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Anatomical evidence for the antiquity of human footwear: Tianyuan and Sunghir

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Abstract

Trinkaus [Trinkaus, E., 2005. Anatomical evidence for the antiquity of human footwear use. J. Archaeol. Sci. 32, 1515–1526] provided a comparative biomechanical analysis of the proximal pedal phalanges of western Eurasian Middle Paleolithic and Middle Upper Paleolithic humans, in the context of those of variably shod recent humans. The anatomical evidence indicated that supportive footwear was rare in the Middle Paleolithic but became frequent by the Middle Upper Paleolithic. Based on that analysis, additional data are provided for the Middle Upper Paleolithic (∼27,500 cal BP) Sunghir 1 and the earlier (∼40,000 cal BP) Tianyuan 1 modern humans. Both specimens exhibit relatively gracile middle proximal phalanges in the context of otherwise robust lower limbs. The former specimen reinforces the association of footwear with pedal phalangeal gracility in the Middle Upper Paleolithic. Tianyuan 1 indicates a greater antiquity for the habitual use of footwear than previously inferred, predating the emergence of the Middle Upper Paleolithic.

Keywords: Feet; Shoes; Neandertals; Modern humans; Phalanges; Paleolithic

One of the distinguishing behavioral characteristics of modern humanity is to employ some form of footwear on a habitual basis, for thermal insulation in cold climates and for protection of the plantar foot in all climates. The oldest direct evidence for such footwear, in the form of woven sandals, dates to the early Holocene/terminal Pleistocene of North America (Cressman, 1951; Geib, 1996; Kuttruff et al., 1998). There is a slightly older footprint from western Europe suggesting some form of boot or moccasin (Clottes, 1995). Moreover, the burials of the Middle Upper Paleolithic Sunghir 1, 2 and especially 3 individuals (Bader, 1998) revealed an abundance of ivory beads around the ankles and feet of these individuals. Assuming that those beads were sewn onto clothing, as their distributions elsewhere on the skeletons suggest, their presence around the Sunghir feet implies that those individuals had some form of footwear.

This archeological evidence has been augmented by anatomical inference based on the diaphyseal robusticity (strength scaled to size) of the middle three pedal proximal phalanges of Late Pleistocene western Eurasian humans (Trinkaus, 2005). There is marked decrease in the robusticity of those bones, in the context of little change in overall lower limb robusticity (Trinkaus, 2006a), between the Middle Paleolithic early modern and late archaic humans on the one hand, and Middle Upper Paleolithic (Gravettian *sensu lato*) humans on the other hand. Since there is no meaningful change in the overall biomechanical load levels placed on these Late Pleistocene human lower limbs, through mobility and burden carrying (Trinkaus, 2006a), this reduction in lesser toe robusticity can only be interpreted as indicating localized mechanical insulation from ground reaction forces during heel-off and toe-off. Since the pedal digital flexor muscles plantarflex the toes into the substrate in these latter portions of the stance phase (Reese et al., 1983), an artificial reduction, or dispersal, of that ground reaction force must have taken place. Some form of protective

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footwear can therefore be inferred to have become habitual by the Middle Upper Paleolithic, after ~28,000 ^{14}C BP, or ~32,000 cal BP.

Since this transition seems to have taken place by the earlier Middle Upper Paleolithic, the question remains as to whether this transition had taken place during the earlier Upper Paleolithic, after the Middle Paleolithic humans but prior to ~32,000 cal BP. In 2003, at the site of Tianyuandong (Tianyuan Cave), near Zhoukoudian, China (39° 39′ 28″ N, 115° 52′ 17″ E), the partial skeleton of an early modern human was discovered (Tong et al., 2004). The Tianyuan 1 remains include a partial mandible and dentition, limited axial remains, portions of all long bones (sufficient on at least one side for reliable length estimation of all major limb segments), hand bones and pedal remains. They have been directly dated to 34,430 ± 510 ^{14}C BP (40,328 ± 816 cal BP) (BA-03222) and bracketted by a series of radiocarbon dates on fauna from the same stratigraphic level (Tong et al., 2004; Shang et al., 2007). It is therefore one of the oldest post-OIS 5 modern humans in both eastern (Barker et al., 2007; Shang et al., 2007) and western (Trinkaus et al., 2003; Rougier et al., 2007) Eurasia. Among its pedal remains are two complete proximal phalanges (a probable second digit phalanx and one from the fifth digit) (Fig. 1).

In addition to the Tianyuandong discovery, data from the Sunghir 1 partial skeleton (Fig. 1), previously not available, provides a test of the original (Trinkaus, 2005) interpretation based on Late Pleistocene toe bones, given the archeological evidence for footwear among these Middle Upper Paleolithic humans.

2. Materials and methods

The comparison of pedal phalangeal robusticity is based on external morphometrics of the available Late Pleistocene late archaic and early modern human phalanges and associated postcrania, divided into three samples: Middle Paleolithic late archaic humans (Neandertals: La Chapelle-aux-Saints, La Ferrassie, Kiik-Koba, Palomas, Regourdou, Shanidar, and Spy; $N = 9/7$); Middle Paleolithic early modern humans (Qafzeh and Skhul; $N = 4/3$), and Middle Upper Paleolithic (Gravettian *sensu lato*: Barma Grande, Dolní Věstonice, Ohalo, Paglicci, Pataud, Předmostí, and Veneri; $N = 10/9$) early modern humans, plus Sunghir 1 and Tianyuan 1 (Table 1). For a recent human framework, similar data are employed for three samples of recent humans: a habitually shod but relatively gracile 20th century Euroamerican cadaver sample (Albuquerque, New Mexico; $N = 35/34$), a habitually shod but more robust prehistoric Inuit sample (Point Hope, Alaska; $N = 31/31$), and a habitually barefoot and robust prehistoric North American Amerindian sample (Pecos Pueblo, New Mexico; $N = 64/46$) sample. (See Trinkaus (2005) for sample details and inferences on degrees of footwear use. Sample sizes are for the number of individuals providing middle proximal phalanges followed by those with body mass estimations in addition.)

The mid-diaphyses of the pedal phalanges are modeled as solid beams despite the presence of a medullary cavity; micro-CT analysis of one Neandertal phalanx (Griffen, 2006) and radiography of others suggest little consistent difference in relative cortical area across the comparative samples, a pattern evident in all of the long bones of Late Pleistocene human remains (Trinkaus, 2006a,b). Dorsoplantar and mediolateral second moments of area for the sub-circular diaphyseal cross-sections were computed using standard ellipse formulae (O'Neill and Ruff, 2004) and summed into polar moments of area. The polar moments of area were compared initially to phalangeal interarticular length (as a proxy for beam length) and secondarily to phalangeal length times estimated body mass, the appropriate scaling for second moments of area especially in the context of the varying body proportions of Late Pleistocene humans (Ruff et al., 1993). Given variable preservation of Pleistocene phalanges and difficulties in assigning isolated phalanges to one of the three middle digits, polar moments of area and phalangeal lengths for rays 2–4 were averaged for the available phalanges when more than one was preserved, so as to provide a composite value for each individual. Prior to the computation of any summary data by individual, right and left measurements, if available, were averaged to furnish an individual value for the given dimension. The data are as presented in Trinkaus (2005), except that original measurements are now available for Kiik-Koba 1, and Palomas 92 has been added.

Body mass estimation for the Pleistocene and recent human comparative samples follows Ruff et al. (1997), using femoral head diameter and/or body geometry as available. The Sunghir 1 body mass was estimated from its femoral head diameter of 50.4 mm. Since the body breadth of Tianyuan 1 or its group is unknown, its probable body mass range derives from its estimated femoral head diameter. The Tianyuan 1 femoral head is not preserved, but it preserves the anteroposterior diameter (Martin #22; Bräuer, 1988) of its right lateral femoral condyle (75.0 mm); using a pooled recent and fossil sample ($N = 46$), its femoral head vertical diameter (Martin #18) was estimated as 52.9 ± 1.8 mm ($\mathrm{FHD} = 0.620 \times \mathrm{LCAP} + 7.09$, $r^2 = 0.849$). The Sunghir 1 and Tianyuan 1 body masses were then estimated from their femoral head diameters using the recent human regression provided by Grine et al. (1995) ($\mathrm{BM} = 2.268 \times \mathrm{FHD} - 36.5$, $r^2 = 0.846$, SE_{est} 4.3); this regression formula provides body mass estimates close to those of other available formulae and appears to be the one best suited for large body mass individuals (Auerbach and Ruff, 2004).

The body mass estimation provides a mean estimate of 77.8 kg (±2σ range 69.2–86.4 kg) for Sunghir 1. Since there is double estimation for the Tianyuan 1 body mass estimation, it was estimated using ±2σ for the femoral head estimation and then ±2σ for the body mass calculation from each femoral head diameter. This provides a mean estimate of 83.5 kg, and an estimation range of 66.7–100.2 kg.

Comparisons employed linear residuals for all individuals relative to the pooled recent human sample's reduced major axis regression lines: $\ln(J) = 5.47 \times \ln(\mathrm{Len}) - 12.7$ ($r = 0.545$, $N = 130$) and $\ln(J) = 2.73 \times \ln(\mathrm{BM} \times L) - 15.4$

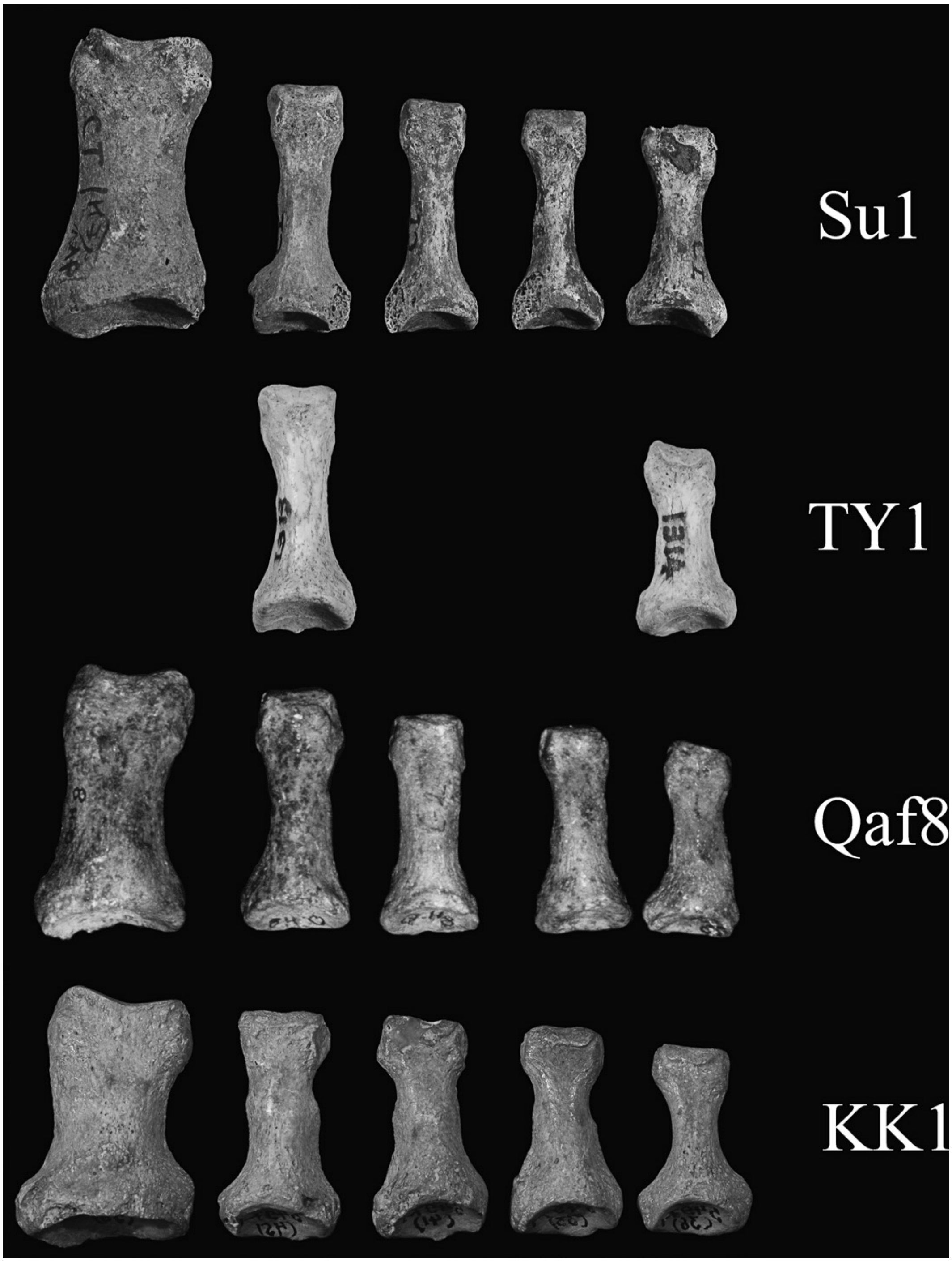

Fig. 1. Dorsal views of Late Pleistocene proximal pedal phalanges, not to the same scale. Su1, Sunghir 1; TY1, Tianyuan 1; Qaf8, Qafzeh 8; KK1, Kiik-Koba 1 (left phalanges reversed).

($r = 0.465$, $N = 111$) (Trinkaus, 2005). Comparisons across the recent and fossil samples employ *t*-tests assuming unequal variances (Hintze, 2007) and adjusted using sequentially reductive multiple comparison corrections (Proschan and Waclawiw, 2000); non-parametric (Wilcoxon) results provide similar results. The relative positions of the Sunghir 1 and Tianyuan 1 phalanges are provided graphically (Figs. 2 and 3) and through *z*-scores adjusted for reference sample sizes (Sokal and Rohlf, 1981) (Table 2).

3. Results

As previously noted (Trinkaus, 2005), the three recent human samples follow the predicted pattern. Whether the polar moments of area of the middle phalanges are compared to phalangeal length alone or to phalanx length times body mass (Figs. 2 and 3), the habitually shod Euroamerican sample has the most gracile phalanges, the habitually barefoot Amerindian sample has the most robust phalanges, and the

Table 1
Articular length and midshaft diameters for the Tianyuan 1 and Sunghir 1 proximal pedal phalanges (PP), in millimeters

	Articular length	Midshaft dorsoplantar diameter	Midshaft mediolateral diameter
Tianyuan 1			
PP2–??	29.2	6.9	6.6
PP5–right	21.4	5.2	7.1
Sunghir 1			
PP1–right	31.8	10.3	13.4
PP2–right	28.6	6.2	6.4
PP3–right	27.0	5.3	5.6
PP3–left	26.8	6.0	5.8
PP4–right	25.3	5.1	5.0
PP4–left	25.2	5.1	5.5
PP5–right	23.6	5.7	5.8
PP5–left	23.3	5.8	6.7

habitually shod but robust Inuit sample has an intermediate distribution. They are highly significantly different (ANOVA $P < 0.0001$) for each comparison. The Middle Upper Paleolithic sample clusters largely with the Inuit sample; even though it overlaps the lower end of the Amerindian sample, it remains significantly different from the two other recent human samples and both of the Middle Paleolithic samples. The Neandertal sample has the highest residuals. However, it remains insignificantly different from the Qafzeh-Skhul sample in the polar moment to length comparison, and it is similar to both the Qafzeh-Skhul and Puebloan samples when body mass is taken into account, thereby compensating for the relatively large body masses to stature (Holliday, 1997) and relatively shorter proximal phalanx lengths (Trinkaus, 1975) of the Neandertals. The relative robusticities of these

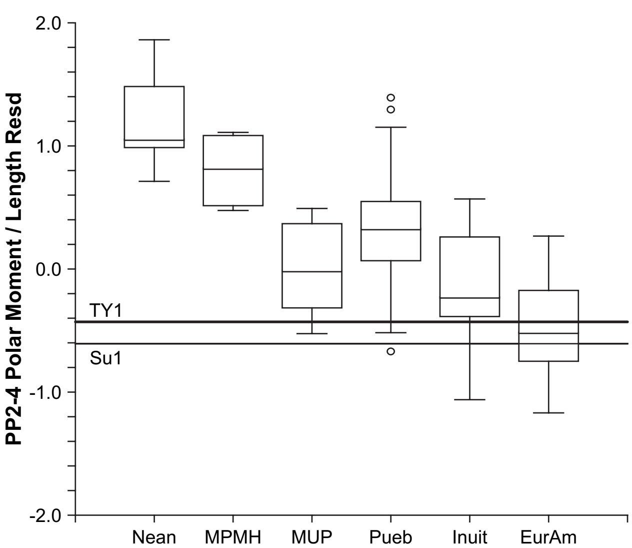

Fig. 2. Boxplot of the residuals for the middle proximal phalangeal midshaft ln polar moments of area versus ln phalangeal length. TY1 and wide line, Tianyuan 1; Su1 and thin line, Sunghir 1; Nean, Neandertals; MPMH, Qafzeh-Skhul Middle Paleolithic early modern humans; MUP, Middle Upper Paleolithic early modern humans; Pueb, Puebloan Amerindians; Inuit, Alaskan Inuits; EurAm, modern Euroamericans.

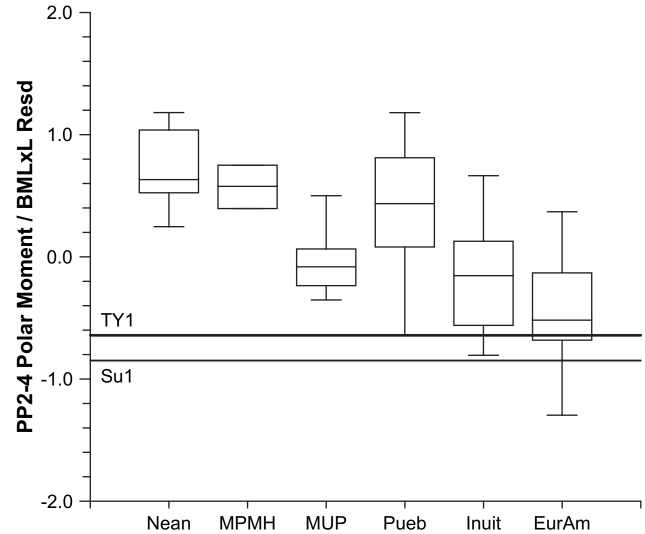

Fig. 3. Boxplot of the residuals for the middle proximal phalangeal midshaft ln polar moments of area versus ln phalangeal length times body mass. Abbreviations as in Fig. 2.

middle pedal proximal phalanges therefore both track with a combination of overall locomotor robusticity and habitual footwear use among recent humans and indicate that there was significant decrease in phalangeal robusticity between the Middle Paleolithic and the Middle Upper Paleolithic.

The rich Sunghir Middle Upper Paleolithic burials (Bader, 1998), with a direct date of 22,930 ± 200 ^{14}C BP (~27,500 cal BP) for Sunghir 1 (Pettitt and Bader, 2000), indicate that these individuals possessed, and presumably habitually wore, footwear as indicated by the distribution of beads around their ankles and feet (see above). The addition of the Sunghir 1 pedal phalanges into these comparisons (Figs. 1–3) indicates that he possessed a marked degree of gracility of the middle toes, despite a level of femoral robusticity similar to that of other Middle Upper Paleolithic and Middle Paleolithic humans (Mednikova and Trinkaus, 2001). Its residuals for phalangeal robusticity are below the means of all of the samples and below the previously known ranges of the Late

Table 2
Z-scores for the Tianyuan 1 and Sunghir 1 middle pedal proximal phalanx robusticity residuals

Relative to:	Sunghir 1		Tianyuan 1	
	J/Len	*J*/BML	*J*/Len	*J*/BML
Neandertals	−4.87*	−4.64*	−4.39*	−4.03*
Qafzeh-Skhul	−4.18*	−6.54*	−3.66*	−5.59*
Mid. Up. Paleolithic	−1.56	−3.00*	−1.11	−2.22*
Puebloans	−2.05*	−2.83*	−1.66	−2.38*
Inuits	−1.09	−1.65	−0.67	−1.15
Euroamericans	−0.40	−1.04	0.05	−0.49

J/Len, polar moment of area versus phalanx length; *J*/BML: polar moment of area versus phalanx length times estimated body mass using the median estimated values for body mass. A negative *z*-score indicates that the Sunghir 1 or Tianyuan 1 residual value is less than the mean of the reference sample. **z*-score >2.00.

Pleistocene samples. Even using the lower end of his body mass estimation (69.2 kg) provides a residual of −0.528, well below the remainder of the Late Pleistocene values and close to the median of only the recent Euroamerican sample (Fig. 3). The Sunghir 1 *z*-scores (Table 2) are all less than −4.0 relative to the Middle Paleolithic samples and less than −2.0 relative to the Middle Upper Paleolithic and Puebloan samples when scaled with body mass. These data therefore reinforce the association of footwear with pedal phalangeal gracility in the Middle Upper Paleolithic.

To these considerations we can now add the Tianyuan 1 partial skeleton from eastern Asia (Shang et al., 2007), which preserves a complete middle pedal phalanx, most likely from ray 2 (Fig. 1). Its relative pedal phalangeal robusticity, when compared to phalanx length alone, is among the more gracile of the Middle Upper Paleolithic and Puebloan phalanges, moderately gracile for an Inuit, similar to the recent Euroamericans, and completely separate from the late archaic and early modern Middle Paleolithic humans (Figs. 2 and 3). Scaling to phalanx length times the median estimated body mass places Tianyuan 1 below all of the other Plesitocene specimens except Sunghir 1 and below all but the most gracile individual in the Puebloan sample; it is among the more gracile of the Euroamerican and especially Inuit specimens.

The relative position of the Tianyuan 1 phalangeal robusticity is not affected by estimation when it is scaled only to phalangeal length. However, it may be affected by the combined estimations of its femoral head diameter and body mass, ultimately from its distal femoral dimension. Its maximum probable residual is −0.028, using the -2σ femoral head diameter of 49.3 mm and the associated -2σ body mass estimate from that femoral head diameter of 66.7 kg. Such a value is in the middle of the Middle Upper Paleolithic and Inuit distributions, among the more gracile of the Puebloan specimens, and moderately robust for a Euroamerican. The other bracketting value for the scaling to bone length times body mass, $+2\sigma$ for femoral head diameter (56.5 mm) and $+2\sigma$ for the body mass estimation (100.2 kg), provides a residual of −1.141, which is below all of the prehistoric sample distributions and among the more gracile of the modern Euroamericans.

The *z*-scores for the residuals of Tianyuan 1 versus the comparative samples are less than −4.0 compared to the Middle Paleolithic samples and less than −2.0 relative to the Middle Upper Paleolithic and Puebloan samples when estimated body mass is taken into account (Table 2). Even the minimum probable body mass estimate of 66.7 kg provides *z*-scores less than −2.0 relative to the Middle Paleolithic samples (−2.21 and −2.94 for the late archaic and early modern human samples respectively), although the other *z*-scores are small and only the Puebloan one is negative.

Preliminary assessment of the Tianyuan 1 tibial diaphyseal robusticity (Shang et al., 2007) indicates that it had a level of locomotor robusticity similar to that of other Late Pleistocene humans. The ∼40,000-year-old Tianyuan 1 partial skeleton therefore exhibits the middle toe gracility associated, in recent humans and at Sunghir, with habitual footwear use, and otherwise anatomically inferable only for the considerably younger Middle Upper Paleolithic western Eurasian humans.

4. Discussion and conclusion

Tianyuan 1 therefore extends back in time during the Late Pleistocene the habitual use of footwear, albeit only for this one individual from mid-latitude eastern Eurasia. Early modern human remains from this time period, Nazlet Khater (Crevecoeur, 2006), Oase (Trinkaus et al., 2003; Rougier et al., 2007), Hofmeyr (Grine et al., 2007), and Niah (Barker et al., 2007), lack pedal phalanges, as do late Neandertals and more recent Early Upper Paleolithic modern humans in western Eurasia. It is therefore not known whether the inference of footwear use by Tianyuan 1 applies generally across early modern humans ∼40,000 cal BP. Yet, the Tianyuan 1 pedal phalanges should be sufficient to indicate that the pattern of middle toe gracility and its probable association with habitual footwear use predates the emergence of the Middle Upper Paleolithic.

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