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Thoracic Vertebral Count and Thoracolumbar Transition in *Australopithecus afarensis*

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Abstract:

The evolution of the human pattern of axial segmentation has been the focus of considerable discussion in paleoanthropology. While several complete lumbar vertebral columns are known for early hominins, to date no complete cervical or thoracic series has been recovered. Several partial skeletons have revealed that the thoracolumbar transition in early hominins differed from that of most extant apes and humans. *Australopithecus africanus*, *A. sediba*, and *Homo erectus* all had zygapophyseal facets that shift from thoracic-like to lumbar-like at the penultimate rib-bearing level, rather than the ultimate rib-bearing level as in most humans and extant African apes. What has not been clear is whether *Australopithecus* had twelve thoracic vertebrae as in most humans, or thirteen as in most African apes, and where the position of the thoracolumbar transitional element was. The discovery, preparation, and synchrotron scanning of the *Australopithecus afarensis* partial skeleton DIK-1-1 (1) from Dikika, Ethiopia, provides the first complete hominin cervical and thoracic vertebral column prior to 60,000 years ago (2). DIK-1-1 is the first *Australopithecus* skeleton to preserve all seven cervical vertebrae and provides the first evidence for twelve thoracic vertebrae with a transition in facet morphology at the eleventh thoracic level. The location of this transition, one segment cranial to the ultimate rib-bearing vertebra, also occurs in all other early hominins (3-7), and is higher than in most humans or extant apes (8-10). At 3.3 million years ago, the DIK 1-1 skeleton is the earliest example of this distinctive and unusual pattern of axial segmentation.

Significance Statement:

The discovery of a 3.3 million-year-old partial skeleton of *Australopithecus afarensis* from Dikika, Ethiopia, is the first to preserve all seven cervical (neck) vertebrae and provides the first and only evidence for the presence of twelve thoracic (rib-bearing) vertebrae in hominins prior to 60,000 years ago. This skeleton has seven cervical and only twelve thoracic vertebrae like humans, rather than thirteen like African apes. However, the anatomical transition from thoracic to lumbar (lower back) vertebral form occurs at the eleventh thoracic segment. This distinctive pattern of vertebral segmentation, rare in modern apes and humans, is also seen in the three other early hominins for which this area is known, with the Dikika skeleton providing the earliest and most complete example.

\body

Introduction:

The modal number of thoracic and lumbar vertebrae has been a key factor in interpretations of the evolution of locomotor adaptations in hominoids (3, 4, 6-15). A larger number of thoracic and smaller number of lumbar vertebrae increases dorsostability of the trunk (8, 16-19) and is found in various combinations in extant apes (10, 11, 13, 15, 17, 19). Like humans, early hominins had five non-rib-bearing lumbar vertebrae, as demonstrated in three species: *Australopithecus africanus*, *A. sediba* and *Homo erectus* (3, 4, 6, 7, 10, 14, 20). However, a lack of a complete thoracic column for any early hominin has made it difficult to determine whether early hominins had only twelve thoracic vertebrae like humans, or thirteen as in extant African apes, or whether variation in segmentation patterns involved addition or deletion of segments or a shift in identity among segments (10, 11, 13, 15).

In addition to uncertainty in thoracic count, there is also variation in the configuration of the thoracolumbar transition, in which early hominins differ from most extant hominids (4, 7, 10, 20). In most extant hominids, the caudal-most rib-bearing vertebra usually has flat cranial zygapophyseal facets facing anteriorly or very slightly anteromedially, as is typical of thoracic vertebrae. In contrast, the caudal zygapophyseal facets of this vertebra are transversely convex and are generally oriented posteromedially, averaging about 30-45° to a sagittal plane, like those of upper lumbar vertebrae (21-23). This vertebra, which exhibits the transition from thoracic-like to lumbar-like zygapophyses, is referred to as the transitional or diaphragmatic vertebra. The transition in facet orientation from thoracic to lumbar patterns occurs gradually over 2-3 segments in 43-93% of human individuals (depending on how facet morphology is quantified), but the transition is usually complete no higher than the last rib-bearing thoracic vertebra (21-30).

When an abrupt transition occurs within only a single vertebra, it typically occurs at the last rib-bearing element, but can be found one segment higher (eleventh thoracic, or T11) in up to approximately 10-23% of individuals (10, 23, 28, 29). Thus, when a transition is abrupt, most modern humans and extant great apes have a transitional vertebra at the last rib-bearing vertebra. Due to differences in the numbers of non-rib-bearing lumbar vertebrae among apes and humans, this transition usually occurs at the sixth presacral level (T12) in modern humans versus the fourth or fifth presacral levels (T13) in extant great apes (8-10).

All four early hominin fossils that preserve the transitional region exhibit a different pattern compared to the most frequent pattern seen in extant hominoids (4, 7, 10). The *Australopithecus africanus* skeleton Sts 14 has an abrupt transitional element situated at the seventh—not sixth—presacral level (Sts 14g), even though the sixth presacral element has a distinct rib on the right side (4, 6). The *A. africanus* skeleton StW 431 also has an abrupt transitional element at the seventh presacral level, and probably had only five non-rib-bearing lumbar vertebrae, based on a tiny raised area adjacent to where a costal facet would be on the sixth presacral vertebra (4, 5). The *Australopithecus sediba* specimen MH2 preserves the penultimate and ultimate rib-bearing vertebrae, with the penultimate vertebra being an abrupt transitional element, as in the *A. africanus* skeletons (7). Similar to what is seen in these earlier *Australopithecus* specimens, the 1.6-million-year-old *Homo erectus* skeleton KNM-WT 15000 also possesses five non-rib-bearing lumbar elements and a transitional vertebra situated at the seventh presacral level (3). The likely presence of the transition occurring at the penultimate rib-bearing level has been suggested for the *Australopithecus afarensis* specimen A.L. 288-1 as well (20). In all of these specimens, therefore, the transitional element is at the second-to-last rib

bearing vertebra, not the last rib-bearing one, contrasting with the most frequent condition seen in extant hominoids.

Because an abrupt transitional element at the penultimate rib-bearing vertebra is only found in 1–23% of modern humans (10, 23, 27), the probability of finding all five of these specimens (Sts 14, StW 431, MH 2, KNM-WT 15000 and DIK 1-1) in a modern human population with a similar frequency is less than 0.0007%, and if the same indeed characterizes A.L. 288-1, the probability drops to less than 0.0001%.

Although the early hominin transitional element has been referred to as the eleventh thoracic vertebra (T11) in the literature (4, 10, 20, 31), this claim was speculative because, at the time, no complete thoracic vertebral column had been recovered for any *Australopithecus* specimen. With the discovery of the juvenile *Australopithecus afarensis* skeleton, DIK-1-1 at Dikika, Ethiopia (1) (Fig. 1), the required evidence has now become available.

Results:

The original description of DIK-1-1 reports the presence of two lumbar vertebrae (1), but subsequent cleaning and preparation as well as evidence from microtomographic images revealed that these were thoracic elements, and no lumbar or sacral elements are preserved. Some of the unfused vertebral bodies were not in anatomical position when discovered, but have now been rearticulated with their corresponding neural arches. Each thoracic vertebra preserves visible articular facets for ribs and portions of all costal elements are represented. Importantly, all of the neural arches are preserved in sequence and in articulation, making identification of the various vertebrae and our interpretation of their morphology and relationship straightforward.

The morphology of the eleventh and twelfth thoracic vertebrae (T11 and T12) of DIK-1-1 is particularly informative. Both preserve single costal facets on both the right and left side, typical of the caudalmost two thoracic elements in all extant hominoids (Fig. 1). The zygapophyseal facets are well preserved. The T11 of DIK-1-1 has flat cranial zygapophyseal facets that lie in a coronal plane ($\sim 90^\circ$ to a sagittal plane) cranially, but has transversely convex and lumbar-like caudal facets that face 30° ventrolaterally relative to a sagittal plane (Fig. 2). This configuration clearly identifies T11 as the transitional element, and documents an abrupt transition in this individual.

Both cranial and caudal facets on T12 are lumbar-like (cranial facets oriented 30° and caudal facets oriented 25° to a sagittal plane). Thus, the transition pattern of zygapophyseal facet morphology found in the T11 and T12 of DIK-1-1 resembles the transition pattern observed in four other early hominins, but not that of a majority of modern humans.

Discussion:

The DIK 1-1 skeleton demonstrates that the distinctive vertebral segmentation pattern seen in four other early hominins, with an abrupt facet transition at the penultimate rib-bearing vertebra, was present at least by 3.3 million years ago in *Australopithecus afarensis*. This specimen also preserves twelve thoracic vertebrae. Because the presence of a transitional vertebra cranial to the penultimate or second-to-last rib-bearing element is very rare among extant hominoids (*Homo sapiens* $<0.1\%$; *Pan troglodytes* 0.4% ; *Gorilla gorilla* 1.5% ; *Gorilla beringei* 1.5% ; *Symphalagus syndactyles* 2.8% ; unobserved in *Pan pansicus*, *Pongo pygmaeus* and *Hylobates lar* [10]) (8-10), it is highly improbable that other *A. afarensis* would have had thirteen thoracic vertebrae. We therefore can conclude confidently that *A. afarensis* had twelve

thoracic vertebrae, as is modal for humans and unlike the pattern in all but a few African apes (10, 11, 13, 15, 16, 18).

The A.L. 288-1 partial skeleton (*Australopithecus afarensis* from Ethiopia; [31]) preserves some lumbar and thoracic vertebrae. Specimen A.L. 288-1ai has been referred to as a last thoracic vertebra based on the transitional morphology of its cranial and caudal facets, with the latter being elongated, convex, and facing anterolaterally, and called T12 under the assumption that *A. afarensis* had 12 thoracic elements (20). However, based on the transition pattern typical for all other early hominins, including DIK-1-1, A.L. 288-1ai is likely a penultimate thoracic (see also 31). If so, the more cranially positioned thoracic vertebrae may also represent higher levels than originally reported

Comparison between the DIK-1-1 T11 and A.L. 288-1ai shows that the curvature and oblique orientation of the caudal zygapophyseal facets are even more prominent in A.L. 288-1, probably reflecting ontogenetic differences in morphology. Developmental changes in lumbar zygapophyseal facet orientation and curvature have been reported for humans (32, 33). Lumbar zygapophyseal joints lie in the coronal plane at birth, similar to those of thoracic vertebrae, and subsequently rotate into the sagittal plane and become more curved during growth, reaching adult morphology by late adolescence or early adulthood (34). This suggests that the rotation into the sagittal plane and curvature of the T11 caudal facets of DIK-1-1 and both sets of T12 facets would likely have increased during development.

Because DIK-1-1 has no preserved lumbar vertebrae, its lumbar count cannot be assessed. However, it is reasonable to hypothesize that DIK-1-1 would have had five lumbar segments, as do all sufficiently preserved (n=3) early hominins. DIK-1-1 is unlikely to have had more than five non-rib bearing lumbar vertebrae because it has the transitional element at the second-to-last

rib-bearing segment. No extant African ape has a transitional element cranial to the seventh presacral vertebra and this morphology is extremely rare in humans (<0.1% [n=1159, 10]). It is unlikely, though less certain, that DIK-1-1 had fewer than five non-rib-bearing lumbar segments. Given that a count of only 16 thoracolumbar vertebrae is rare in modern humans (4.9%, [n=1159; 10]) and unknown in other early fossil hominins, this scenario is much less likely. Seventeen thoracolumbar vertebrae also is the most common pattern in most African apes, although a count of 16 or less is slightly more common in apes than in humans (*Pan paniscus* 6.3% (n=48), *P. troglodytes* 24.3% (n=239), *Gorilla gorilla gorilla* 29.6% (n=86), although *G. g. beringei* is 95.5% (n=66) (10). It is therefore possible to infer that early hominins modally had twelve thoracic and five non-rib-bearing lumbar vertebrae as their modal vertebral counts, with a transitional element at T11. This evidence supports the early hominin modal vertebral formula proposed by Pilbeam (11) and Williams and colleagues (10). The shifting morphology and identity of the thoracolumbar transitional vertebrae appears to have been a change involving a shift in segment identity, or identity of parts of the segment (i.e., costal articulations versus zygapophyseal morphology), rather than a meristic shift involving addition or deletion of elements (11, 13).

The location of the thoracolumbar transitional element may affect function of the vertebral column. Medially oriented lumbar-like zygapophyseal facets restrict rotation of the vertebral motion segments, as the center of rotation is located within the intervertebral disc (29, 34). Having a more cranial transition to this type of facet would in principle result in more limited rotation of the lumbar spine in early hominins, perhaps by 2–3°. In DIK-1-1, the mammillary processes of T12 extend dorsally to flank the T11-T12 zygapophyseal joint, forming a “mortice” style joint like that found in up to 47% of modern humans (25). Such a

configuration would have further limited rotational capacity (36-39), at least in this individual (28). However, the range for spinal flexion and extension may have been equivalent to that of modern humans (34-35) even given the deep lumbar capture between the iliac blades found in *Australopithecus* (41). A higher thoracolumbar transition may have permitted the ability to achieve a lumbar lordosis in *A. afarensis*—a key component of habitual upright bipedal locomotion in hominins (41, 42). Shifting the transition back to the ultimate rib-bearing element in later *Homo*, perhaps also indicating a freed lower lumbar region with reduced lumbar, may have increased the capacity for lumbar spinal rotation between the torso and pelvis (8, 13, 40-44) during modern human walking and running. This movement, in conjunction with other joint rotations (e.g., shoulders and knees), acts to balance and cancel angular moments around the spinal column during bipedal locomotion (45-48). The caudal shift in the thoracolumbar transition may be a component of a suite of derived features that has been argued to represent an adaptation for more efficient long-distance walking and endurance running in later *Homo*, and if so, this particular component would have occurred only after 1.6 Ma with KNM-WT 15000 (48,49).

Regardless of the functional significance of the modern human pattern, the DIK-1-1 skeleton provides the first evidence that *Australopithecus afarensis* had twelve thoracic vertebrae with a thoracolumbar transitional element at T11, and that the thoracolumbar transitional morphology, present in four other known early hominins, evolved by at least 3.3 million years ago. This distinctive early hominin vertebral configuration may be a key to building and testing scenarios for the evolution of bipedality and body form in early hominins.

Materials and Methods:

The upper part of the DIK-1-1 skeleton, which includes the skull and most of the torso, was found largely articulated and encased in a highly compact sandstone block, making preparation difficult and time-consuming. Significant mechanical preparation has been done at the National Museum of Ethiopia by ZA and Christopher Kiarie for over 13 years since its discovery and continues. Many of the elements, particularly the vertebrae, are now exposed (Fig. 1). In addition, the fossil was scanned using propagation phase contrast synchrotron microtomography on beamline ID17 at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, using a 100 keV monochromatic beam, with a voxel size of 45 micrometers and 5 meters of propagation, providing us with the opportunity to virtually examine the vertebrae. These tomographic images were segmented by TKN to isolate individual vertebral elements and their morphology. The DIK 1-1 fossil is housed at the National Museum of Ethiopia, requests to study it should be made to the museum and to ZA (alemseged@uchicago.edu). Scan data are archived at the University of Chicago and the ESRF and requests for these data should also be made to ZA.

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Figure Legends:

Figure 1: a) Photograph of the DIK 1-1 vertebrae in block with skull, pectoral girdle and rib fragments before complete preparation. Vertebral column highlighted. B) Entire articulated cervical and thoracic column of DIK 1-1, with vertebral levels indicated on each bone, demonstrating the presence of seven cervical and twelve thoracic (rib-bearing) vertebrae. Most of these vertebrae cannot be disarticulated mechanically. c) The three caudalmost preserved vertebrae, T10, T11 and T12, with rib facets indicated on T11 and T12.

Figure 2: *In silico* digital reconstructions of the eleventh and twelfth thoracic vertebrae of DIK 1-1 and a modern *Homo sapiens* juvenile (age estimated at roughly 6-8 years of age), kindly provided by Dr. Libby Cowgill of the University of Missouri Department of Anthropology. DIK 1-1 reconstruction is based on synchrotron data; *H. sapiens* specimen from surface scans taken with a NextEngine desktop laser scanner. The DIK 1-1 T11 has flat, paracoronally-oriented cranial zygapophyseal facets, but obliquely oriented, transversely convex caudal zygapophyseal facets, and so is the transitional vertebra. On the DIK 1-1 T12, both cranial and caudal zygapophyseal facets are obliquely oriented and transversely convex. This contrasts with the typical human condition, shown here, in which T11 has flat, paracoronally-oriented zygapophyseal facets cranially and caudally, but shows the transitional morphology on T12.