Supporting Online Material for

# The Pelvis and Femur of *Ardipithecus ramidus*: The Emergence of Upright Walking

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**This PDF file includes:**

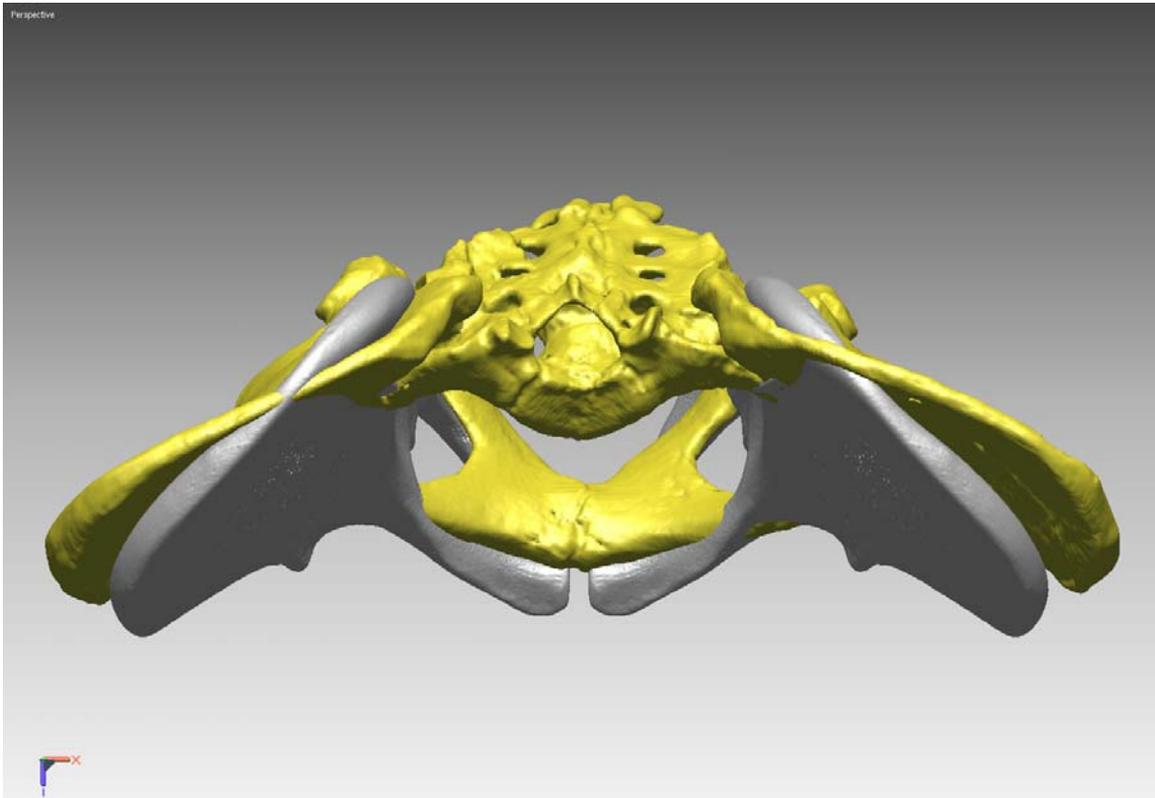Figs. S1 to S11
Table S1
References

**Figure S1. Superior View of Superimposed Reconstructed os Coxa of *ARA-VP-6/500* and Restored Pelvis of *A.L.288-1*.** *A.L.288-1* has been enlarged to 115% of its original size and the two specimens were then aligned by their acetabulae (the reconstructed interacetabular distance of *ARA-VP-6/500* is therefore approximately 115% that of *A.L.288-1*). The ilium of *ARA-VP-6/500* is less flared than is that of *A.L.288-1* (see also Fig. S3), and its ischiopubic region more massive and anteriorly projecting. Because of its partial arboreal habitus, it is likely that lordosis in *Au. ramidus* was situationally dependent, whereas in *Au. afarensis* it had likely become a permanent ontogenetically developed feature as in *H. sapiens*. This is suggested by the marked reduction in iliac height, which permitted the anterior gluteals to contract isometrically at a near a constant resting length, a capacity indicated by the stereotypic trabecular patterns of the proximal femora of the species (*1*). In *Ar. ramidus*, these muscles would still have played a significant role in arboreal locomotion, and would therefore have required more variation in their contractile ranges. The massive ischial region in *Ar. ramidus* indicates that the fundamental shift in hamstring/quadriceps function for bipedality had not yet occurred, whereas the region's marked reduction and angled tuberosity in *Au. afarensis* suggest that this shift had occurred in this species.
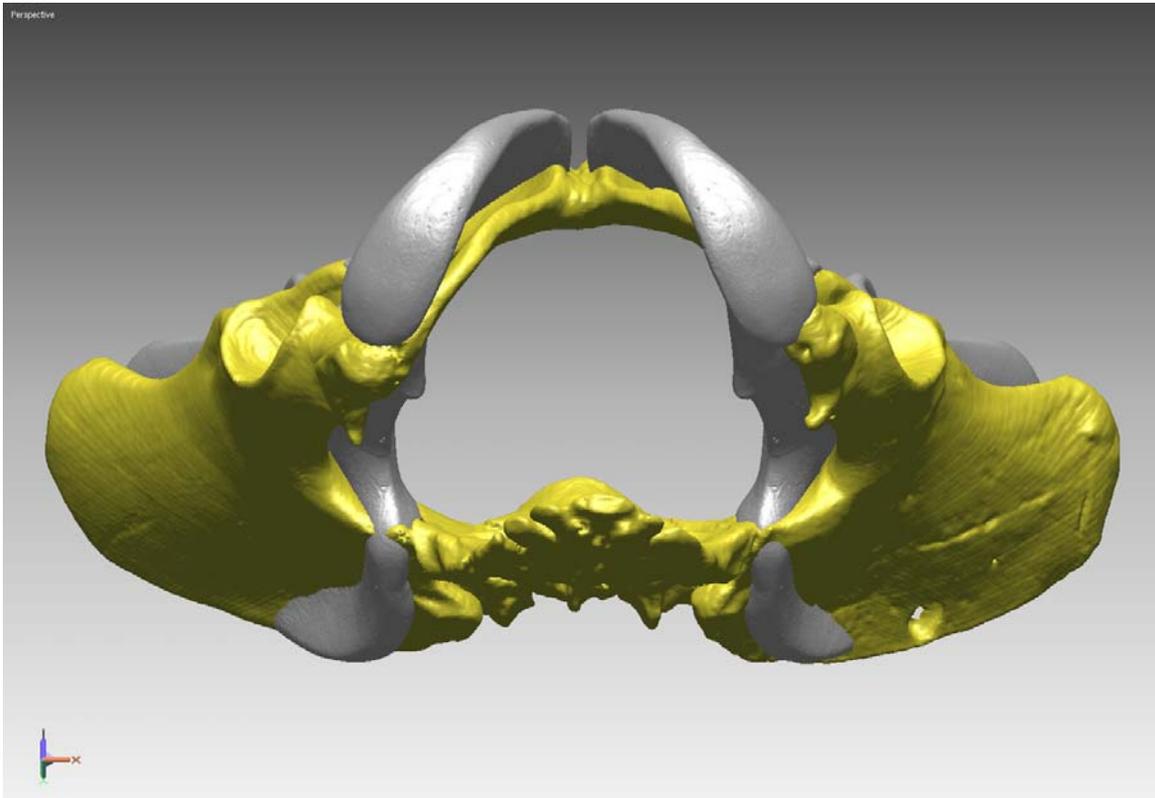
**Figure S2. Inferior View of Superimposed Reconstructed os Coxa of *ARA-VP-6/500* and Restored Pelvis of *A.L.288-1*.** For method of superimposition see Fig. S1. The massive, African ape-like ischial region of *ARA-VP-6/500* is obvious. The shortening and angulation of the tuberosity in *Au. afarensis* probably reflect the unique role of the hamstrings in hominid bipedal gait (i.e., limb deceleration)(*2*), and possibly that of the *m. gluteus maximus* as well, since the latter passes over a bursa on the inferior part of the tuberosity. A reticulated surface of the ischial tuberosity, like that in *Pan*, was presumably present in *Ar. ramidus*, but no attempt has been made to duplicate it in this reconstruction.
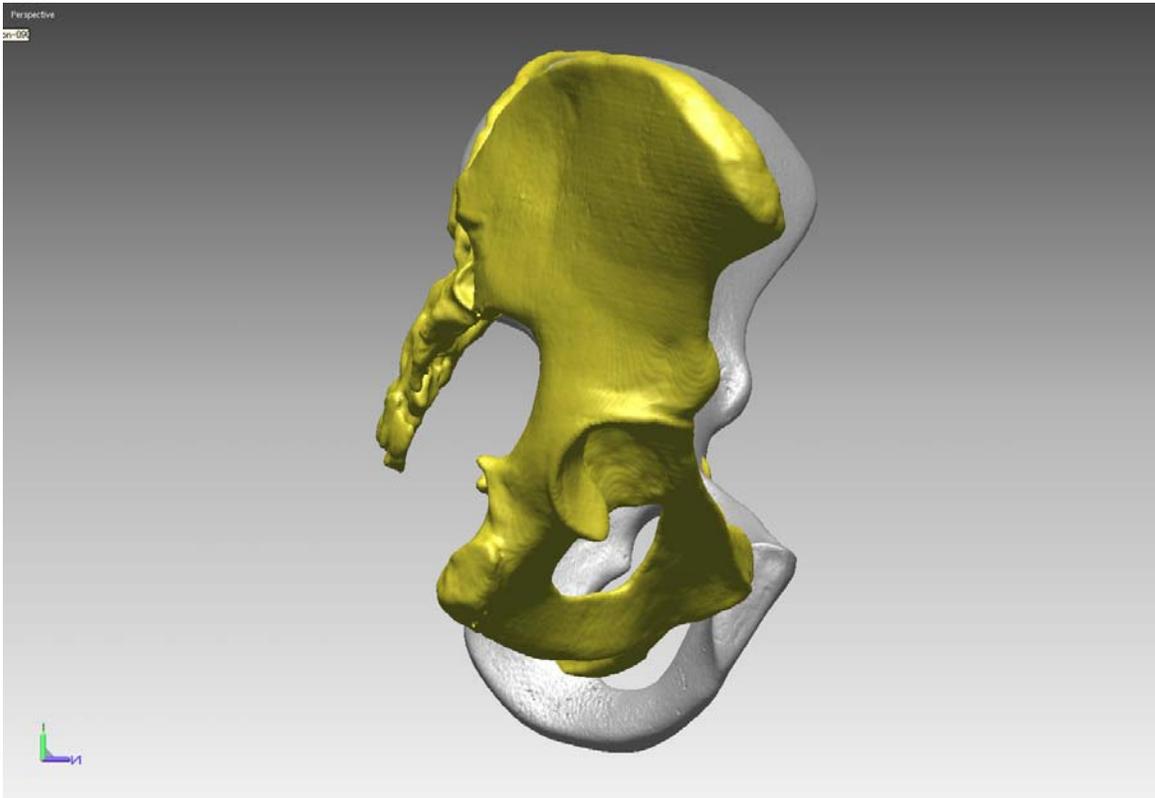
**Figure S3. Lateral View of Superimposed Restored Pelvis of *A.L.288-1* upon the Reconstructed os Coxa of *ARA-VP-6/500*.** For methods of alignment see Fig. S1.The massive, African ape-like ischial region is again obvious. The functional role of the gluteus minimus and medius for abduction in stance phase appears to be largely similar in the two species, although the retained arboreal behavior of *Ar. ramidus* suggests that the lordosis necessary to locate its ASIS in a position similar to that seen in *A.L.288-1* was probably situationally dependent. The wholesale reduction of the ischial region in *Au. afarensis*, along with changes in its proximal femur, including a more posterior placement of the *m. gluteus maximus* insertion (see text), confirm virtually complete transformation of the hip joint for habitual terrestrial bipedality in *Au. afarensis*, and a complete abandonment of arboreal locomotion.
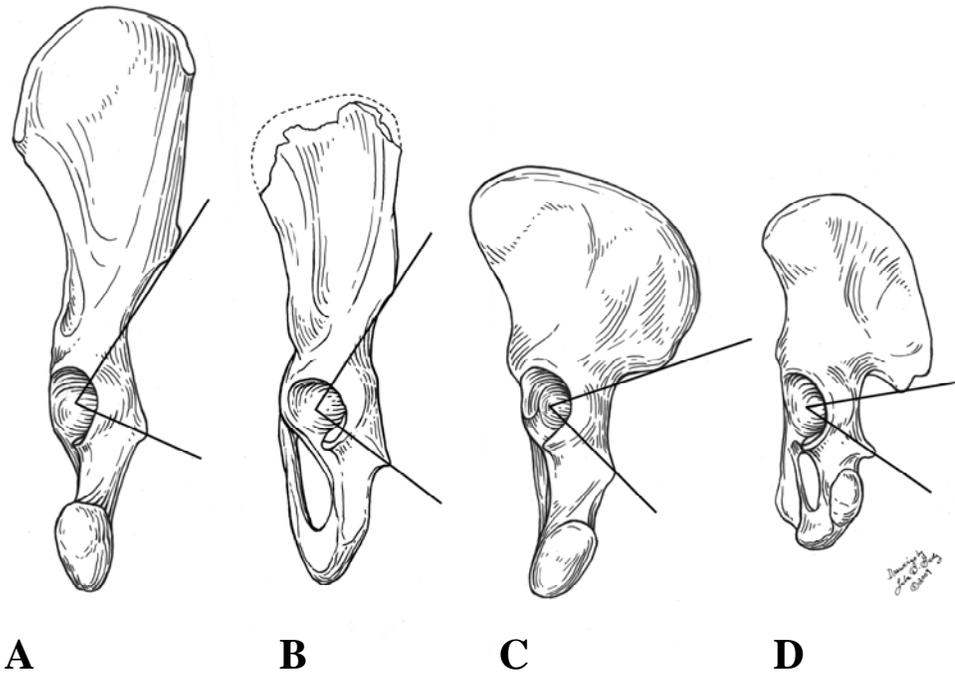
**A**     **B**     **C**     **D**

**Figure S4. Craniocaudal Pelvic Height and Pelvic Geometry in Hominoids**.
Posterolateral views of the os coxae of hominoids: **A)** *Pan*; **B)** *Proconsul (KNM-MW 13142 D)*; **C)** *Ar. ramidus*; **D)** *Au. afarensis (A.L.288-1)*. Views have been arranged in approximately the same acetabular plane. Two chords are indicated on each specimen: one from the acetabular center to the most caudal point on the auricular surface (upper chord), and the other from the acetabular center to the ischial spine (lower chord). Angles shown here are for reference only; actual angles require calculation of a third chord directly on each specimen (see legend of Fig. 3C). Note that the angle between the two chords is most obtuse in *Proconsul* and declines in the other taxa but for different reasons. In *Pan* it declines because of the posteriorly directed elongation of the iliac isthmus (see text); in hominids it declines because of the posterior extension of the iliac blade and craniocaudal *shortening* of the iliac isthmus. Note the dramatically more robust ischial mass in *Ar. ramidus* compared to *Au. afarensis* and the introduction of a distinct separation of the hamstring origins from those of the adductor magnus (the *transverse ridge* (*3*) of the ischium). Both the angulation and ridge are absent in the African apes and were likely also absent in *Ar. ramidus*, given the mass and length of its ischium (the actual surface of the tuberosity is not preserved in the original specimen). © Luba Gutz, 2009.
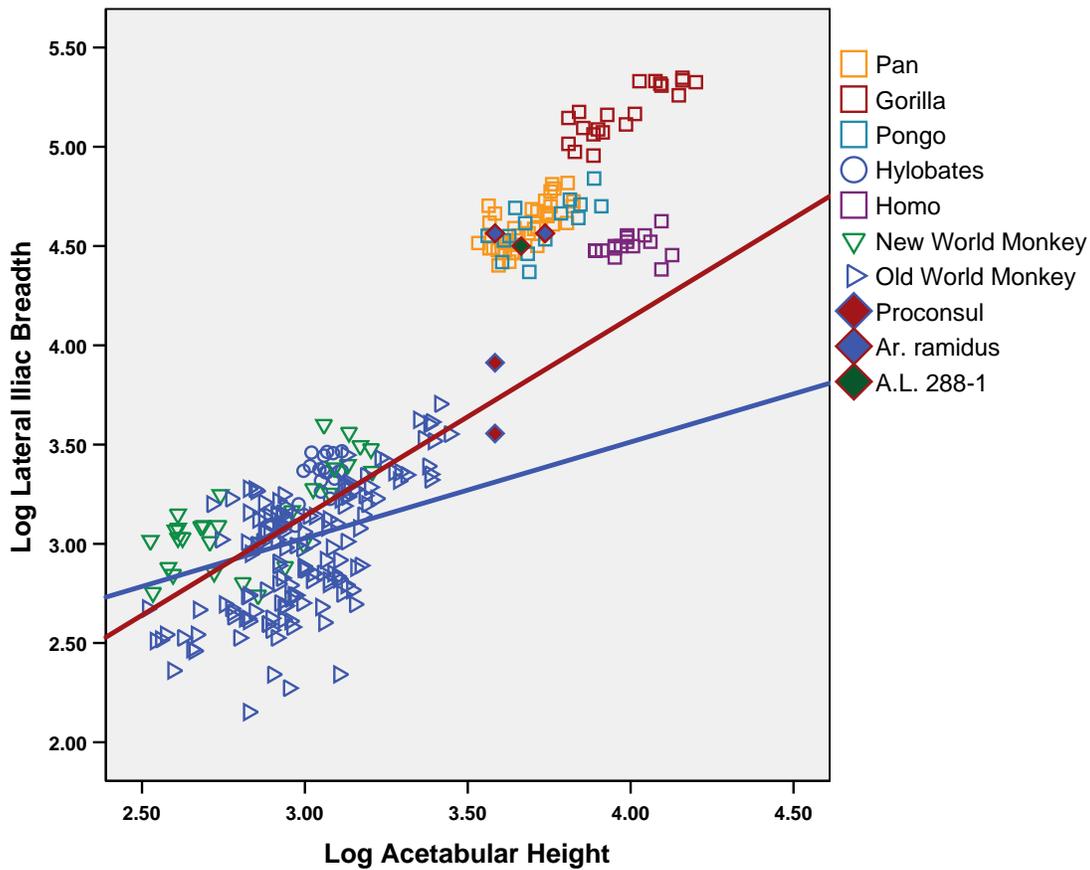
**Figure S5. Relative lateral Iliac Breadth in Anthropoids**. Natural log-log scatterplot of lateral iliac breadth (distance from the most lateral point on the auricular surface to the ilium's lateral margin taken at the location of maximum iliac breadth)(*4*) and acetabular height in anthropoids. A regression line (blue: RMA: y = .485x + 1.573; r = .938; N = 107) has been fitted to the Old World monkey data, and another of slope equal to one (red) has been fitted through two points estimated as possible upper and lower limits of *Proconsul* (based on *KNM-MW 13142 D*). Upper and lower limits of possible acetabular height have been used for *ARA-VP-6/500*. Hominoids show dramatic positive allometry of this portion of the ilium. This may reflect, *inter alia*, disproportionately increased gut size, which appears to reach its apex in *Gorilla (5)*. The pelves of *Ar. ramidus* and *Au. afarensis* plot with extant hominoids, suggesting that this shift in pelvic geometry was likely present in the GLCA (last common ancestor of African apes and hominids). However, great caution must be used in interpreting lateral iliac breadth in hominids because they uniquely broadened their iliac isthmus as an adaptation to bipedality. Data from (*4*) and this study.
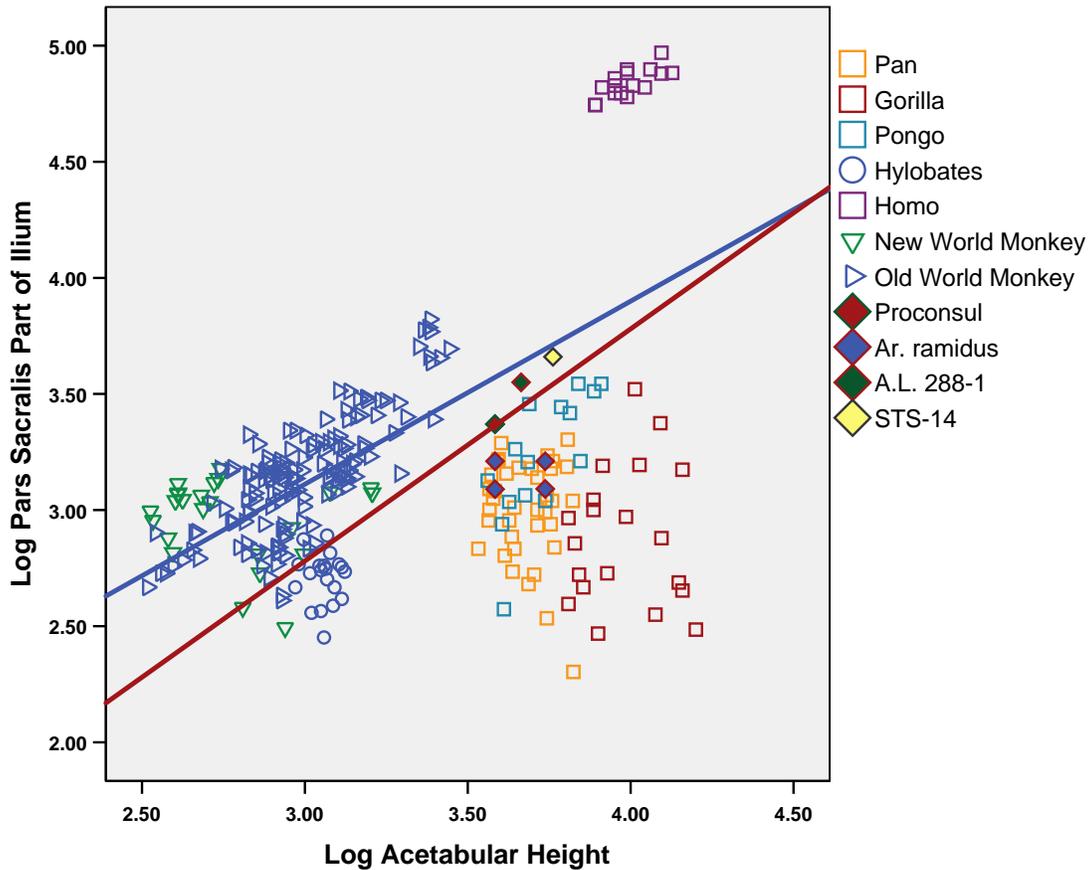
**Figure S6. Relative *pars sacralis* Proportions in Anthropoids.** Natural log-log scatterplot of sacral iliac breadth [distance from the lateral most point on the auricular surface to the medial edge of the ilium (*4*)] and acetabular height in anthropoids. A regression line (blue, RMA: y = .789x + 745; r = .578; N = 107) has been fitted through Old World monkey taxa and another of slope equal to one (red) has been fitted through *Proconsul* (based on estimated iliac breadth in *KNM-MW 13142 D*). In stark contrast to lateral iliac breadth, sacral iliac breadth exhibits a marked negative and far less regular relationship with body size, reflecting invagination of the vertebral column and associated reduction of the erector spinae mass that accompanied lateralization of the scapula on the thorax (*see 6-8*). This portion of the *ARA-VP-6/500* os coxa is much less well-preserved than that used for lateral iliac breadth (which is well preserved). Therefore, four points encompassing possible ranges of both acetabular height and sacral iliac breadth have been plotted. These are estimated from the original and are not exact, but the broad ranges chosen are very likely to have included the specimen within their limits. Whereas *Ar. ramidus* plots in the upper half of the *Pan* and *Gorilla* distributions, *A.L.288-1* plots above the *Proconsul* line, possibly reflecting early reversal of the hominoid trend of retroauricular abbreviation, *i.e.*, hominids may have begun re-enlarging their retroauricular space as they broadened their sacra for bipedality and expanded their *m. gluteus maximus*. An opposite trend of narrowing the trans-iliac space (TIS, see Fig. S10) for back stiffening (and therefore reducing sacral iliac breadth) has

occurred in all apes. Because sacral iliac breadth only partially reflects these contrasting trends, data points for *Ar. ramidus* do not provide definitive evidence of retroauricular space dimensions in the GLCA, although the remarkable breadth of the sacrum of *A.L.288-1* suggests that no post-GLCA sacral narrowing ever occurred in hominids, and was probably not present in the GLCA which probably also retained a long lumbar column (*9*). Note that *Pongo* shows somewhat less retroauricular narrowing than African apes. This is consistent with a different developmental pathway of lumbar abbreviation (*9*). Note also that New World monkeys (largely *Ateles*) do not show any corresponding differentiation from Old World monkeys in the *pars sacralis* of the ilium, although *Hylobates* does. However, the latter's thoracic form appears to be entirely distinct from that of other extant hominoids (*10*)(for discussions see text).
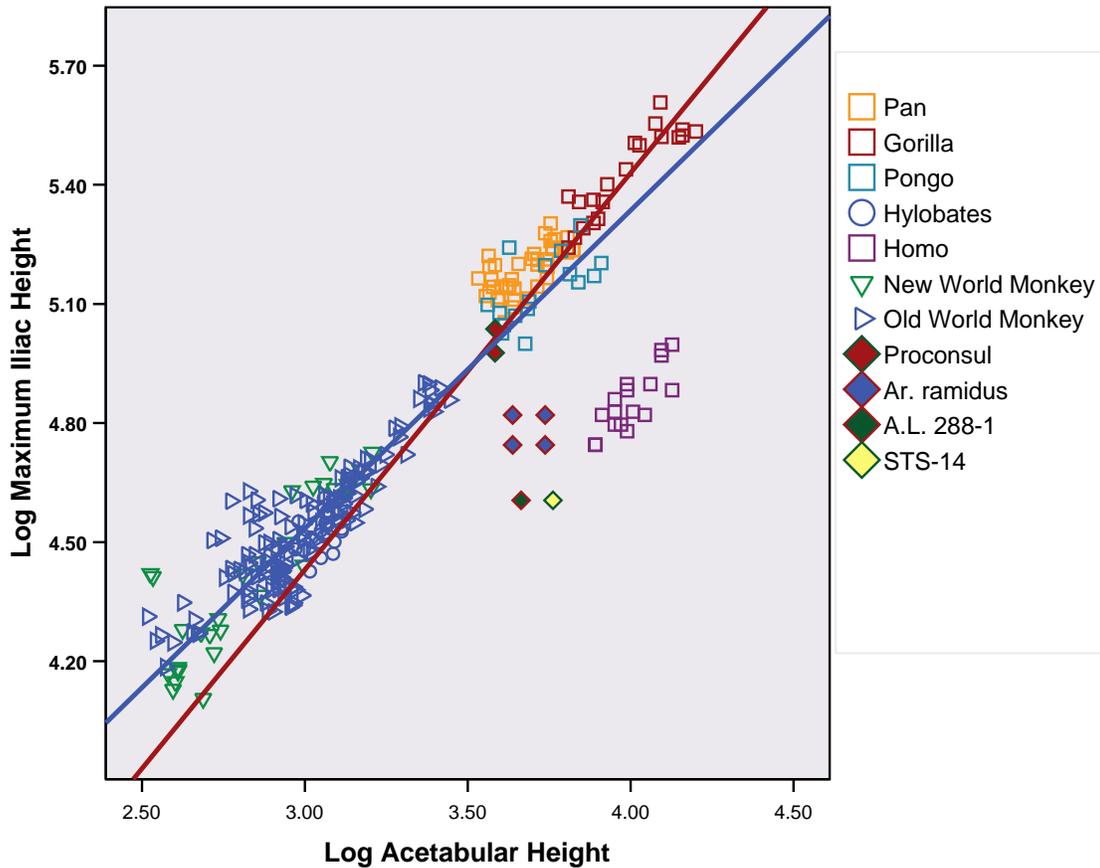
**Figure S7**. **Relative Maximum Iliac Height in Anthropoids.** Natural log-log scatterplot of maximum iliac length [distance from the center of the acetabulum to the most cranial point on the iliac crest (*4*)] and acetabular height in anthropoids. A regression line (blue: RMA: y = .802x + 2.130; r = .876; N = 145) has been fitted through Old World monkey taxa and another of slope equal to one (red) has been fitted through *Proconsul* (*KNM-MW 13142 D*). Four points are provided for *ARA-VP-6/500* reflecting upper and lower limits for both dimensions (acetabular height and maximum iliac length). Note that the ilia of African apes (but not *Pongo*) appear slightly elongated relative to *Proconsul* (distinctly so in *Pan*), but that hominid ilia are dramatically shortened. The strong shift made by modern humans largely reflects enlargement of the acetabulum.
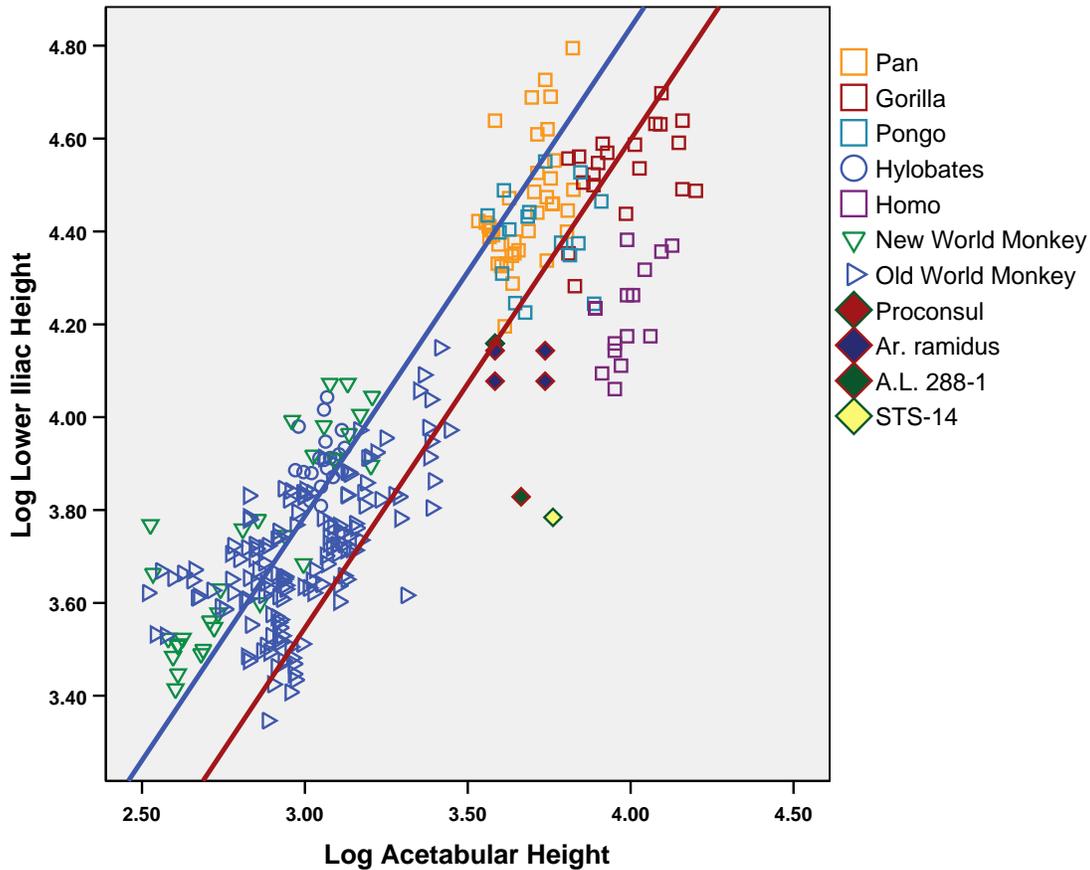
**Figure S8. Relative Lower Pelvic Height in Anthropoids**. Natural log-log scatterplot of lower iliac height [distance from the acetabular center to the most caudal point on the auricular surface (*4*)] and acetabular height in anthropoids. A regression line (blue: RMA: y = 1.052x + .631; r = .791; N = 145) has been fitted through Old World monkey taxa, and another of slope equal to one (red) has been fitted through *Proconsul* (*KNM-MW 13142 D*). While *Gorilla* specimens fall around this line, all of those from *Pan* fall above it, suggesting that shortening of the back for suspensory locomotion and vertical climbing has generated spatial compensation by further elongation of the iliac isthmus (see main text). Four points are provided for *ARA-VP-6/500* reflecting upper and lower limits for acetabular height and lower iliac height. These points plot close to *Proconsul*, suggesting maintenance or slight shortening of lower iliac height relative to its dimension in the GLCA. However, this particular metric is again confounded by other changes in the hominid os coxa, and again therefore requires great caution in its interpretation. The demonstrable shift from the two early hominids *A.L.288-1* and *STS-14* to modern humans reflects several effects on lower iliac height by later pelvic evolution, but especially elongation of the posterior ilium to increase the sagittal diameter of the birth canal (*11, 12*).
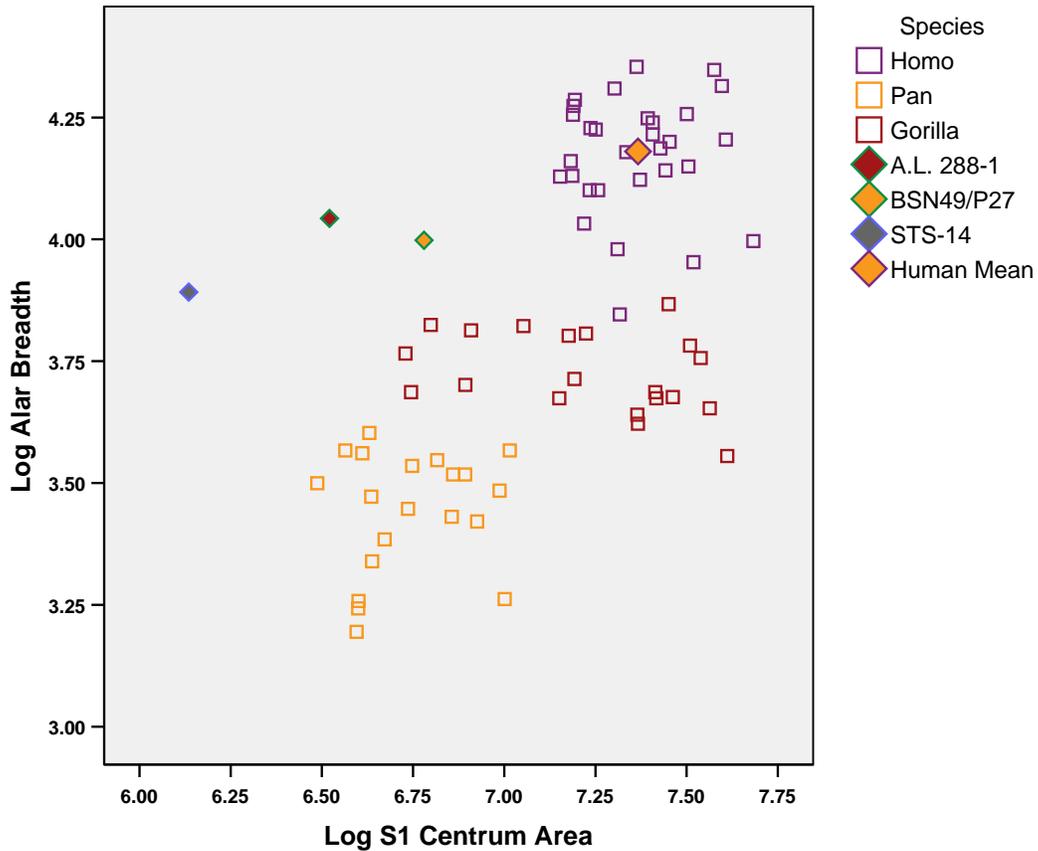
**Figure S9. Relative Alar Breadth in African Apes, Humans, and Early Hominids.**
Natural log-log plot of S1 centrum area (mediolateral diameter x anteroposterior
diameter) and mediolateral breadth of both alae (maximum mediolateral breadth of
sacrum [always taken for the first sacral segment] minus the mediolateral breadth of the
S1 centrum). Data for *STS-14* from (*13*). Data from *BSN49/P27*, a *Homo erectus* pelvis
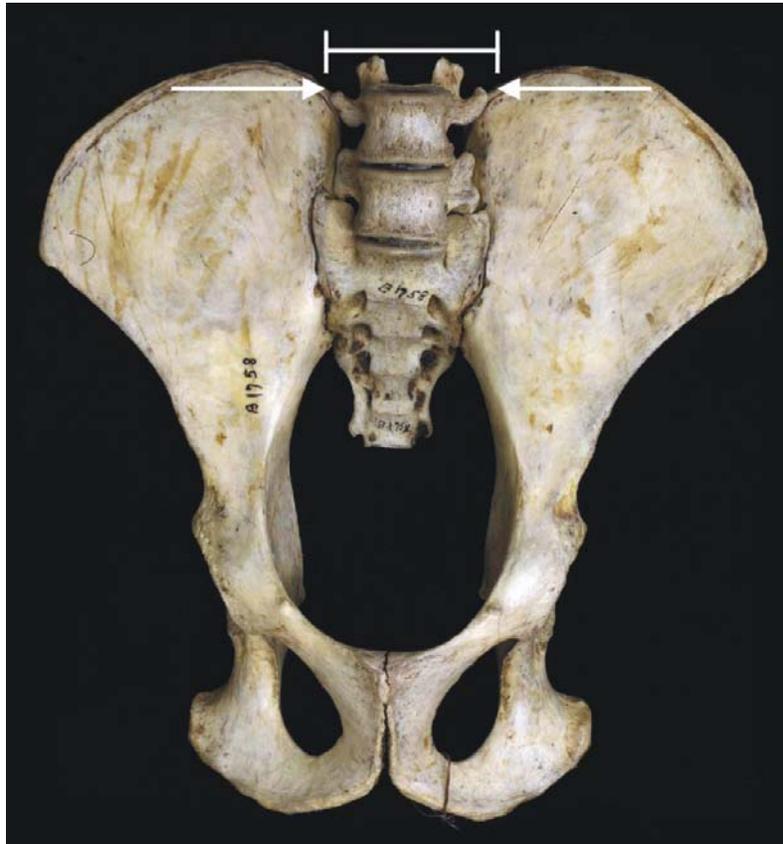from Busidima, from S. W. Simpson (personal communication).

**Figure S10. Correlates of the Trans-Iliac Space in Hominoids.** Viewed anteriorly, the posteromedial edges of right and left ilia and cranial edge of the sacrum form a "U", the trans-iliac space, indicated here by the horizontal bracket. It contains and consequently confines the lower lumbar vertebrae. Its height is determined by the proximal extension of each ilium above the sacroiliac joint, and its breadth is that of the first sacral segment. If the trans-iliac space is sufficiently narrow, iliolumbar contact eliminates any potential motion of the entrapped vertebrae via syndesmotic fixation (indicated here with horizontal arrows). African apes evidence unique ligaments between the ilium and these lowest lumbar vertebrae (*14*). Conversely, either broad sacral alae and/or reduction of iliac height evacuates the trans-iliac space, freeing the lowest lumbars and enhancing their mobility for lordosis. Specimen shown here is a female *Pan* (*CMNH-B1758*). *Gorilla* also exhibits this trait (for more discussion, see the legend of Fig. S6).
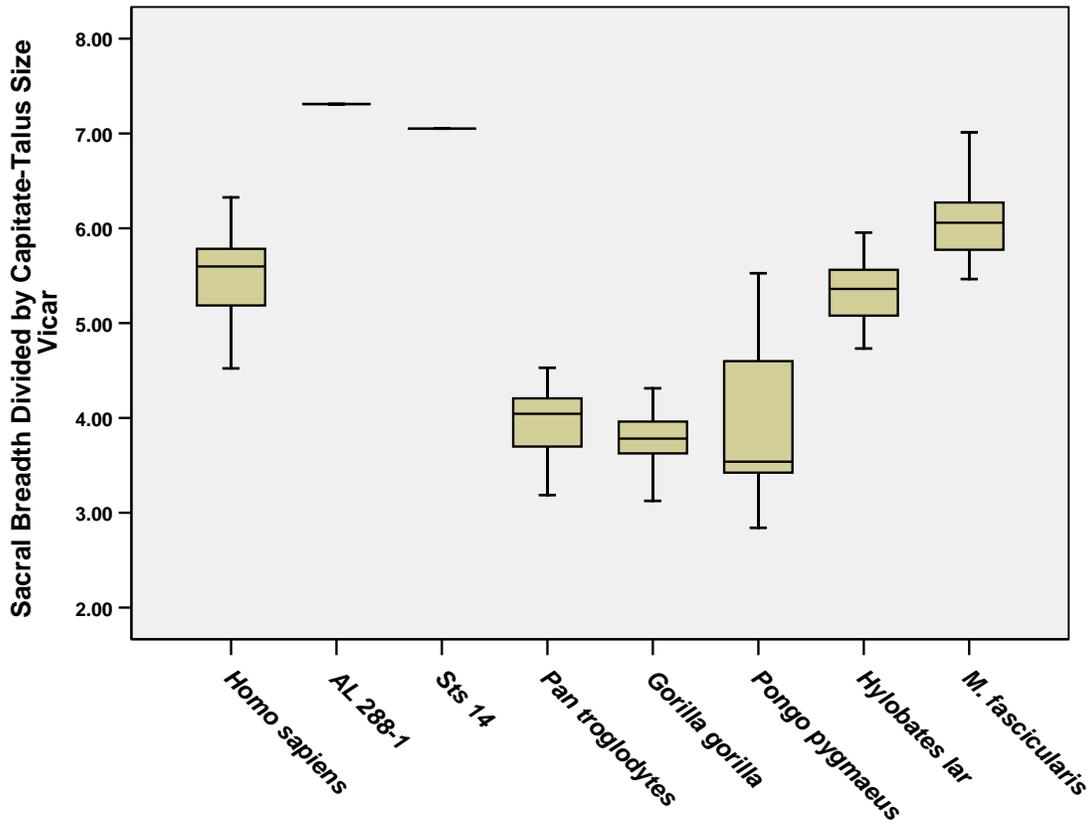
**Figure S11. Maximum Sacral Breadth Divided by the Capitate-Talus Size Vicar in Various Anthropoids.** The maximum breadth of the sacrum has been divided by the geometric mean of several metrics of the capitate and talus. The latter bears a strong relationship to body size (for discussion see *6*). These two bones were not available for *STS-14*, so its body size was estimated as 85% that of *A.L.288-1*, based on a number of linear metrics of the innominate shared by the two specimens (e.g., lower iliac height, acetabular height, *etc.*). Taxa include a typical Old World monkey [*Macacca fasicularis* (N = 21)], *Homo* = 30, *Pan* = 30, *Gorilla* = 19, *Hylobates* = 20, and *Pongo* = 17. Note the marked relative breadth of the two *Australopithecus* specimens, and the striking narrowness of the sacra of *Pan*, *Gorilla*, and *Pongo*. So narrow a sacrum assures entrapment of the most caudal lumbar(s), usually two, within the trans-iliac space. For further discussion and data on average lumbar immobilization see also (*9, 15*).

**Table S1**
**Mean Number of Mobile Lumbars in Extant Hominoids**

| Taxon | N | Mean Number Mobile Lumbars* |
|---|---|---|
| *Hylobates* | 40 | 3.9 |
| *Pongo* | 14 | 2.4 |
| *Gorilla* | 128 | 2.0 |
| *P. troglodytes* | 70 | 2.1 |
| *P. paniscus* | 25 | 2.3 |
| *Homo* | 122 | 4.7 |

*A lumbar was considered mobile if it met four criteria:

1) it exhibited transverse processes and not ribs;
2) both postzygapophyses were in lumbar rather than thoracic orientation;
3) it was separated from each ilium in the trans-iliac space by at least one cm (see text);
4) it was not fused to the sacrum (*i.e*., sacralized). Data from (*15*) and this study.

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