum and the anterior most part of the vertebral arch.

The two halves of the vertebral arch fuse during the first year of life to form the spinous process, which then continues to grow from apophyses at the tip. Fusion begins in the lower thoracic and upper lumbar regions, progressing both cranially and caudally, with the cervical arches fusing early in the second year and L5 fusing at the end of the fifth. However, the union of the arch in the sacrum may be delayed until early childhood (Schmorl, 1971; Scheuer and Black, 2000; Usher and Christensen, 2000). The vertebral arch surrounds more than two thirds of the spinal canal and forms much of the posterior portion of the final vertebral body. The arches fuse to the centra between three and six years of age, though fusion may be delayed into adolescence (Schmorl, 1971). The junction of the centrum and the neural arch, the neurocentral junction, persists well into adulthood as a dense plate of bone, and is particularly suitable for the anchoring of pedicle screws used in spinal surgery (Maat et al., 1996; Scheuer and Black, 2000).

The mediolateral width between the articular facets of each vertebra increases from first (L1) to fifth (L5) lumbar, with L5 having especially widely spaced facets due to its articulation with the sacrum. This feature, along with transverse processes extending laterally from the entire length of the pedicle, makes the fifth lumbar vertebra morphologically distinct (Fig. 2-1).

The vertebral or neural canal and intervertebral foramina form around the spinal cord and nerve roots during development. At 20 weeks the fetal spinal cord extends down to L4, and does not reach the adult level, L2, until two months after birth (Scheuer and Black 2000); nerves extending inferiorly from the spinal cord are the cauda equine and filum terminale. These spinal nerves pass through the spinal canal before exiting the intervertebral foramina (Fig. 2-7), and thus are subject to impingement from the bony structures, namely those that are altered with a LSTV. The exiting spinal nerves, and associated blood vessels, are potential sources of pain in the lumbosacral area, both with and without the presence of LSTV (Adams et al., 2002); and the last presacral intervertebral foramen is always narrower than the ones above it (Schmorl, 1971). Further, these structures are extremely important and must be carefully avoided during any invasive surgery; LSTV alter the anatomy of such structures, making it especially difficult to approach from the anterior perspective (Weiner et al., 2001).

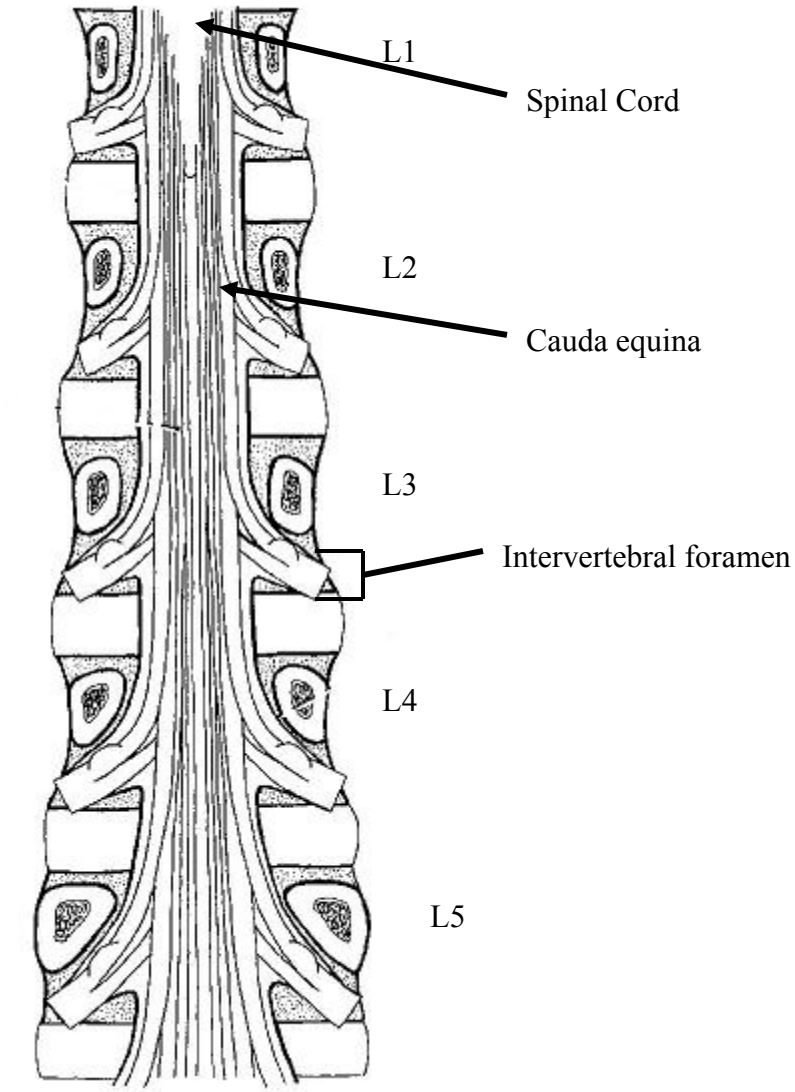


Fig. 2-7. Diagram showing the spinal nerves of the cauda equina exiting the vertebral foramina after passing through the spinal canal following the terminus of the spinal cord at the L1/L2 intervertebal space. Modified from Adams et al. (2002).

Lumbar Anatomical Variation

The improper formation and union of somites can cause vertebral abnormalities, including block vertebrae, cleft vertebra, and unilateral and bilateral hemivertebrae (Schmorl, 1971; Barnes, 1994). Block vertebrae are the result of improper separation of the superior and inferior portions of adjacent somites, causing a single continuous vertebral body to form composed of two segments. Cleft vertebrae are the result of

improper union of the two halves, resulting in paired hemivertebrae that assume a "butterfly" shape. Unilateral and bilateral hemivertebrae result from improper pairing of the left and right halves of the somite, with some somites being excessive, resulting in the formation of wedge shaped vertebrae on one side (Schmorl, 1971; Barnes, 1994).

A further abnormality of the lumbar vertebrae is the formation of lumbar ribs, usually at the L1 or L2 levels. These can be unilateral or bilateral, and usually resemble elongated transverse processes and never articulate with the costal cartilage or the sternum. These vertebrae, despite the presence of ribs, are considered lumbar vertebrae due to the lumbar orientation of the articular facets. While these lumbar ribs have no direct effect on the lumbosacral border, they are a potential further cause of degeneration of intervertebral discs at lower levels due to reduction in mobility of the adjacent motion segments.

The primary cause of LSTV is border shifts, with a cranial shift resulting in the sacralization of the last lumbar vertebrae, and a caudal shift resulting in the lumbarization of the first sacral segment (Barnes, 1994). However, while the terms 'lumbarization' and 'sacralization' are useful to understand the source and direction of the shift, they don't give much clue as to the morphology they produce. Both types can result in either fusion or contact of any part of the transitional vertebra, and be either unilateral or bilateral. Examples of LSTV morphology are shown in Fig. 2-8. Partial shifts can cause unilateral fusion of the transverse processes of the lumbar segments, which can have significant biomechanical implications. For example, with some types of LSTV there can be contact between the transverse processes of L5 and the sacro-iliac joint or with the ilium itself. In some not-so-rare cases there is a half-shift where the pelvis articulates with L5 and S1 on

one side and with the sacrum alone on the other (Fig. 2-9). The number of motion segments is also affected by the direction of the shift, with lumbarization either having the normal number or one extra, and sacralization resulting in one fewer motion segment. When examining LSTV, ossification defects are another potential cause of variation that warrants consideration. However, it is difficult, if not impossible, to differentiate between ossification defects and other types of developmental defects when creating the classification system, as both types could result in the same morphology. As a result, the classification system developed in this study does not differentiate between LSTV caused by border shift and those caused by ossification defects.

The inheritance of vertebral developmental defects has been studied in some depth. Schmorl (1971) reports that cephalad (cranial) shifts are often at only one or two transitional areas (borders) but caudad (caudal) shifts often involve three or four borders, and the shifts are often in the same direction. He also reports that the cranial shifts are dominant over the caudal shifts. Further, the specific shift does not seem to be inherited but the direction of the shift does. That is, the offspring may not inherit the shift at the same junction (i.e. lumbosacral or thoracolumbar) as the parent, but parent and offspring will both have either a cranial or caudal shift.

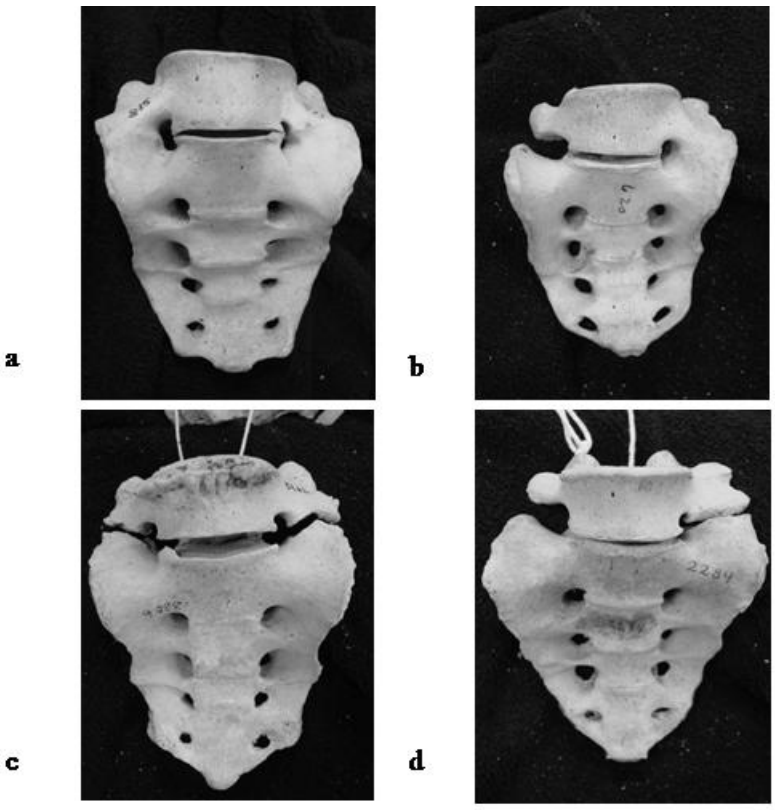


Fig. 2-8. Examples of LSTV morphology. a) Bilateral fusion b) Unilateral fusion c) Bilateral contact d) Unilateral contact.

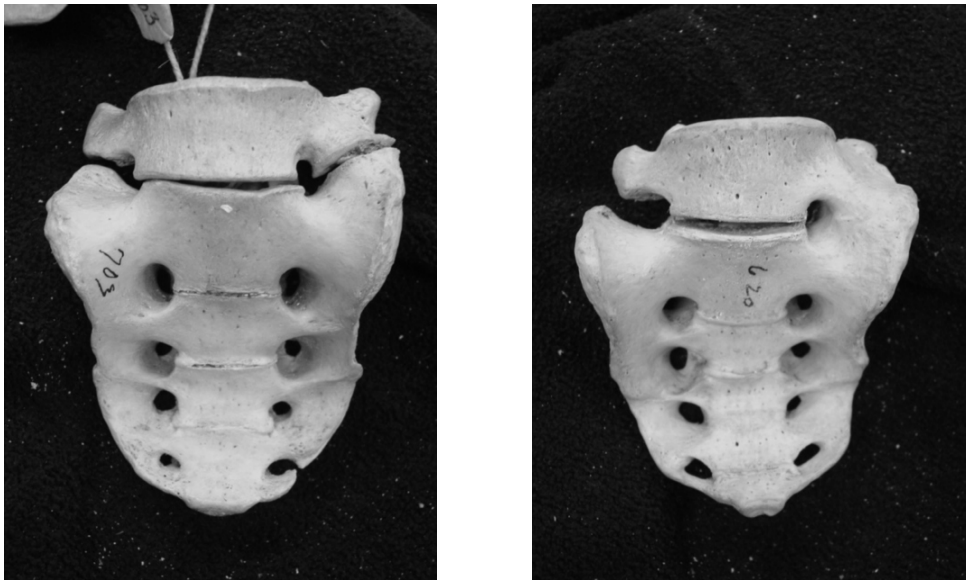


Fig. 2-9. Lumbosacral Transitional Vertebrae. Left – Transitional vertebra with normal articulation of the pelvis with the sacrum; Right – Transitional vertebra with uneven articulation of the pelvis and sacrum.

Classification Systems

Previous attempts at classifying LSTV have had mixed results. Schmorl (1971) reports the system developed by Blumensaat and Clasing (1932), was devised for clinical purposes and based upon anatomical changes. Their system consists of three groups: Group 1 is complete sacralization or complete lumbarization. Group 2 is partial sacralization or lumbarization and is separated into three groups; bilateral forms, unilateral forms, and combination forms of sacralization and lumbarization. Group 3 is transitional forms of transverse processes with no connection to the sacrum. The primary deficiency of this system is the vagueness of sacralization and lumbarization as designating characteristics. This is especially difficult when extra segments are present. This system also does not differentiate between the presence of fusion or contact of the transitional vertebra, nor does it consider the number of lumbar motion segments, a potentially vital component with biomechanical implications (Adams et al., 2002).

In 1984, Castellvi et al. (1984) devised a new classification system, "based upon the morphologic and clinical characteristics with respect to herniated nucleus pulposus (493)." This system consists of four types, subdivided into unilateral and bilateral types, categorized according to the degree of lumbarization and sacralization present, but neglects to consider the number of lumbar motion segments. With consideration of herniated discs only, alternate causes of back pain and biomechanical considerations are ignored. While herniated discs are a potential source of back pain, they are not the only cause, nor has it been confirmed that it is the herniated disc itself causing pain or if it merely influences the true source of pain (Adams et al. 2002).

A third classification system was proposed by Barnes (1994) and uses lumbarization (caudal shift) and sacralization (cranial shift) as major types. Each of these two major types are divided into three subgroups: complete expression, incomplete expression, and mild expression. As with the others, there can be uncertainty as to whether lumbarization or sacralization is taking place, especially when extra segments are present, and the number of motion segments is ignored.

Due to the problems associated with the classification systems discussed, it is necessary to develop a system that not only takes the morphological aspects of lumbarization and sacralization into account, but also recognizes the importance of the number of lumbar motion segments and other biomechanical considerations, and is useful in a clinical setting. The system developed in this study, as outlined below, was constructed in such a way as to take both the anatomical variation and biomechanics into account.

Pain

Pain sensation is highly subjective and the exact physiological causes of pain are not yet completely understood. What is known is that pain is the result of the stimulation of three types of nociceptors: thermal, mechanical and polymodal. While all three are naked nerve endings, they serve slightly different functions. The first two are responsible for fast pain responses which are highly localized and characterized as a sharp prickling sensation. The last type, polymodal, is the slow pain response, and is responsible for the very unpleasant lingering pain sensation (Sherwood, 2001). All pain response pathways can be sensitized by prostaglandins. The slow pain pathway, in addition, is activated by bradykinin and capsaicin, the active ingredient in hot peppers.

Pain sensation is then sent from the nociceptors, through the dorsal horn of the spinal cord, to three areas in the brain: the somatosensory cortex, thalamus, and reticular formation. The roles of these three areas, with respect to pain, are not well understood; the cortex is thought to be important for localizing the pain, the thalamus for receiving pain sensation and, with signals from the reticular formation, which also increases alertness, send impulses to the hypothalamus and limbic system which produce the behavioral and emotional responses. Further, glutamate can act to increase the sensitivity of the injured area by increasing the excitability of the dorsal horn neurons (Sherwood, 2001).

There are many factors associated with LSTV that may potentially be the source of pain: 1) disc degeneration, 2) disc prolapse, 3) spinal stenosis, 4) nerve root compression, 5) olisthesis, 6) sacroiliac joint pain, 7) muscle, tendon, or ligament strain or sprain, 8) chemical irritation, 9) vertebral collapse, and 10) damage to other nearby structures receiving innervation. A transitional vertebra that reduces the mobility in the inferior motion segment stabilizes the inferior intervertebral joint and protects the disc, but results in fewer motion segments to accommodate movement. This reduction in mobility at the inferior segment causes each of the other lumbar discs to receive excess mobility, which stresses the discs. The excess mobility and disc stress has been shown to cause degeneration in the disc immediately superior to the LSTV (MacGibbon and Farfan, 1979; Abe et al., 1997; Vergauwen et al., 1997; Brault et al., 2001). The excess mobility could also potentially cause the disc to bulge or prolapse, putting pressure on the spinal nerves. While the degeneration of intervertebral discs may or may not be the source of the pain, the reduced disc height may reduce the size of the intervertebral

foramen, pinching exiting spinal nerves, or lead to olisthesis, a subluxation of the associated vertebrae.

Sacroiliac joint pain could be the result of interference of the joint by the enlarged transverse processes of a transitional vertebra, potentially causing separation of the joint. A potential cause of muscle strain and/or sprain is the uneven weight-bearing that results from a unilateral transitional vertebra. When the weight of the upper body is applied to the low back unevenly, it caused the muscles, ligaments, tendons, and bones of the low back to compensate for the added stress that is applied to the side receiving the majority of the weight. Chemical irritation, as a source of pain, is caused by the release of noxious chemicals from damaged structures, such as the release of nitric oxide from a prolapsed disc (Adams et al., 2002), or prostaglandins from damaged nerves and other structures (Sherwood, 2001). Vertebral collapse, caused by compressive failure, results in either endplate fracture or anterior wedge-shaped fractures which can result in back pain. Damage to nearby structures leads indirectly to back pain through the release of noxious chemicals, muscle fatigue, and altered biomechanics, or directly through nociceptors in the damaged structure itself. Differentiating between the type and location of the back pain may be useful in identifying the exact cause.

Because there are multiple possible sources of pain associated with LSTV, it is very difficult to isolate the exact source of back pain (Deyo, 2001; Adams et al., 2002; Winkelstein, 2004). Thus, for the purposes of the current study, it is assumed that the defective vertebra is a factor involved in the source of pain, although the source of pain could be unrelated or multiple sources could be responsible. Only with future study of the neurophysiology of pain pathways and procedures performed to correct the defective

segment can a direct association between LSTV and any specific cause of pain be established.

Clinical Studies

Low back pain is a very common condition, affecting two-thirds of all adults at some point in their lives, and second only to upper respiratory problems as a reason to see a physician (Deyo, 2001). Jensen et al. (1994) report that 80% of Americans experience LBP over the course of their lifetime. Factors that have been found to positively correlate with back and neck pain are obesity, age, gender, and socioeconomic conditions (Webb et al., 2003), as well as disc degeneration, slippage, herniation, and muscle sprain and strain (Adams et al. 2002). This wide range of both physiological and psychosocial factors emphasizes the elusive nature of identifying the cause of LBP, and for many patients the specific cause of LBP may never be discovered. Further, sensitization of the central nervous system due to glutamate activity can lead to heightened pain responses and persistant pain. In addition to nociceptive responses, neuroimmunological pathways contribute to the sensitization and pain perception (Winkelstein, 2004). Isolating the exact cause of pain, clearly, can be quite difficult.

Transitional vertebrae have been associated with numerous additional anatomical defects and physiological changes, including disc height (Hsieh et al., 2000), disc degeneration, especially at the level supradjacent to the transitional vertebrae (MacGibbon and Farfan, 1979; Abe et al., 1997; Vergauwen et al., 1997; Brault et al., 2001), facet degeneration (Vergauwen et al., 1997), altered vascular anatomy (Weiner et al., 2001), foraminal stenosis (Abe et al., 1997; Vergauwen et al., 1997), and change in dermatome boundaries (Seyfert 1997). While these defects can also be present in patients

with normal lumbar spines, the pattern and frequency of the physiological changes just mentioned, especially the degeneration of the supradjacent disc, differs with the presence of a LSTV. Due to these differences, the presence of a LSTV should be assessed and taken into consideration before any surgical intervention involving the lumbosacral junction is undertaken (Wigh and Anthony, 1981). However, in a clinical setting it is much more difficult to assess the type of transitional vertebra variation than in a dry skeleton, mostly due to the lack of anatomic detail visible on standard radiographs.

The Visual Analogue Scale (VAS) pain scale is commonly used in clinical settings to determine the initial degree and change in intensity of pain (Crichton, 2001). This scale is typically a 100 mm line with word descriptions at the ends; the patient then marks where on the scale they feel the severity of their pain lies (Fig. 2-10). This mark is then measured from the left hand end to get a numerical score. Due to the nature of the scale, it is easily converted into an oral scale from 1 to 10 that can be recorded in a patient's chart.

Mark on the following line where you feel your pain is today.

No Pain |_____| Very Severe Pain

Fig. 2-10. Example of VAS scale used in clinical settings.

There is a vast literature on the use of VAS pain scales for measuring LBP. Although there is some discrepancy as to exactly how to administer the test (Ogon et al., 1996), there is general agreement as to what constitutes clinically significant changes in the severity of pain reported. As reported in Todd et al. (1996), and later Gallagher et al. (2001), a change of 13 mm on a 100 mm scale constituted clinical significance, or the point at which the patient was able to notice a change. However, Bird and Dickson

(2001) report that this value, 13 mm, is different depending on the initial pain value reported, with those patients reporting higher initial values also having higher changes in values to reach clinical significance; though this is refuted by Kelly (2001). While there is no consensus on the exact level of clinically significant change in pain, the "rule of two," or a reported change of two digits on a ten point scale, seems to be a valid constraint.

Regardless, due to the highly subjective nature of pain sensation, it is more useful to compare VAS scores across time within a single individual rather than across a synchronic sample (Crichton, 2001). However, since the VAS scale is so commonly used, and pain is so subjective, there is currently no better method of comparing pain among individuals. There does not seem to be a difference in clinically significant change in reported acute pain in the emergency room setting with regard to gender, age, or cause of pain (Kelly, 1998).

MATERIALS AND METHODS

This study is a two-phase project. The first phase uses a morphogenetic approach to develop a classification system for lumbosacral variation and a biomechanical approach to understand how LSTV can cause pain. The second applies that system to a clinical sample of patients suffering from low back pain to test whether there is a significant correlation between LSTV types and LBP.

Skeletal Sample

For the first phase of the study, I examined skeletal remains in the Hamann-Todd osteological collection, housed at the Cleveland Museum of Natural History, for the presence or absence of lumbosacral variants. There are 3710 specimens in this collection, of which 2803 could be assessed for this study (Table 3-1). Individuals lacking a thoracolumbar vertebra with transitional facet morphology, any lumbar vertebrae, a sacrum, and those less than 18 years of age were not considered for this study.

In the Hamann-Todd collection, the predominant group is White males, accounting for just over half of the population (52%). Approximately 28% of the collection is represented by Black males, and females of both ancestries represent just under one-fifth (19%) of the collection. Most individuals in the Hamann-Todd collection are accompanied by fairly complete records documenting age-at-death, sex, height, weight, ancestry and birthplace.

While the collection is heavily biased towards males and Whites, there are sufficient numbers of specimens from both sexes and both Whites and Blacks to obtain sufficient overall sample sizes for statistical analysis. Further, given the developmental,

TABLE 3-1. Hamann-Todd sample demographics

	n	Age Range (years)	Height Range (mm)	Weight Range (lbs)
Black Males	828	19-105	1322-1975	48-220
Black Females	257	19-89	1405-1841	52-300
White Males	1512	19-96	1295-1946	57-360
White Females	204	19-93	1219-1772	38-250
Total	2803	19-105	1219-1975	38-360

TABLE 3-2. Clinical sample demographics

	n	Age Range (years)	Height Range (mm)	Weight Range (lbs)
White Males	52	14-64	1750 – 2000	130-317
White Females	52	15-69	1475 – 1700	105-302
Other	12	21-53	1800	216
Total	116	14-69	1475 – 2000	105-317

non-lethal, nature of LSTV, it is not thought that the collection has a bias for or against this defect.

Clinical Sample

In the second phase, a clinical sample is evaluated for the presence or absence of lumbosacral defects. The clinical sample was obtained from a private clinic in Boone County, Missouri. This part of the study was IRB exempt under 45 CFR 46.101(b)(4), (BHC #0407) because patient information was de-identified. This retrospective sample (Table 3-2) consisted of a combination of 532 radiographs and MRI's evaluated by a research assistant (Mr. James Ronan) for the presence of LSTV variants according to the classification scheme developed in the first phase. Radiographs were used because they were the most accessible medium from which LSTV variation can be determined, and the MRI's available were of patients for whom radiographs were also available. Due to record access restrictions, I was not able to view the radiographs myself, thus it was necessary to have a research assistant employed by the hospital view and assess the radiographs. Before any typological designation was done, I reviewed the classification system with the research assistant to minimize interobserver error. Further, whenever a controversial specimen arose we discussed the proper designation until a consensus was reached.

Metric Observations

Each specimen in the Hamann-Todd collection was evaluated for the presence of LSTV. The specimen was considered to have a defect if it exhibited contact or bony fusion between the sacrum and the first presacral vertebra at any of the six structures described below.

In order to accurately assess the metric variation present, specific measurements were obtained from the specimens in the Hamann-Todd collection. These measurements were recorded to the nearest hundredth of a millimeter using Mitutoyo® Digital Calipers for all specimens exhibiting lumbosacral variation as well as a control group of 100 (25 Black males, 25 White males, 25 Black females, and 25 White females) normal individuals. Normal individuals were identified as those exhibiting lumbar spines with uninhibited joint spaces, symmetrical vertebrae, and six (6) lumbar intervertebral disc spaces, and were chosen from the unaffected population to represent a wide range of heights, weights, and ages. The control group was used to assess the range of variation within a normal population with respect to vertebral size, shape, and symmetry.

I measured vertebral body height, length, and width; right and left pedicle length and width; and spinal canal length and breadth (Fig. 3-1 and Table 3-3). The pedicle measurements were selected to capture variation in the size and shape of the pedicle while taking into account the unique features of the fifth lumbar vertebra, especially the way the transverse process extends from the pedicles. In addition, the range of variation in the pedicle measurements may be useful to physicians in selecting appropriate screw length during lower back surgeries, both for normal patients and those with LSTV.

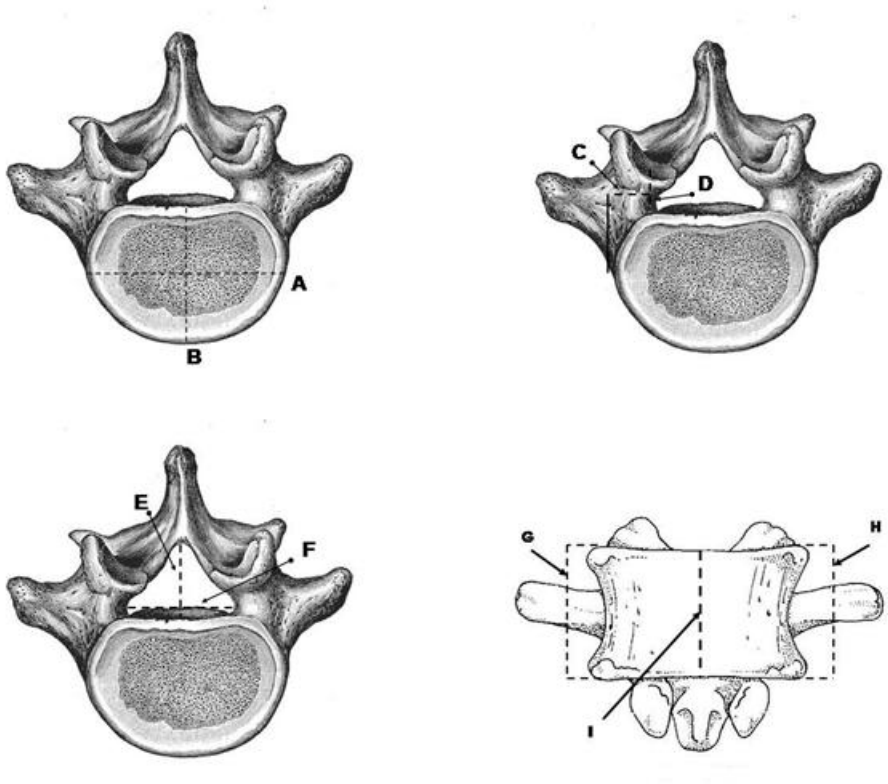


Fig. 3-1. Superior (a-c) and anterior (d) view of fifth lumbar vertebra illustrating vertebral measurements: A) body width, B) body length, C) pedicle width, D) pedicle length, E) canal length, F) canal width, G) left body height, H) right body height, and I) anterior body height. Superior views modified from Clemente (1985) and anterior view modified from Adams et al. (2002).

TABLE 3-3. Vertebral metrics descriptions.

Measurement	Code	Description
Right Body Height	RBH	Distance from the superior to inferior surfaces at the right most lateral point of the vertebral body.
Left Body Height	LBH	Distance from the superior to inferior surfaces at the left most lateral point of the vertebral body.
Anterior Body Height	ABH	Distance from the superior to inferior surfaces at the anterior midline of the vertebral body.
Posterior Body Height	PBH	Distance from the superior to inferior surfaces at the posterior midline of the vertebral body.
Body Width	BW	Maximum mediolateral distance across the superior surface of the body.
Body Length	BL	Maximum anteroposterior distance across the superior surface of the body.
Canal Width	CW	Maximum mediolateral internal distance of the spinal canal.
Canal Length	CL	Maximum distance from the posterior edge of the superior surface of the body to the inside edge of the spinous process.
Right Pedicle Width	RPW	Distance from the right lateral edge of the spinal canal to the lateral edge of the body extended posteriorly to the same level as the canal.
Right Pedicle Length	RPL	Distance from the posterior surface of the right superior articular process to the point where the pedicle joins the body.
Left Pedicle Width	LPW	Distance from the left lateral edge of the spinal canal to the lateral edge of the body extended posteriorly to the same level as the canal.
Left Pedicle Length	LPL	Distance from the posterior surface of the left superior articular process to the point where the pedicle joins the body.

Data obtained from the Hamann-Todd collection was used to examine the following questions:

Q1: Are there significant differences between individuals with (having a defect) and without LSTV in L5 body, canal, and pedicle size and shape? This question was addressed by testing the following null hypotheses:

1a. There is no difference in L5 vertebral body height between individuals with LSTV and the control individuals.

1b. There is no difference in L5 vertebral body length between individuals with LSTV and the control individuals.

1c. There is no difference in L5 vertebral body width between individuals with LSTV and the control individuals.

1d. There is no difference in L5 pedicle length between individuals with LSTV and the control individuals.

1e. There is no difference in L5 pedicle width between individuals with LSTV and the control individuals.

1f. There is no difference in L5 vertebral canal length between individuals with LSTV and the control individuals.

1g. There is no difference in L5 vertebral canal width between individuals with LSTV and the control individuals.

1h. There is no difference in vertebral canal shape (length/width) between individuals with LSTV and the control individuals.

Q2: Do individuals with LSTV have greater asymmetry in pedicle or vertebral body height dimensions than individuals without the defect? Three null hypotheses were tested to address this question.

2a. There is no difference in pedicle length asymmetry (abs(R-L)) between individuals with and without LSTV.

2b. There is no difference in pedicle width asymmetry (abs(R-L)) between individuals with and without LSTV.

2c. There is no difference in body height asymmetry (abs (R-L)).

Q3: Are there any significant differences between the 12 specific types of LSTV in L5 body, canal, and pedicle size and shape? This question was addressed by the following null hypotheses:

3a. There is no difference between LSTV types in L5 vertebral body height.

3b. There is no difference between LSTV types in L5 vertebral body length.

3c. There is no difference between LSTV types in L5 vertebral body width.

3d. There is no difference between LSTV types in L5 pedicle length.

3e. There is no difference between LSTV types in L5 pedicle width.

3f. There is no difference between LSTV types in L5 vertebral canal length.

3g. There is no difference between LSTV types in L5 vertebral canal width.

3h. There is no difference between LSTV types in vertebral canal shape (length/width).

Q4: Does asymmetry in pedicle or vertebral body height dimensions differ between the 12 different LSTV types? Three null hypotheses were tested to address this question using Hamann-Todd individuals with LSTV.

4a. There is no difference in pedicle length asymmetry (abs(R-L)).

4b. There is no difference in pedicle width asymmetry (abs(R-L)).

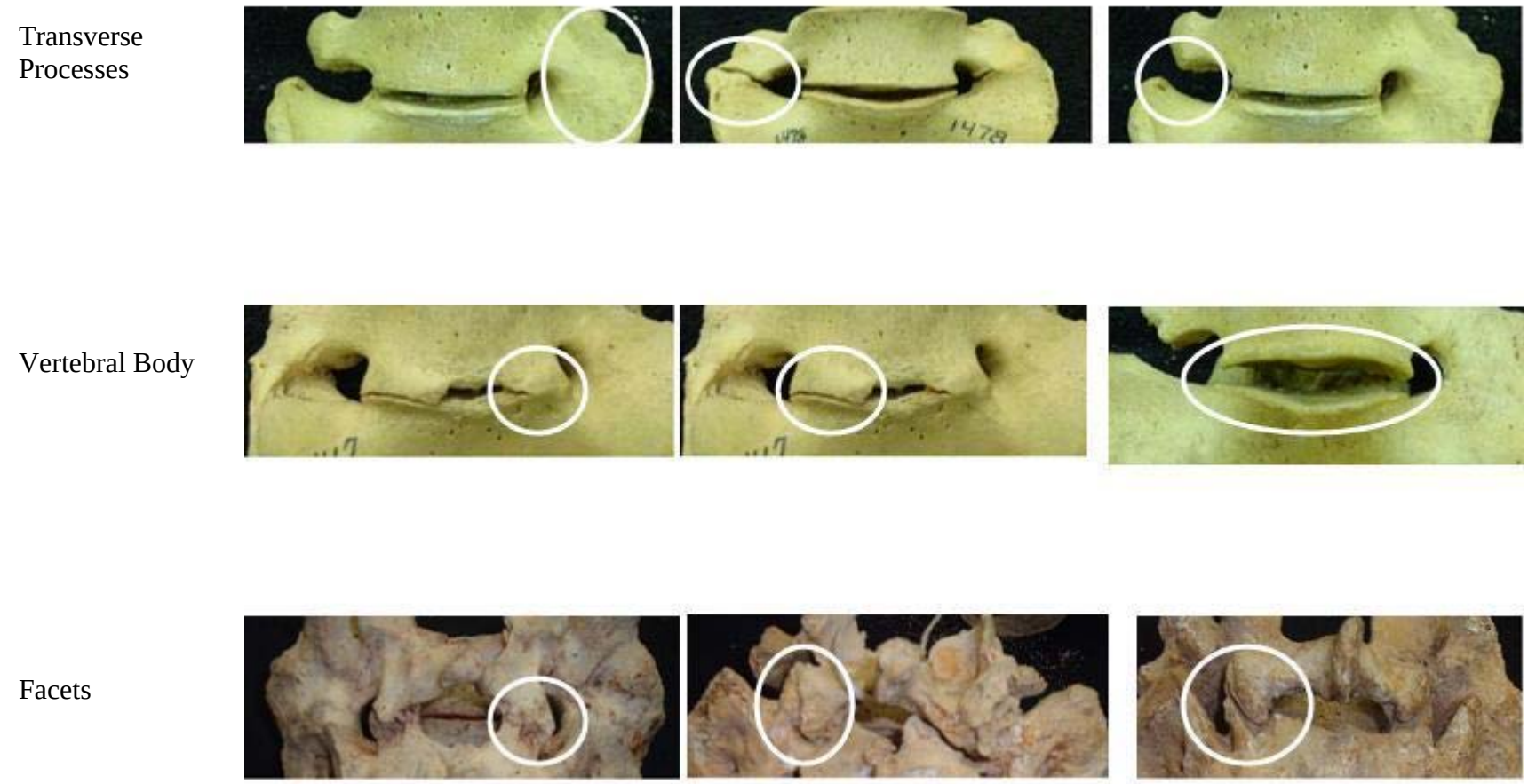
4c. There is no difference between LSTV types in body height asymmetry.

Q5: Are there significant differences in L5 body, pedicle, and canal size and shape based on the number of motion segments, whether the defect is unilateral or bilateral, or whether there is fusion or contact? This question was addressed by testing each metric measurement according to each of the three criteria: fused or contact, number of motion segments, and unilateral or bilateral, and all paired combinations thereof. This generated too many hypotheses to list.

Nonmetric Observations

To assess the type and frequency of nonmetric variation present, each specimen (n=196) in the Hamann-Todd collection with a lumbosacral defect was rated in six structures for the presence of bony fusion, contact, or open space between the affected vertebra and subjacent one. The six structures assessed were the left and right inferior articular facets, left and right transverse processes, and the left and right sides of the vertebral body (Fig. 3-2). A score of one (1) was given if fusion was present, a two (2) for contact, and a three (3) if the space between the vertebral structures was open. A specimen exhibited fusion if the bone had grown together, preventing any motion between the segments. If the vertebral segments were touching but not fused, with or without evidence of connective tissue, then it was classified as exhibiting contact. Open segments were such that the full range of motion was possible. Figure 3-2 illustrates the variation in the components assessed. As well as assessing the specimens in these six structures, the segment affected, number of thoracic, lumbar, and sacral vertebrae present,

Fig. 3-2. Examples of fusion, contact, and open condition for the three structures assessed (both right and left sides were assessed).



the number of lumbar motion segments present, the thoracolumbar facet transition vertebra, and any miscellaneous comments, including the presence of any pathological conditions were recorded.

After these observations were recorded, a typological designation was assigned to each specimen, as described below. Subsequently, frequencies were calculated for each type, normal vs. abnormal, and according to demographic properties (sex and ancestry) as well as height, weight, and body mass index or BMI. This allowed me to address the following questions:

Q6: Does the prevalence of LSTV in the Hamann-Todd population vary by sex, ancestry or the interaction between sex and ancestry? This was determined by testing the null hypotheses below:

6a. There is no difference in the prevalence of LSTV based on sex.

6b. There is no difference in the prevalence of LSTV based on ancestry.

6c. There are no interaction between sex and ancestry in the prevalence of LSTV.

Q7: Does the prevalence of LSTV in the Hamann-Todd population vary based on the individual's body height, body weight, or the combination of height and weight (assessed using BMI)? The following hypotheses were tested to address this question:

7a. There is no difference in the prevalence of LSTV based on body height.

7b. There is no difference in the prevalence of LSTV based on body weight.

7c. There is no difference in the prevalence of LSTV based on BMI.

Classification System

The classification system developed from the nonmetric data is shown in Table 3-4. First, the specimen was analyzed for the presence of contact or fusion, with fusion of

any one of the six structures listed above qualifying the specimen as fused, even with the presence of contact elsewhere. Second, the number of motion segments was counted from the thoracolumbar facet transition to the last disc superior to the affected segment (typically from T12 to an affected L5), with designations of less than six, six, and greater than six motion segments. Finally, whether the specimen exhibited unilateral or bilateral presence of contact or fusion was determined. This system generated 12 different possible types of LSTV.

Table 3-4. Classification system

1. Fused (no joint space)
    - A. >6 motion segments – counted from thoracic transition to effected lumbar segment (i.e. T12 to an affected L5 = 5 motion segments)
        - b. Bilateral
        - u. unilateral
    - B. 6 motion segments (normal)
        - b. Bilateral
        - u. unilateral
    - C. <6 motion segments
        - b. Bilateral
        - u. unilateral
2. Contact/Pseudapophysis (touching but not fused/some joint space)
    - A. >6 motion segments – counted from thoracic transition to effected lumbar segment (i.e. T12 to an affected L5 = 5 motion segments)
        - b. Bilateral
        - u. unilateral
    - B. 6 motion segments (normal)
        - b. Bilateral
        - u. unilateral
    - C. <6 motion segments
        - b. Bilateral
        - u. unilateral

Radiographs

Analysis of the radiographic material included classification according to the system developed from the osteological collection. All patients presenting LBP to Dr. Parker within the last two years were considered for the clinical sample, yielding 532 patients. For the purpose of efficiency, all patients with radiographically diagnosed LSTV were included, as well as an equal number of normal lumbar spine patients also presenting LBP (n=137). In addition, only those patients between the ages of 18 and 60 were considered as older patients often exhibited ambiguous radiographic findings.

In addition, the level of pain that patients experienced was assessed using a VAS (visual analogue scale) pain scale (See Chapter 2). The extent of pain intensity was obtained from patient records. A VAS is a subjective ten point scale, widely used in clinical settings for the assessment of pain intensity (Crichton, 2001).

By classifying the type of LSTV in the clinical sample in the same way as the Hamann-Todd sample, it was possible to assess the frequency of LSTV types in the same fashion, as well as compare the two samples. The clinical data allowed me to address the following research questions:

Q8: Is the prevalence of LSTV greater in the clinical sample compared to the Hamann-Todd sample?

8a. There is no difference in the prevalence of LSTV between the clinical and skeletal samples.

Q9: Is the intensity of lower back pain in the clinical sample associated with the individual's sex, body height, body weight, or BMI?

9a. The intensity of back pain is not different between males and females.

9b. The intensity of back pain is not correlated with body height.

9c. The intensity of back pain is not correlated with body weight.

9d. The intensity of back pain is not correlated with BMI.

Q10: Do individuals with LSTV suffer with more intense LBP than individuals without the defect?

10a. The intensity of back pain does not vary between individuals with or without LSTV.

Q11: Does the intensity of lower back pain among individuals with LSTV in the clinical sample vary by the type of LSTV present?

11a. There is no correlation between the intensity of low back pain and the type of LSTV.

Q12: Does the intensity of low back pain among individuals with LSTV vary in the clinical sample due to the number of motion segments, whether the defect is unilateral or bilateral, or whether there is fusion or contact.

12a. The intensity of low back pain does not differ between individuals based on the number of motion segments.

12b.The intensity of low back pain does not differ between individuals with unilateral or bilateral defects.

12c.The intensity of low back pain does not differ between individuals with complete fusion or contact defects.

Q13: Do the Hamann-Todd and clinical sample frequencies differ by criteria?

13a. The Hamann-Todd and clinical samples do not differ with respect to fusion or contact.

13b. The Hamann-Todd and clinical samples do not differ with respect to the number of motion segments.

13c. The Hamann-Todd and clinical samples do not differ with respect to defect symmetry.

Statistics

All statistical analyses were performed with the SAS 8.2 program (SAS, 2001), and the significant results were considered to have a p-value ≤ 0.05. Statistical analysis of the skeletal sample included assessing frequencies, computing descriptive statistics for the abnormal and normal groups, and determining the correlation between independent and dependent variables. Metric analysis by classification type was not performed as part of the current study. Frequencies were obtained with the PROC FREQ procedure for both sex and ancestry. When assessing the differences in measurement means and variances, the GLM procedure was used to determine significance. This ANOVA assessing procedure is used to determine if no difference exists between groups on the basis of multiple outcome variables. In addition, a Bonferroni t-test was used to asses the direction of the variance and the degree of significance when multiple groups were considered.

For the clinical data, frequencies of the different types of LSTV were also assessed, as well as the association between LSTV (in general, by each categorization criterion, and by specific types) and LBP as measured by the VAS parameter. In addition, height, weight, BMI and VAS were assessed according to specific LSTV types as well as the three categorization criteria to see if there was any significant correlation and to provide a corroboration of the classification system itself. The test used to calculate these

was the GLM procedure and Bonferroni t-test. When analyzing the frequencies of LSTV types in the clinical sample, Fisher's exact test was used instead of a chi-square due to the inaccuracy of the chi-square statistic caused by small cell frequencies (Schlotzhauer and Littell, 1987; Everitt, 1992).

RESULTS

Skeletal Sample

Under the classification system developed here, there are 12 possible types of LSTV, of which ten appear in the Hamann-Todd collection (1Au and 2Ab are not present). Both types that are absent have greater than six motion segments, a condition that, under the current system, would necessitate having two extra segments in the lumbar spine, with the first extra segment being a normal lumbar vertebrae and the second being transitional. The frequency of LSTV in the Hamann-Todd sample population was 7.0% (n=196 out of 2803), with 6.7% of males and 8.2% of females exhibiting the defect (Table 4-1). The number of motion segments was unavailable for six specimens, due to lack of vertebral elements, and thus they were dropped from the analysis. There was no significant difference found in LSTV frequency based on ancestry or sex (question 6).

Sex, defect, and sex*defect interactions were assessed by the GLM procedure using 2x2 and 2x3 factorial analysis. Analysis of the combined metric data showed consistent defect and sex effects ($p=<.0001$ in both cases) but no significant sex*defect interaction effect (Table 4-2). Not only were the measurements significantly affected by defect, but body height asymmetry and canal ratio were also significantly affected ($p=0.0009$, and $p=0.0002$ respectively). For this reason, males and females were separated for further analysis. However, it should be noted that some of the interaction results approached significance, suggesting that the significant results for sex and defect separately may be due in part to the interaction.

TABLE 4-1. Rates of LSTV by sex and ancestry in HTH

Group	Affected	Total	%
Black Females	21	257	8.2
Black Males	60	828	7.2
White Females	17	204	8.3
White Males	98	1512	6.5

TABLE 4-2. ANOVA results for combined male/female measurements

Var	Effect	P value[1]	Var	Effect	P value[1]
RBH	Defect	0.7063	RPW	Defect	**0.0014**
	Sex	**0.0097**		Sex	**<.0001**
	Sex*defect	0.8013		Sex*defect	0.4772
LBH	Defect	**0.0001**	RPL	Defect	**0.0004**
	Sex	0.3864		Sex	**0.0075**
	Sex*defect	0.0754		Sex*defect	0.3698
ABH	Defect	0.2621	LPW	Defect	**0.0005**
	Sex	**<.0001**		Sex	**<.0001**
	Sex*defect	0.9193		Sex*defect	0.6911
PBH	Defect	0.1645	LPL	Defect	0.0615
	Sex	**0.0275**		Sex	0.0795
	Sex*defect	0.4855		Sex*defect	0.3944
BW	Defect	0.0983	PWA	Defect	0.9723
	Sex	**<.0001**		Sex	0.7574
	Sex*defect	0.5459		Sex*defect	0.5387
BL	Defect	0.8328	PLA	Defect	0.0788
	Sex	**<.0001**		Sex	**0.0410**
	Sex*defect	0.5995		Sex*defect	0.1949
CW	Defect	**<.0001**	BHA	Defect	**0.0009**
	Sex	**0.0438**		Sex	0.6272
	Sex*defect	0.4250		Sex*defect	0.9955
CL	Defect	0.4135	CR	Defect	**0.0002**
	Sex	**0.0084**		Sex	0.2145
	Sex*defect	0.9999		Sex*defect	0.5992

[1]Bolded p-values are statistically significant.

Research questions 1 and 2, and associated hypotheses, were addressed with the following results. There is a clear defect effect on many of the measurements for males (Table 4-3), especially in the pedicles and spinal canal width (p=0.0022). This difference in canal width affected the canal ratio, also causing it to show significance. For males, canal width is wider, right pedicle length is shorter, and body height is more asymmetrical than normal for all LSTV types, except 2Au. Type 2Au is represented by one individual and thus it is unknown whether he is the average for that type in the general population. Table 4-4 addresses research questions 3 and 4, showing the results for males with respect to differences in measurements based on type. There appear to be some statistically significant differences; however, when examined more closely using the Bonferroni t-test there is no discernible pattern to the differences.

The female results for defect differences address research questions 1 and 2 and are shown in Table 4-5. In females the right and left pedicle widths and canal width are significantly affected (p=0.0064, p=0.0090, and p=0.0003, respectively). Canal width is wider for all LSTV types than it is for the control group, right pedicle length is shortest in unilateral contact with six motion segments, and body height being more asymmetrical in all LSTV types save one (1Bb). However, like the male data, the female data show significant differences by type (p=<.0001) but with no discernible pattern. Table 4-6 addresses research questions 3 and 4 and summarizes the results.

Since dividing the sample by sex and LSTV type creates a very small sample size for most sex/type groups, I analyzed differences in metric dimensions by each of the three classification criteria (i.e. fusion or contact, number of motion segments, and unilateral or bilateral) as well as all pairs of criteria. Also, due to the lack of pattern by

TABLE 4-3. ANOVA comparison of measurements in males with and without defect

Measurement[1]	P- value[2]
RBH	0.9145
LBH	0.0744
ABH	0.2915
PBH	0.5305
BW	0.0579
BL	0.8019
CW	**0.0022**
CL	0.4804
RPW	**0.0378**
RPL	**0.0001**
LPW	**0.0098**
LPL	**0.0239**
PWA	0.5559
PLA	**0.0141**
BHA	**0.0067**
CR	**0.0041**
Overall Defect Effect	**<.0001**

[1]See table 3.3 for measurement descriptions.
[2]Bolded p-values are statistically significant.

TABLE 4-4. ANOVA comparison of male metric measurements by type

Measurement[1]	P- value[2]
RBH	**0.0043**
LBH	0.1645
ABH	0.6667
PBH	0.1251
BW	0.5275
BL	0.0581
CW	**0.0107**
CL	0.9877
RPW	0.0518
RPL	**0.0438**
LPW	**0.0467**
LPL	0.2904
PWA	0.8796
PLA	0.0624
BHA	**0.0239**
CR	0.0551
Overall Type Effect	**<.0001**

[1]See table 3.3 for measurement descriptions.
[2]Bolded p-values are statistically significant.

TABLE 4-5. ANOVA comparison of measurements in females with and without defect

Measurement[1]	P- value[2]
RBH	0.6853
LBH	**0.0004**
ABH	0.5170
PBH	0.2301
BW	0.4766
BL	0.5407
CW	**0.0003**
CL	0.6037
RPW	**0.0064**
RPL	0.0983
LPW	**0.0090**
LPL	0.4750
PWA	0.7402
PLA	0.7157
BHA	**0.0147**
CR	**0.0131**
Overall Defect Effect	**<.0001**

[1]See table 3.3 for measurement descriptions.
[2]Bolded p-values are statistically significant.

TABLE 4-6. ANOVA comparison of female metric measurements by type

Measurement[1]	P- value[2]
RBH	0.0570
LBH	**0.0051**
ABH	0.5695
PBH	0.6760
BW	0.2115
BL	0.2300
CW	**0.0073**
CL	0.6334
RPW	0.0674
RPL	**0.0010**
LPW	0.0918
LPL	0.0616
PWA	0.6500
PLA	0.0842
BHA	**0.0234**
CR	**0.0091**
Overall Type Effect	**<.0001**

[1]See table 3.3 for measurement descriptions.
[2]Bolded p-values are statistically significant.

specific type, each classification criterion was assessed for each sex. This addresses research question 5. The results are shown in Table 4-7 for males and in Table 4-8 for females. For males, the presence of fusion or contact (designated x1) had significant effects on the most measurements, especially body heights and body length, canal width, and canal ratio (See Appendix A for descriptive statistics.). The number of motion segments (x2) only had a significant effect on body length ($p=0.0188$), and when combined with symmetry (x3) it had an effect on right pedicle length ($p=0.0153$). Symmetry had significant effects on right body height ($p=0.0211$), right pedicle width ($p=0.0260$), and body height asymmetry ($p=0.0104$). However, there was no consistent pattern to any of the effects for any single criteria or combination of criteria. The results for females mirrors that for the males, some criteria had some effects but with no consistent pattern. There were also fewer significant effects on female measurements.

Finally, the prevalence of LSTV in the Hamann-Todd sample was tested to see if body height, body weight, or BMI had an effect, addressing research question 7. Analysis shows that none of these parameters had any effect on the prevalence of LSTV in the skeletal sample.

Clinical Sample

In the clinical sample, the frequency of LSTV among patients reporting back pain, research question 8, was 13.5%. Table 4-9 shows the frequency of each type. Due to very few minority individuals, the clinical data was not assessed with ancestry as a parameter. It was found that not only did the specific type of LSTV not vary between the groups in the clinical sample, but no classification criteria did either (Table 4-10). Table 4-11

TABLE 4-7. ANOVA comparison of metric measurements in males by categorization criteria

Var[1]	Criteria[2]	P- value[3]	Var	Criteria	P - value	Var	Criteria	P- value	Var	Criteria	P - value
RBH	x1	**<.0001**	BW	x1	0.5500	RPW	x1	0.0739	PWA	x1	0.9824
	x2	0.7693		x2	0.6806		x2	0.7682		x2	0.8276
	x3	**0.0211**		x3	0.2568		x3	**0.0260**		x3	0.0781
	x1*x2	0.1327		x1*x2	0.9141		x1*x2	0.5578		x1*x2	0.6024
	x1*x3	0.8182		x1*x3	0.4800		x1*x3	0.6991		x1*x3	0.1961
	x2*x3	0.4593		x2*x3	0.2794		x2*x3	0.3355		x2*x3	0.8789
LBH	x1	**0.0084**	BL	x1	**0.0447**	RPL	x1	0.5329	PLA	x1	0.7232
	x2	0.8304		x2	**0.0188**		x2	0.2898		x2	0.4042
	x3	0.2934		x3	0.3513		x3	0.6681		x3	0.2268
	x1*x2	0.9421		x1*x2	0.6520		x1*x2	0.7806		x1*x2	0.1080
	x1*x3	**0.0125**		x1*x3	0.9341		x1*x3	0.7748		x1*x3	0.5826
	x2*x3	0.6904		x2*x3	0.3643		x2*x3	**0.0153**		x2*x3	0.4537
ABH	x1	**0.0036**	CW	x1	**0.0005**	LPW	x1	0.0613	BHA	x1	0.3213
	x2	0.4506		x2	0.3159		x2	0.5758		x2	0.2124
	x3	0.2751		x3	0.3893		x3	0.1117		x3	**0.0104**
	x1*x2	0.6639		x1*x2	0.4434		x1*x2	0.6040		x1*x2	0.8682
	x1*x3	0.5380		x1*x3	0.9735		x1*x3	0.8007		x1*x3	**0.0488**
	x2*x3	0.3357		x2*x3	0.8425		x2*x3	0.0957		x2*x3	0.3997
PBH	x1	0.3519	CL	x1	0.2852	LPL	x1	0.0807	CR	x1	**0.0003**
	x2	0.2925		x2	0.6055		x2	0.1859		x2	0.8885
	x3	0.2135		x3	0.6645		x3	0.8101		x3	0.1384
	x1*x2	0.1577		x1*x2	0.5193		x1*x2	0.1736		x1*x2	0.2452
	x1*x3	0.9521		x1*x3	0.3304		x1*x3	0.6333		x1*x3	0.2327
	x2*x3	0.3475		x2*x3	0.5703		x2*x3	0.1903		x2*x3	0.4098

[1]See table 3.3 for measurement descriptions.
[2] X1=fusion or contact, X2=# motion segments, X3=unilateral or bilateral
[3] Bolded p-values are statistically significant.

TABLE 4-8. ANOVA comparison of metric measurements in females by categorization criteria

Var[1]	Criteria[2]	P- value[3]	Var	Criteria	P- value	Var	Criteria	P- value	Var	Criteria	P- value
RBH	x1	0.1831	BW	x1	0.9064	RPW	x1	0.4614	PWA	x1	0.8762
	x2	0.0908		x2	**0.0210**		x2	0.0549		x2	0.9907
	x3	**0.0236**		x3	0.5002		x3	0.3193		x3	0.9550
	x1*x2	0.6974		x1*x2	0.3926		x1*x2	0.6306		x1*x2	0.1959
	x1*x3	.		x1*x3	**0.0011**		x1*x3	0.3499		x1*x3	0.1428
	x2*x3	.		x2*x3	0.5642		x2*x3	0.7118		x2*x3	0.9995
LBH	x1	0.1605	BL	x1	0.4328	RPL	x1	0.1051	PLA	x1	0.6009
	x2	0.5246		x2	0.8591		x2	**0.0293**		x2	0.0876
	x3	0.6584		x3	**0.0108**		x3	0.5594		x3	**0.0379**
	x1*x2	.		x1*x2	0.1054		x1*x2	**0.0280**		x1*x2	0.7786
	x1*x3	.		x1*x3	0.0710		x1*x3	0.8659		x1*x3	0.2825
	x2*x3	.		x2*x3	**0.0296**		x2*x3	0.9171		x2*x3	0.3193
ABH	x1	**0.0117**	CW	x1	0.1342	LPW	x1	0.6847	BHA	x1	0.2095
	x2	0.0984		x2	0.5701		x2	0.3258		x2	0.9872
	x3	0.0931		x3	0.9151		x3	0.4300		x3	0.7431
	x1*x2	**0.0117**		x1*x2	0.9839		x1*x2	0.1561		x1*x2	.
	x1*x3	0.4640		x1*x3	0.6613		x1*x3	0.2112		x1*x3	.
	x2*x3	**0.0436**		x2*x3	0.9203		x2*x3	0.2319		x2*x3	.
PBH	x1	0.7434	CL	x1	0.5250	LPL	x1	0.0995	CR	x1	0.4469
	x2	0.5775		x2	0.4398		x2	0.1565		x2	0.2538
	x3	0.1536		x3	0.0675		x3	0.1425		x3	0.0914
	x1*x2	0.3827		x1*x2	**0.0137**		x1*x2	**0.0272**		x1*x2	**0.0183**
	x1*x3	0.9214		x1*x3	0.8397		x1*x3	0.3666		x1*x3	0.7714
	x2*x3	0.6720		x2*x3	0.2602		x2*x3	0.4140		x2*x3	0.4694

[1]See table 3.3 for measurement descriptions.

[2] X1=fusion or contact, X2=# motion segments, X3=unilateral or bilateral

[3] Bolded p-values are statistically significant.

shows that the only significant finding was that BMI was correlated with type ($p=0.0184$), but with no meaningful pattern.

Research question 9 addresses correlations between the intensity of LBP and various physical parameters. The results show that there was no significant difference in the intensity of pain reported by sex ($p=0.5760$) nor was there any significant correlation between back pain intensity and body height, body weight, or BMI. Research questions 10 and 11 address the intensity of pain and LSTV, in general and by type. Those patients with a transitional vertebra show no significant correlation with back pain intensity ($p=0.1881$), nor is there any correlation between back pain intensity and any specific type ($p=0.6653$). Finally, there was no significant correlation between back pain intensity and classification criteria, addressing research question 12.

The comparison of the skeletal and clinical samples, research question 13, revealed a number of significant results. Table 4-12 shows that there is an overall significant difference in the composition of the two samples ($p=0.0002$). Both the number of motion segments and the symmetry of the defect are significantly different as well ($p=0.0183$, and $p=0.0023$ respectively); however, whether there was fusion or contact was not significant ($p=0.7005$).

TABLE 4-9. Frequencies of LSTV types in the clinical sample

Type[1]	Frequency	%
1Bb	14	22.6
1Bu	7	11.3
1Cb	5	8.1
1Cu	8	12.9
2Au	1	1.6
2Bu	22	35.5
2Cb	2	3.2
2Cu	3	4.8

[1]See table 3-4 for type designations

TABLE 4-10. ANOVA comparison of clinical frequencies by criteria

Criteria[1]	P - value
Overall	0.2603
X1	0.4597
X2	0.2107
X3	0.1322

[1]X1=fusion or contact, X2=# motion segments, X3=unilateral or bilateral

TABLE 4-11a. ANOVA correlations of clinical parameters and criteria

Parameter	Criteria[1]	P - value
Height	x1	0.8408
	x2	0.3954
	x3	0.2530
BMI	x1	0.0812
	x2	0.2117
	x3	0.5022
Weight	x1	0.0734
	x2	0.6750
	x3	0.6359
VAS	x1	0.6637
	x2	0.6000
	x3	0.2397

[1]X1=fusion or contact, X2=# motion segments, X3=unilateral or bilateral

TABLE 4-11b. ANOVA correlations of clinical parameters and type

Parameter	P – value[1]
Height	0.3698
BMI	**0.0184**
Weight	0.2111
VAS	0.6653

[1]Bolded p-values are statistically significant.

TABLE 4-12. ANOVA comparison of the Hamann-Todd and clinical samples by criteria

Criteria[1]	Chi-square[2]
All types	**0.0002**
x1	0.7005
x2	**0.0184**
x3	**0.0023**

[1]x1=fusion or contact, x2=# motion segments, x3=unilateral or bilateral
[2]Bolded Chi-square values are statistically significant.

DISCUSSION

Skeletal Sample

With the number of different LSTV classification systems in the literature (Schmorl, 1971; Castellvi, 1985; Barnes, 1994), and the conflicting interpretations of the biomechanical and clinical evidence that follow from them, it is necessary to identify the characteristics of the transitional vertebrae that are valid for a useful categorization scheme. While the intended use of such a scheme dictates some of its features, it is certainly important to create a system that both distinguishes the important anatomical features, as well as providing important reference points for contemporary research and clinical applications. The classification system created in this study does just that. By distinguishing fusion from contact and unilateral from bilateral types, the important anatomical features are identified; though few metric measurements seem to be affected by these features, they are certainly the most visually striking. Further, by including the number of motion segments, I have attempted to identify a clinically and biomechanically important feature commonly overlooked by others.

While there are slight differences in the frequency of LSTV between sexes and ancestries, it is not significant. This stands in contrast to previously published studies suggesting that some populations may have higher rates of LSTV than others (Schmorl, 1971). However, the nonsignificant results in this study may be due in part to sample bias. Even though all of the specimens in the Hamann-Todd collection came from the Cleveland area, few were born there, and thus the collection represents such a heterogeneous mix that any population differences would be lost in the overall sample.

Due to the genetic and developmental origins of LSTV, it is possible that sex and population differences may occur. Having a transitional vertebra is not, by itself, a debilitating condition, thus it is unlikely to have very high selective pressures against it in any given context. Further, if it is caused primarily by *Hox* gene product concentration, there may be no mechanism to effectively select against it. While the literature is unclear about the exact origin of LSTV, it is likely a product of both genetic predisposition and developmental influences, and it is unlikely that a sex or population differences would be evident when sampling a large, diverse population.

In addition to documenting frequencies, I examined the effects of transitional vertebrae on specific metric dimensions of lumbar vertebrae. My finding that there is a significant sex effect reflects body size sexual dimorphism in humans, and was the reason for separating the sexes for further analysis of the metric dimensions. In both sexes there was a significant defect effect on some measurements (Tables 4-3 & 4-5). While some of the affected measurements are the same, many are not. This reveals the uniqueness of each case, and may reflect the numerous and complicated genetic and developmental factors involved. While there are certain unifying features, each instance of LSTV is individually unique and thus very difficult to quantify. The only consistent parameters that show an effect in both sexes are pedicle width, body height asymmetry and spinal canal size and shape. The reason for these effects is likely related to the sacral characteristics that the transitional vertebrae assume, either bilaterally or unilaterally. The sacrum has a wider spinal canal and shorter pedicles than does L5. In individuals with LSTV, the first presacral vertebrae take on these sacral characteristics, making them

significantly different from normal L5 vertebrae. This has important implications for clinical and biomechanical applications, which will be discussed later.

When separated by LSTV type, a few metric dimensions are affected, but there is no consistent pattern correlated with defect types. The major difference between LSTV types in both sexes are right pedicle length, body height asymmetry, and canal width, with no other significant effects in common. Again, these results illustrate the uniqueness of each case, and that even though two individuals may be classified as the same type under the current system, each individual has slightly different features. As with the overall defect effects, trying to quantify the idiosyncratic differences between individuals is extremely difficult and would generate many more types than are currently being considered, further decreasing individual sample sizes and obscuring results.

The lack of significant results by type led me to consider each criteria separately and in pairs. This was also done because there was no prior information on which criteria would be most important for distinguishing the lumbosacral junction variation present, and thus the classification system was created without knowing what the proper order of criteria should be. When analyzing the metric data in this manner, there was a random effect on some of the measurements but no consistent effect. This suggests that it is possible that the wrong criteria were chosen. Alternatively, it is also possible that the lumbosacral junction variation, as discussed above, was too great to group into such broad categories. If it is the former, then the correct criteria have not been discovered in any of the literature reviewed for this study. Thus, the criteria I chose, and the order I chose to utilize them, are just as valid as any other; but future research should focus on identifying additional appropriate criteria if such criteria exist.

Finally, I tested whether body height, body weight, or BMI had a significant effect on the presence of LSTV, both by the presence or absence of LSTV and by specific LSTV type. In both analyses it was found that none of these factors had any effect on LSTV prevalence. However, this is what would be expected given the developmental nature of LSTV defects; none of these parameters should have an effect on the prevalence of LSTV if the condition is acquired at birth or shortly thereafter, before height or body size can significantly alter anatomy.

The classification system developed here also divides the available variation into twelve different categories, some with very few or no representatives. The lack of significant results when analyzed by type may be the result of dividing the sample too finely. The advantage of using criteria is that it allows for increased flexibility when grouping specimens, and can be altered to incorporate new criteria as necessary or to create sample sizes that are sufficiently robust to perform the desired analysis. For instance, since symmetry of defect and the number of motion segments were significant in the clinical sample, those criteria would be retained, and since there was no significant difference between fusion and contact, that criteria could be dropped, yielding only six categories instead of twelve. Additionally, in many instances the number of motion segments cannot be determined (i.e. some vertebrae may be missing from a skeleton for various reasons, or a radiograph may not include all lumbar vertebrae), so that criteria may have to be ignored; this can be done without devising a completely new system. Thus, the system developed here has a broad range of applications, both anatomically and clinically.

Clinical Sample

The prevalence of LSTV in the clinical sample (13.5%) was found to be almost twice as common compared to the skeletal sample (7%). This is strong evidence that the presence of a transitional vertebra is a causal factor for people seeking medical attention for low back pain. However, when examined by classification criteria there were no significant differences in the frequency of LSTV types, likely due to very small sample sizes for most of the different LSTV types.

Significant differences were apparent when I compared the frequency of LSTV in the clinical sample to the frequency of LSTV in the skeletal sample, both by LSTV type and by classification criteria (see Table 4-12). It was shown that both the number of motion segments as well as the symmetry of the defect had significant effects on the frequency of clinical patients, demonstrating that these criteria reflect the morphological differences that cause back pain.

The most common number of motion segments for the clinical patients was six (69%), the same number as a normal lumbar spine, while only 49% of individuals with LSTV had six motion segments in the Hamann-Todd collection. This indicates that lumbarization, or extra vertebrae, are more common in the clinical sample than in the general population as represented by the Hamann-Todd collection, giving them both a transitional vertebra and the normal number of motion segments. This is not what was expected from review of the biomechanical literature. Fewer motion segments should increase the wear on the remaining lumbar discs, causing increased disc degeneration and resulting in increased incidence of LBP. Further, when a LSTV is present, the disc just above the transitional vertebra is the most degenerated and the one below is often

protected (MacGibbon and Farfan, 1979; Abe et al., 1997; Vergauwen et al., 1997; Brault et al., 2001). Thus it was hypothesized that fewer motion segments would cause increased disc degeneration and an increase in the prevalence of types with fewer motion segments in the clinical sample because the lumbar region would be biomechanically compromised resulting in greater LBP. A possible confounding factor may be the procedure for assessing motion segments. For the skeletal sample, it was possible to determine the facet orientation, counting motion segments from the point where lumbar facets start. However, it is very difficult to determine facet orientation in radiographs with a high degree of accuracy, and thus the last thoracic segment was the segment with the last set of true ribs. This may have skewed the actual number of motion segments in some patients, although the last thoracic vertebra commonly has both articular facet transition and the last set of true ribs.

For these reasons, it is important for physicians to obtain radiographs that show the last thoracic vertebra as well all lumbar vertebrae in order to assess the total number of motion segments and evaluate the best course of treatment. Most patients have the normal number of motion segments, and are not at a biomechanical loss if the transitional vertebra is fused to the sacrum. However, those that do not have six motion segments may be at increased risk of disc degeneration if fusion is performed on the affected segments due to the biomechanical disadvantage they acquire with fewer motion segments.

Based on the clinical observations by Dr. Jeffrey Parker, it was hypothesized that unilateral defect types would be more prevalent in the clinical sample. In addition to being more prevalent, these types could cause increased intensity of pain due to uneven

weight-bearing and the effects of the additional mass of the transitional vertebrae on the sacro-iliac joint. The presence of unilateral types was nearly twice as common as bilateral types (41 vs. 21) in the clinical sample, as expected. However, the intensity of pain was no greater in unilateral types than in bilateral types. This indicates that there is some effect that unilateral types have on the biomechanics of the lumbar spine that cause those affected to seek treatment at a greater frequency, but it does not necessarily cause more intense pain. One possible reason is that unilateral types cause uneven weight-bearing, equivalent to having one leg slightly longer than the other or walking with only one shoe on. This can commonly cause muscle aches, which can be painful enough to seek medical attention but not cause severe pain. It is also hypothesized, based on clinical observation, that the additional mass of the transverse processes interfere with the sacroiliac joint in some patients, causing the ilium to separate from the sacrum, and that this condition causes extreme pain (Ronan, personal communication). However, the prevalence of this condition may not vary with symmetry, thus obscuring the evidence in the current study. Another possible explanation is that unilateral types have an effect on the intervertebral disc or spinal nerves, causing discs to wear unevenly or to compress on only one side, also possibly compressing the spinal nerve on that side, causing pain.

To further elucidate the specific factors that may affect LBP in the clinical sample, I looked at the intensity of pain in some specific contexts. When evaluated by having or not having a transitional vertebra, there was no significant difference in pain intensity. Reasons for this result may be very simple or quite complex. Simply, the presence of LSTV may not cause more intense pain than other reasons for having back pain. More complex reasons include psychosomatic responses, pain tolerances, and

becoming accustomed to the pain due to having the defect from birth or shortly after. Also, there was no significant difference in the intensity of pain reported by either sex, thus eliminating sexual differences as possible causal factors. While all of these reasons are possible, the issue cannot be addressed with the available data.

Hopefully this will lead to more finely tuned hypotheses for future research. In order to understand the factors involved in pain sensation, as it relates to back pain, it may be important to have patients report on common pain experiences to get a baseline for intensity comparisons. It would also prove useful to ask patients about their past to understand the psychological factors that may be involved in their pain response as well as their pain tolerance. Further, asking patients to differentiate between muscle pain and nerve pain would help to understand the source of the pain as well as to determine how long the patient has had the condition causing the pain.

Finally, I tested whether body height, body weight, or BMI had an effect on the prevalence of specific LSTV types and on the intensity of pain. I hypothesized that the biomechanical effects of increased body height and/or weight may interact with certain LSTV types to cause increased pain intensity, thus increasing the frequencies of those types in the clinical sample. However, none of these factors had a significant effect on either the prevalence of specific LSTV types or the intensity of pain reported. While it does not seem unusual for height to not have an effect on pain intensity, I would have expected weight and/or BMI to affect pain intensity, especially if the pain were weight-bearing related. This may indicate that weight does not have an effect on the intensity of back pain or that the sample was too small to truly assess this parameter, as there were

only 48 patients with both height and weight recorded, of which 12 were classified as normal, leaving only 36 patients to be separated into 12 possible categories.

It is easy to see why there is so much controversy in the literature over whether or not LSTV cause LBP. The idiosyncratic nature of the defect, coupled with classification systems that have been inadequate for grouping the variation present make investigating this phenomena very difficult. Add in all the issues with pain (subjective reporting, tolerance, psychosomatic effects, etc.) and reaching definite conclusions becomes that much more difficult.

Schmorl (1971) reports the classification systems devised by others, including Blumensaat and Clasing (1932), and reinforces some of the critiques I have made here. Many systems have little clinical basis, or little developmental or anatomical basis, and are thus only useful in very specific situations. Further, with numerous systems based on different criteria it is very confusing, and the conclusions can be contradicting. It is my conclusion that the terms 'lumbarization' and 'sacralization' must be dropped as categorization criteria for the reasons previously stated. Also, discrete groups may or may not be appropriate to the study, and thus, a system based on appropriate criteria will yield more fitting results.

Castellvi et al. (1984) propose a system primarily for clinical application, namely with respect to disc herniations. Their system reflects radiological findings but neglects some important biomechanical considerations, namely the number of lumbar motion segments. They found that 31 of 200 patients (15.5%) in their sample of patients with positive myelograms "present true transitional characteristics." They conclude that there is no increased incidence of disc herniation in Types I, III, and IV (dysplastic transverse

processes, complete lumbarization/sacralization, and mixed respectively). Type II (incomplete lumbarization/sacralization) however, did present increased incidence of disc herniation at the proximal disc as well as incidence of herniation at the level of the transitional vertebra. In my investigation, I found no significant difference between fused transitional vertebrae (their Type III) and LSTV that exhibited contact (their Type II). Further, they found little difference between the incidence of unilateral and bilateral LSTV, or any correlation between symmetry and disc herniation. I suspect the difference between my findings and their findings relates to the variety of examined causes of back pain. While Castellvi et al. (1984) just looked at incidence of herniation, I examined LBP in general. They also did not look at the number of motion segments, possibly causing further differences between our respective results.

Using the system created by Castellvi et al. (1984), Dai (1999) found that both the prevalence and type of LSTV were highly significant. In this study, 35.1% of patients had a transitional vertebra (compared to 15.8% of the control group). In agreement with Castellvi et al. (1984), Dai (1999) found that Type II was significantly higher in patients with LBP than in the control group. Such a high rate of LSTV, both in patients and the control group, may reflect population differences or sampling bias. The control group was composed of patients referred to the hospital for other conditions, yet was assumed to represent the general population. Dai (1999) found no significant difference between sexes, which is in agreement with my findings. Further, the incidence of unilateral types was more prevalent, though this parameter was not analyzed statistically in Dai's (1999) study. A major discrepancy between my clinical findings and those of both Castellvi et al. (1984) and Dai (1999) is that they both found a much higher prevalence of patients with

contact than with fusion, while I found approximately equal prevalence between the two conditions. This may be the result of sample biases, definition of what constitutes fusion or contact, or the difficulty in assessing this parameter radiographically.

A third study was done by Luoma et al. (2004) and found no significant correlation between LSTV and LBP. The methodology of this study differs such that comparison of results is difficult, further underscoring the need for a consistent system. While a higher prevalence of LSTV was found, it was determined that it was not associated with any type of LBP, as assessed through analysis of various parameters of disc degeneration. Further, symmetry had no affect on the presence of LBP. Differences between the classification systems are likely the cause of much of the disagreement; small sample size may also contribute. As with the previously discussed classification systems, Luoma et al. (2004) did not consider the number of motion segments; nor did they differentiate between fusion and contact of the transitional vertebra and the sacrum.

While this study has focused on the modern lumbosacral variation present, there are some bigger anthropological implications. As reported in Schmorl (1971), and discussed earlier, the prevalence of LSTV, and of specific types, may vary by population, thus making the identification of defects important for bioarchaeological studies, and possibly for forensic identification. The developmental nature of transitional vertebrae is still something of a puzzle, with the exact cause unknown. Once we discover the cause(s) it will then be possible to assess the variation present by developmental origin and what causes deviations from normal. This could also have implications for all of axial skeleton development, and the defects present in the entire vertebral column.

Conclusion

The controversy in the literature centers around the issue of whether or not lumbosacral transitional vertebrae cause low back pain. This confusion may result from conflicting classifications and descriptions of LSTV. First, an understanding of the variation present must be achieved, complete with a standard, convenient way to categorize that variation. Second, the possible connections among the categories and both frequencies and intensities of low back pain must be investigated as thoroughly as possible.

This study provides the first part of the answer, and gives a good start to answering the second part. After conducting a thorough survey of over 2800 specimens in the Hamann-Todd collection, and documenting 16 different vertebral dimensions, I have collected the data necessary to describe the variation present and to devise a classification system to conveniently group the types for systematic comparisons. By using three simple criteria to create the classification system, I have created a simple yet dynamic system that can be applied to a variety of areas including bioarchaeology, forensic anthropology, and paleoanthropology. Further, by using criteria instead of set types, it is possible to investigate LSTV by criteria, adding or subtracting and grouping as necessary or appropriate to the goals of the study.

With such a small clinical sample it was difficult to tease out definite answers to the second part of the controversy. However, some of the results are quite informative and provide a jumping-off point for future research. This study demonstrates that LSTV, at least some types, do cause pain that requires medical intervention. Not only were

LSTV almost twice as common in the clinical sample than in the reference population, unilateral types and types with the normal number of motion segments were present at a much higher frequency, although the intensity of the pain was not significantly different. This suggests that unilateral defects and the number of motion segments result in biomechanical complications that lead to LBP, prompting people to seek medical attention.

Future studies need to focus on identifying other parameters that are relevant to distinguishing lumbosacral variation, as well as corroborating the results obtained here with data from other samples. Clinically, studies need to continue to analyze large samples to expose any correlations between LSTV variants and LBP, as well as to understand the precise mechanisms that lead to back pain, and how transitional vertebra affect those mechanisms. With these goals to guide further study, I am confident that the controversy can be resolved.

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APPENDIX A

Descriptive Statistics

TABLE A-1. Descriptive Statistics for HTH abnormal males.

Var[1]	n	Mean	Std Dev	Min	Max
RBH	124	26.95	2.61	20.62	35.27
LBH	122	27.01	2.39	18.99	31.69
ABH	139	28.83	2.05	23.45	33.92
PBH	128	23.94	2.03	18.59	28.47
BW	162	54.05	4.67	42.61	68.78
BL	156	35.21	3.35	26.97	44.47
CW	162	28.07	3.53	19.34	41.14
CL	158	16.40	2.49	10.50	25.10
RPW	162	10.77	2.73	4.15	19.40
RPL	162	9.51	1.48	5.53	14.10
LPW	162	11.63	2.63	6.48	18.76
LPL	162	10.07	1.67	4.61	14.04
PWA	162	1.74	1.31	0	6.48
PLA	162	1.02	0.85	0.01	4.37
BHA	116	2.05	1.81	0.05	9.99
CR	158	1.74	0.27	1.15	2.56

[1]See table 3.3 for measurement descriptions.

TABLE A-2. Descriptive Statistics for HTH normal males.

Var[1]	n	Mean	Std Dev	Min	Max
RBH	50	26.65	1.96	22.83	30.84
LBH	50	26.18	1.74	21.81	29.81
ABH	50	28.79	1.78	24.79	34.02
PBH	50	23.60	1.92	18.57	27.27
BW	50	52.90	3.74	45.30	61.18
BL	50	35.19	2.73	30.10	41.40
CW	50	26.03	2.97	19.98	32.04
CL	50	16.87	2.67	11.62	22.39
RPW	50	11.75	2.33	6.19	17.00
RPL	50	10.41	1.35	7.40	13.04
LPW	50	12.84	2.18	8.19	18.09
LPL	50	10.64	1.44	7.44	13.63
PWA	50	1.86	1.32	0.13	5.13
PLA	50	0.73	0.62	0.01	2.98
BHA	50	1.31	1.10	0.04	4.15
CR	50	1.57	0.24	1.18	2.13

[1]See table 3.3 for measurement descriptions.

TABLE A-3. Descriptive Statistics for HTH abnormal females.

Var[1]	n	Mean	Std Dev	Min	Max
RBH	28	25.96	2.57	18.68	30.82
LBH	25	27.18	1.75	21.58	29.66
ABH	33	27.51	1.74	23.58	31.07
PBH	28	23.40	2.15	19.70	27.90
BW	38	48.26	3.87	41.80	56.83
BL	38	30.89	3.09	26.68	43.36
CW	38	28.02	2.83	18.68	34.95
CL	38	15.54	2.43	11.03	23.29
RPW	38	8.13	2.14	4.40	13.79
RPL	38	10.09	1.74	6.49	13.90
LPW	38	9.34	2.40	5.36	14.91
LPL	38	10.49	1.52	8.02	14.44
PWA	38	1.73	1.51	0.08	8.32
PLA	38	0.75	0.64	0.01	2.30
BHA	25	1.90	1.75	0.08	7.18
CR	38	1.84	0.32	1.15	2.57

[1]See table 3.3 for measurement descriptions.

TABLE A-4. Descriptive Statistics for HTH normal females.

Var[1]	n	Mean	Std Dev	Min	Max
RBH	50	25.68	1.82	19.23	28.87
LBH	50	25.33	2.03	19.04	29.54
ABH	50	27.47	1.77	20.39	30.85
PBH	50	22.73	2.04	16.32	26.87
BW	50	47.63	3.33	40.48	53.06
BL	50	31.47	1.86	27.77	36.10
CW	50	24.79	2.28	18.97	30.48
CL	50	15.86	2.56	10.30	20.88
RPW	50	9.84	1.88	5.36	14.71
RPL	50	10.80	1.27	7.19	13.45
LPW	50	10.92	1.83	6.30	13.99
LPL	50	10.85	1.24	7.94	14.30
PWA	50	1.68	1.24	0.01	5.01
PLA	50	0.65	0.55	0	2.57
BHA	50	1.19	0.92	0.03	4.83
CR	50	1.60	0.27	1.18	2.39

[1]See table 3.3 for measurement descriptions.