Electronic Supplementary Material (ESM) for
Three-Dimensional Kinematics and the Origin of the Hominin Walking Stride

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ESM Discussion

A comment on measuring pelvis and hip motion. Herein, we include measurements of three-dimensional (3-D) pelvis motion in the global reference frame for bipedal macaques, bipedal chimpanzees and humans walking at similar dimensionless and dimensional speeds (figures 3,S1). Measurement of pelvis motion is essential to computing true 3-D hip motion over a stride (figures 4,S2), and is of direct relevance to studies on the mechanics, energetics and control of facultative and habitual bipedal walking.

The hip flexion-extension measurements herein contrast with most previous studies of facultative bipedal walking (but see 1-2), in which hip flexion-extension has been measured from some approximation of 'trunk inclination' (i.e. tilt). This is most often represented as a vector passing through a hip and a shoulder (or neck/head) marker. 'Hip' flexion-extension is then measured as thigh orientation relative to this vector. This is often a pragmatic solution to the absence of anatomical markers (or other means, e.g. 1) for approximating pelvis motion. However, because the trunk is a non-rigid element – and facultative bipeds are variable in the extent of decoupling of their pelvis and thorax (e.g. 1-3,6,11; figures 3,S1) – this measurement approach may be inadequate for comparing the effects of lower back and ilia design on hip motion during bipedal walking. Indeed, the results herein indicate that bipedal macaques walk with more anterior pelvis tilt (i.e. M v. C: RMSE=9°; table 4) and greater hip flexion (i.e. M v. C: RMSE=9°; table 4) than bipedal chimpanzees at similar dimensionless velocities, despite previous reports of a bit less trunk inclination in bipedal macaques overall (M: ~25°, 6; C: ~30-35°, 4-6).

The absence of direct measurements of pelvis motion in earlier sagittal plane kinematics may underlie some of the interspecific variation in 'hip' flexion-extension among bipedal chimpanzees, macaques, atelids and gibbons (e.g. 7-10), although more measurements of pelvis motion are needed to evaluate this. Of course, un-matched speeds and the lack of variance measures in these earlier comparisons also make it difficult to assess the significance of some of the observed differences. Given this, some caution is warranted when parsing the effects of lower back and/or pelvis size and shape on hip motion using these earlier data (e.g. 11,12).

ESM Discussion References

1. Ogihara N, Makishima H, Nakatsukasa M. 2010 Three-dimensional musculoskeletal kinematics during bipedal locomotion in the Japanese macaque, reconstructed based on an anatomical model-matching method. *J. Hum. Evol.* **58**, 252-261.

2. O'Neill MC, Lee LF, Demes B, Thompson NE, Larson SG, Stern JT Jr., Umberger BR. 2015 Three-dimensional kinematics of the pelvis and hind limbs in chimpanzee (*Pan troglodytes*) and human bipedal walking. *J. Hum. Evol.* **86**, 32-42.

3. Thompson NE. 2016. *The Evolution of Upper Body Stability in Hominins*. Ph.D. Dissertation, Stony Brook University School of Medicine. Stony Brook, NY USA.

4. Kimura T, Yamaguchi N. 2009. Development of bipedal walking in humans and chimpanzees: a comparative study. *Folia Primatol*. **80**, 45-26.

5. Pontzer H, Raichlen DA, Rodman PS. 2014 Bipedal and quadrupedal locomotion in chimpanzees. *J. Hum. Evol.* **66**, 64-82.

6. Hirasaki E, Ogihara N, Hamada Y, Kumakura H, Nakatsukasa M. 2004 Do highly trained monkeys walk like humans? A kinematic study of bipedal locomotion in bipedally trained Japanese macaques. *J. Hum. Evol.* **46**, 739-750.

7. Yamazaki N. 1985 Primate bipedal walking: Computer simulation. In *Primate Morphophysiology, Locomotor Analyses, and Human Bipedalism* (ed. S. Kondo), pp. 105-130. Tokyo: U Tokyo Press.

8. Yamazaki N, Ishida H, Kimura T, Okada M. 1979 Biomechanical analysis of primate bipedal walking by computer simulation. *J. Hum. Evol.* **8**, 337-349.

9. Yamazaki N. 1985 Primate bipedal walking: Computer simulation. In *Primate Morphophysiology, Locomotor Analyses, and Human Bipedalism* (ed. S. Kondo), pp. 105-130. Tokyo: U Tokyo Press.

10. Okada M. 1985 Primate bipedal walking: Comparative kinematics. In *Primate morphophysiology, locomotor analyses, and human bipedalism* (ed. S. Kondo), pp. 47-58. Tokyo: U Tokyo Press.

11. Machnicki AL, Spurlock LB, Strier KB, Reno PL, Lovejoy CO. 2016 First steps of bipedality in hominids: Evidence from the atelid and proconsulid pelvis. *PeerJ* **4**, e1521.

12. Lewton KL, Scott JE. 2017 Ischial form as an indicator of bipedal kinematics in early hominins: a test using extant anthropoids. *Anat. Rec.* **300**, 845-858.

Figure S1

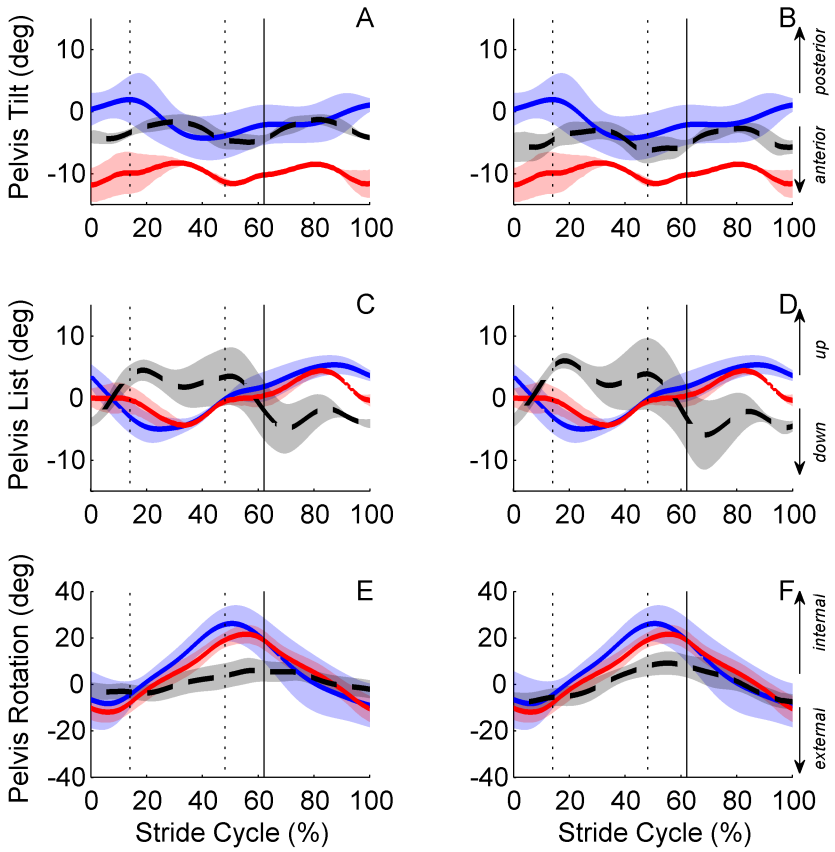

Figure S1. The pelvis (A-B) tilt, (C-D) list and (E-F) rotation angles, relative to the global coordinate system, over a walking stride (mean ± s.d.) for macaques (solid red line), chimpanzees (solid blue line) and humans (dashed black line) at similar dimensional (H: v=1.08 m s^{-1}; column 1) and dimensionless velocities (H: v=1.66 m s^{-1}; column 2). Each stride begins and ends at ipsilateral heel strike. Gait cycle and events are as in figure 3.

Figure S2

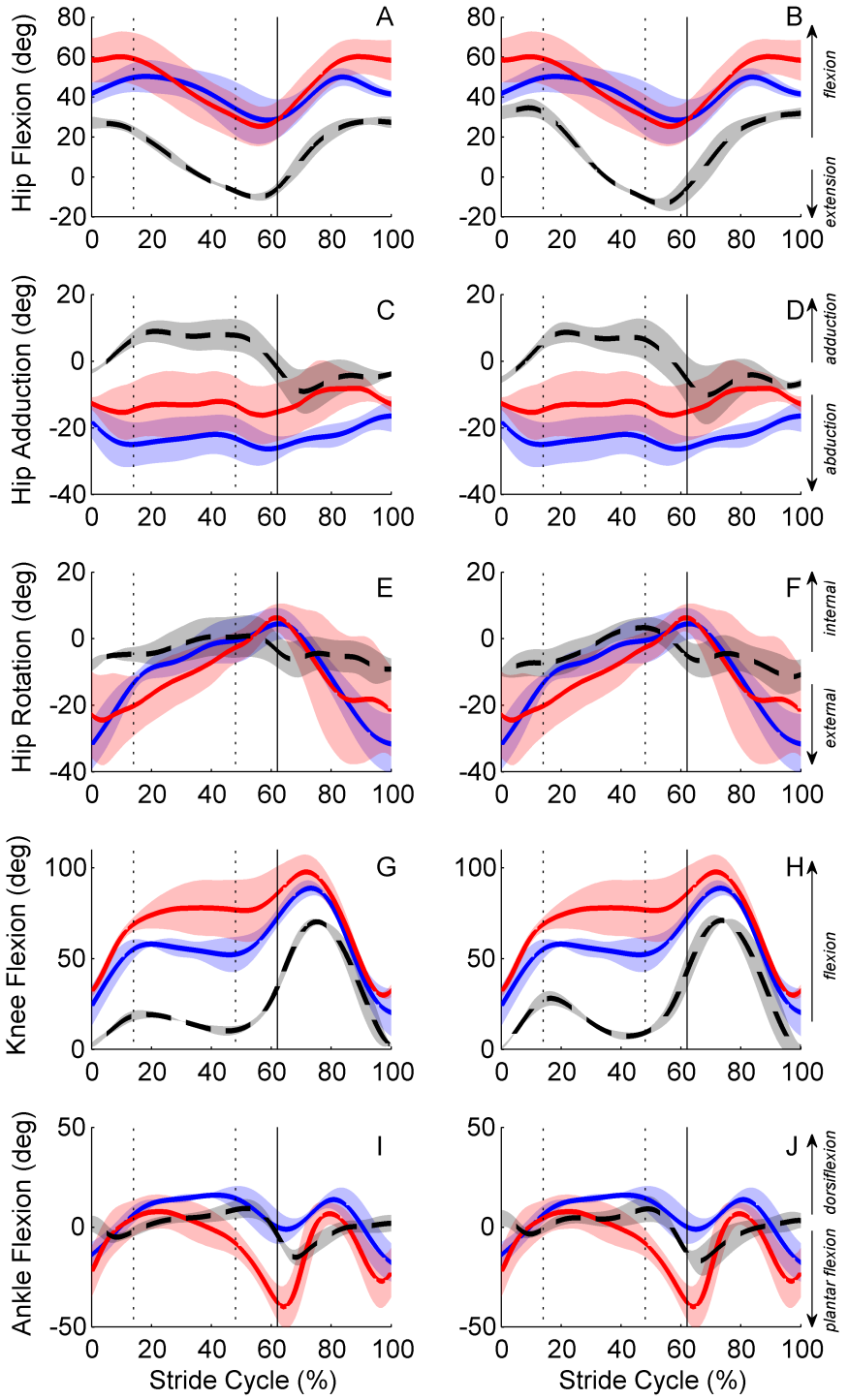

Figure S2. The hip (A-B) flexion, (C-D) adduction, (E-F) rotation, (G-H) knee flexion and (I- J) ankle flexion angles over a walking stride (mean ± s.d.) for macaques and chimpanzees and humans (dashed black line) at similar dimensional (H: v=1.08 m s^{-1}; column 1) and dimensionless velocities (H: v=1.66 m s^{-1}; column 2). Each stride begins and ends at ipsilateral 'heel strike'. Gait cycle and events are as in figure 4.

Table S1. Zero-lag cross-correlations (*r*) of macaque (M), chimpanzee (C) and human (H) pelvis and hind limb motion over a full stride for walking at similar dimensional velocities.

	Pelvis Tilt	Pelvis List	Pelvis Rotation	Hip Flexion	Hip Adduction	Hip Rotation	Knee Flexion	Ankle Flexion
M v. H	0.964	-0.660	0.901	0.822	-0.284	0.830	0.850	0.189
C v. H	0.521	-0.834	0.760	0.739	-0.233	0.860	0.901	0.315

Table S2. Root mean square error (RMSE) of macaque (M), chimpanzee (C) and human (H) pelvis and hind limb motion over a full stride for walking at similar dimensional velocities.

	Pelvis Tilt	Pelvis List	Pelvis Rotation	Hip Flexion	Hip Adduction	Hip Rotation	Knee Flexion	Ankle Flexion
M v. H	7°	5°	9°	35°	16°	11°	48°	16°
C v. H	3°	6°	11°	32°	25°	11°	33°	11°