Modern humans are characterized by a highly specialized foot that reflects our obligate bipedalism. Our understanding of hominin foot evolution is, although, hindered by a paucity of well-associated remains. Here we describe the foot of *Homo naledi* from Dinaledi Chamber, South Africa, using 107 pedal elements, including one nearly-complete adult foot. The *H. naledi* foot is predominantly modern human-like in morphology and inferred function, with an adducted hallux, an elongated tarsus, and derived ankle and calcaneocuboid joints. In combination, these features indicate a foot well adapted for striding bipedalism. However, the *H. naledi* foot differs from modern humans in having more curved proximal pedal phalanges, and features suggestive of a reduced medial longitudinal arch. Within the context of primitive features found elsewhere in the skeleton, these findings suggest a unique locomotor repertoire for *H. naledi*, thus providing further evidence of locomotor diversity within both the hominin clade and the genus *Homo*. 

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The Homo sapiens foot is highly adapted to striding bipedalism, and possesses a suite of anatomical features that functionally relate to this form of locomotion. These include a non-opposable hallux, a medial longitudinal arch, a locking calcaneocuboid joint and an elongated tarsal region in conjunction with short, straight toes. In the last 20 years, our understanding of the evolution of human pedal function has become complicated by fossil discoveries that point to diversity in the types of terrestrial bipedalism found throughout the hominin clade, including several instances where contemporary hominin taxa possessed different combinations of pedal morphologies, indicating distinct differences in foot function. In light of recent discoveries, there is also ambiguity concerning the locomotor affinities of basal members of the genus Homo. It follows, that associated pedal remains of new fossil hominin taxa have the capacity to better our understanding of the complex evolutionary history of bipedalism.

Excavations at Dinaledi Chamber, located in the Rising Star Cave System, Gauteng, South Africa, have recovered 107 pedal remains that are assigned to the new hominin taxon Homo naledi. These include a well-preserved right adult foot (Fig. 1), and isolated remains representing nearly all pedal elements (Supplementary Table 1). A subset of these elements can be provisionally assigned to two adult and two juvenile feet based on anatomical congruence and taphonomic association (Supplementary Table 2).

We show here that the foot of H. naledi is predominantly modern human-like in bony morphology and inferred function. When considered against the primitive features found elsewhere in the H. naledi postcrania, these results indicate a locomotor repertoire that would have been distinct from that of other basal members of the genus Homo, such as H. erectus and H. habilis. The foot of H. naledi thus expands the range of locomotor diversity in both the hominin lineage and the genus Homo.

Results
Talus and calcaneus. Full descriptions of talus and calcaneus, as well as all other pedal elements currently assigned to H. naledi, are provided in Supplementary Note 1. The Dinaledi assemblage includes eight tali (Supplementary Fig. 1 and Supplementary Table 3) and four calcanei. The H. naledi talus trochlea is proximodistally flatter than that of Australopithecus sediba, but has only a moderate trochlear groove, and medial and lateral trochlear margins at a similar elevation to each other. The H. naledi trochlea is thus derived, as in A. afarensis and later species of Homo, including H. sapiens, and distinct from the markedly grooved, mediallylaterally sloping trochlea of African apes, OH 8 (Supplementary Fig. 2) and several specimens from Koobi Fora. In combination with the modern human-like wedging of the trochlea (Supplementary Fig. 3), these features suggest H. naledi had comparatively limited ankle mobility, and a modern human-like trajectory of the leg over the foot during the stance phase of gait. Neither the talar head nor the proximal navicular facet is extended dorsally, indicating a modern human-like range of dorsiflexion and rotation at the talonavicular joint, which is limited compared with that of chimpanzees. In addition, the average head and neck torsion angle of 38° is within the range of modern humans, and implies a rigid midfoot with non-parallel calcaneocuboid and talonavicular joint axes during foot supination. Relative to the trochlea, the neck and head of the tali are medially angled 20°–26° (Supplementary Table 4), which is intermediate between average values for modern humans and extant apes.

There are, however, several features of the H. naledi talus that are distinct from the modern human configuration. The lateral and medial malleolar facets are relatively flat (Supplementary Fig. 4), and, for the three intact adult Dinaledi tali, the angle of plantar declination of the talar head ranges between 10° and 18°, which is outside the human range of variation and within that of extant great apes (Fig. 1). Low head declination has been suggested to imply a low or absent medial longitudinal arch, and has been linked to pes planus in a computed tomography-based study of modern human feet.

Multivariate analysis of articular facet-based talar landmark configurations shows that the two most complete H. naledi tali (University of the Witwatersrand (UW) 101–148/149 & −1417) fall just at the edge of the human range of variation, and outside those of Pan, Gorilla and Pongo (Supplementary Fig. 5). Humans and H. naledi (along with A. afarensis and the most intact talus from Koobi Fora, KNM-ER 1464) separate from the great apes (and OH 8) due to a flatter trochlea, less flared malleolar facets and a flatter posterior calcaneal facet.

The most complete calcaneus of H. naledi (U.W. 101–1322) is well-preserved along much of its length, but exhibits some damage proximally such that only a small portion of the Achilles insertion on the tuberosity remains. The posterior subtalar joint is flat as in humans and A. afarensis, and unlike that of A. sediba and African apes, implying a limited range of motion. The orientation of the sustentaculum tali is low compared with that of modern humans and the Omo calcaneus (33–74–896) (Fig. 2), and falls within the great ape range, along with the values for A. afarensis and A. sediba. This feature has been argued to relate to a low or absent medial longitudinal arch in non-human primates. The peroneal trochlea is weakly developed, unlike in P. troglodytes, A. sediba, A. afarensis, A. africanus and the Omo calcaneus, but is similar to that of modern humans and Neanderthals, perhaps indicative of reduced peroneal musculature in H. naledi. Although the lateral plantar process is not preserved, the retrotrocchlear eminence suggests a modern human-like plantar position rather than the more dorsal one as in A. sediba and chimpanzees. This modern human-like morphology is argued to help create a locking mechanism at the calcaneocuboid joint, yielding a rigid lateral column as the stance phase of gait approaches toe-off.

Figure 1 | Digital reconstruction of the foot of H. naledi. All elements belong to Foot 1. (a) Dorsal view. (b) Distal view of the cuneiforms and cuboid showing transverse arch reconstruction. (c) Medial view showing the moderate longitudinal arch. Scale is in cm.
Cuboid, cuneiforms and navicular. Three cuboids, six naviculars, three medial cuneiforms, six intermediate cuneiforms and three lateral cuneiforms (Supplementary Tables 1 and 6–10) represent the midfoot morphology of *H. naledi*.

The cuboid is proximodistally elongated and exhibits a pronounced medioplantarly positioned beak, traits found in modern humans, *H. floresiensis* and the OH 8 foot. In contrast, the calcaneus of chimpanzees and *Au. sediba* possesses a large and laterally projecting PT, with a more horizontally oriented rete and a dorsally positioned LPP. Calcanei have been scaled to roughly the same proximodistal length. As found in modern humans, the *H. naledi* first metatarsal head is expanded dorsally, a product of parallel oriented lateral and medial rims of the articular surface. In contrast, the chimpanzee head tapers dorsally. STW 562 (*Au. africanus?*) is intermediate, with a mediolaterally wide metatarsal head, but still some dorsal tapering. Metatarsals have been scaled to roughly the same size.

The talus of *H. naledi* has human-like head and neck torsion relative to the talar trochlea. In contrast, the STW 88 (*Au. africanus?*) talus has low torsion, more similar to that found in modern apes. Similar to that found in apes and in some australopiths (STW 88 shown here), the *H. naledi* head and neck are positioned dorsally relative to the trochlear body (line drawn passes through the proximal and distal extent of the articular surface of the talar trochlea). Modern humans tend to have a more planterly oriented head and neck—an anatomy that has been linked to an arched foot. Tali scaled to roughly the same size.

Figure 2 | Salient features of the *H. naledi* foot. (a) The calcaneal anatomy of *H. naledi* resembles that of modern humans. The peroneal trochlea (PT) is markedly reduced and is connected to the lateral plantar process (LPP) by a diagonally oriented retrotr vacancy (RE), which helps position the LPP plantarly. In contrast, the calcaneus of chimpanzees and *Au. sediba* possesses a large and laterally projecting PT, with a more horizontally oriented RE and a dorsally positioned LPP. Calcanei have been scaled to roughly the same proximodistal length. (b) As found in modern humans, the *H. naledi* first metatarsal head is expanded dorsally, a product of parallel oriented lateral and medial rims of the articular surface. In contrast, the chimpanzee head tapers dorsally. STW 562 (*Au. africanus?*) is intermediate, with a mediolaterally wide metatarsal head, but still some dorsal tapering. Metatarsals have been scaled to roughly the same size. (c) The talus of *H. naledi* has human-like head and neck torsion relative to the talar trochlea. In contrast, the STW 88 (*Au. africanus?*) talus has low torsion, more similar to that found in modern apes. (d) Similar to that found in apes and in some australopiths (STW 88 shown here), the *H. naledi* head and neck are positioned dorsally relative to the trochlear body (line drawn passes through the proximal and distal extent of the articular surface of the talar trochlea). Modern humans tend to have a more plantarly oriented head and neck—an anatomy that has been linked to an arched foot. Tali scaled to roughly the same size.
Metatarsals and phalanges. There are eight complete metatarsals, five of which were found in association as part of Foot 1 (UW 101–1443, 1456-8, 1439; Fig. 4 and Supplementary Tables 11–15), and a large number of metatarsal fragments. For Foot 1, the metatarsal robusticity ratio is 1 > 5 > 4 > 3 > 2, a condition shared with ~60% of modern humans, but subtly different from the 1 > 5 > 3 > 4 > 2 configuration of OH 8 (ref. 22). Compared with the lateral metatarsals, the hallucus is modern human-like in relative length (Supplementary Fig. 9), which is in contrast to the markedly short hallucal of H. floresiensis. The intermetatarsal facets are dorsally positioned and orientated dorsolaterally as in humans. The base of the 1st metatarsal is oriented perpendicularly to the long axis of the shaft and is more narrow mediolaterally than OH 8, StW 562 and 595 (but similar to H. sapiens). The diaphyseal axes of the lateral metatarsals are oriented more proximolaterally to distomedially than OH 8, StW 89 and StW 114/115 (again, similar to H. sapiens). The bases of the 3rd metatarsals are gracile, whereas those of the 4th metatarsals are tall and robust (Supplementary Fig. 10). The dorsoplantarly flat articular surface of the cuboid facet of the 4th metatarsals (Supplementary Fig. 11) indicates that the lateral midfoot was modern human-like and rigid during heel lift, unlike the foot of apes and Au. sediba. Metatarsal head torsion values generally fall within modern human ranges of variation (Fig. 5) and signify the presence of a transverse arch and at least an incipient medial longitudinal arch. The heads exhibit dorsal doming, and in many specimens there is a dorsal sulcus just proximal to the head, as in modern humans and australopiths, and indicative of increased loading in dorsiflexion. The first metatarsal head is mediolaterally wide dorsally (Fig. 1), as found in modern humans, but has a relative dorsoplantar (DP) height at the low end of the human range (Supplementary Fig. 12). The robust head of the first metatarsal is consistent with H. naledi having a modern human-like windlass mechanism during toe-off.

There are 40 pedal phalanges in the H. naledi sample (Supplementary Tables 1 and 16–18). The proximal hallucial phalanx exhibits a robust base and narrow shaft similar to the adducted halluces of Homo and Australopithecus. The average dorsal cantiing angles of the proximal facets of the hallucial (n = 2; 102.5°) and lateral proximal phalanges (n = 4; 112.2°) also fall within the modern human range (Supplementary Table 19), indicating increased dorsiflexion at the metatarsophalangeal joints. However, as with the H. naledi manual phalanges, the proximal pedal phalanges exhibit significantly greater curvature than those of modern humans, falling within the range of Gorilla, Hylobates, Papio, Macaca, Pan paniscus and Au. afarensis (Fig. 6 and Supplementary Table 20). This anatomy may be indicative of elevated pedal grasping abilities in the H. naledi 2nd to 5th rays compared with modern humans.

Discussion

The size of the Dinaledi pedal sample and the clear association among many of the pedal elements provides a rare opportunity to make inferences about foot function in a fossil hominin. The relatively complete Foot 1 has a power arm/load arm ratio of 40.8, which is close to the human mean and distinct from that of chimpanzees (Supplementary Table 21). Such a value indicates a foot capable of efficient weight transfer through to a terrestrial substrate. Given an ankle joint that is orthogonal to the long axis of the tibia, a flat subtal joint, diminutive peroneal trochlea, locking calcaneocuboid joint, limited dorsiflexion at the talonavicular joint, modern human-like metatarsal lengths, torsion and head proportions, and dorsiflexing phalanges, we infer the Dinaledi hominin’s pedal function was broadly similar to that of modern humans. However, although the H. naledi foot was undoubtedly stiff during the stance phase of the walking cycle, the ape-like orientation of the sustentaculum tali and low talar head declination are features that may signal a relatively low medial longitudinal arch, at least in Foot 1, although this hypothesis will require further testing of the relationship between arch height and bony anatomy of the foot. The relative flaring of the medial and lateral malleolar facets on the talus also point to increased stability when the foot was maximally inverted or everted. These characters, in combination with relatively low calcaneal robusticity and the more curved proximal pedal phalanges, result in a foot morphology that differed subtly from that found in modern humans.

This combination of primitive and derived features in the H. naledi foot (Table 1) is thus distinct when compared with the well-known foot assemblages OH 8 (refs 3,12,14,22), StW 573 (refs 3,31) and pedal remains assigned to H. floresiensis, Au. afarensis, Au. africanus, and Ar. ramidus. Given that there are no dates currently assigned to the Dinaledi sample, there are several possible scenarios when considering the H. naledi foot: (i) If the remains are from the early to mid Pliocene, they represent a foot more derived than in any other hominin taxon from that time period, indicating selection for human-like pedal function early in the hominin fossil record; (ii) a date from the late Pliocene/early Pleistocene would indicate a foot more derived than those of a similar age from Koobi Fora, Olduvai (Supplementary Table 20) or South Africa (refs 3,5,23,31), and, although not fully modern human-like, perhaps most similar to that from Dmanisi; (iii) a more recent date would indicate a foot that, although largely human-like, was distinct from that of H. sapiens, H. floresiensis and H. neanderthalensis, extending the range of variation in Homo foot morphology, and indicating

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**Figure 3 | Orientation of the sustentaculum tali relative to the mediolateral axis of the calcaneal tuberosity.** There is clear separation between African apes and H. sapiens. Dinaledi, along with Au. afarensis (A.L. 333-8) and Au. sediba (MH2) fall outside the human range of variation.
possible stasis for primitive characters such as pedal phalangeal curvature.

Aside from that of *H. sapiens* and the Neanderthals, the Dinaledi foot possesses some of the most derived pedal morphologies in the hominin fossil record. Although there are members of the genus *Homo* known with primitive feet and relatively small brains (*H. floresiensis*\(^6\)) and with derived feet and larger brains than *H. naledi* (for example, early *H. erectus*\(^9\)), *H. naledi* is the first known hominin with this combination of such derived feet and legs with a small brain size\(^10\). Postcranially, the juxtaposition of such a derived foot in combination with the numerous primitive features found throughout the *H. naledi* skeleton is a unique mosaic previously unknown in the human fossil record. In particular, the primitive shoulder joint\(^10\) and curved manual phalanges\(^29\) indicate a decoupling of upper and lower limb function in *H. naledi* that offers an important insight into postcranial form and function that may have characterized basal *Homo*. Accordingly, the Dinaledi pedal remains provide further evidence of locomotor diversity within the hominin clade\(^3–6\), and expands that diversity within the genus *Homo*.

**Methods**

**Descriptions.** All Rising Star material was described by two or more individuals.

**Two-dimensional (2D) measurements.** All linear measurements were taken with digital calipers; angular measurements from photographs or with a goniometer.

Any measurement discrepancies in linear and angular measurements were rechecked by a third team member for accuracy. Unless otherwise specified, all proximodistal (PD) lengths were taken from the midpoint of the proximal articular surface to the midpoint of the distal articular surface, mediolateral (ML) lengths were taken from the midpoint of the medial surface to the medial point of the lateral surface, and DP lengths were taken from the midpoint of the dorsal surface to the midpoint of the plantar surface. The following are exceptions to this protocol:

- Lateral cuneiform PD (measured by placing the caliper edge along the 3rd metatarsal facet and measuring to the proximolateral corner);
- Lateral cuneiform ML (measured by placing calipers along the lateral edge and measuring to the distomedial corner);
- Talar neck PD (measured parallel to the trochlea).

**Talar wedging.** Talar wedging was measured as the ratio between the maximum ML width of the distal talar trochlea and the maximum ML width of the proximal talar trochlea. African apes were measured at the Cleveland Museum of Natural History (CMNH), American Museum of Natural History (AMNH) and Harvard Museum of Comparative Zoology (MCZ). Humans were measured at Kent State University (Libben) and the Hamann-Todd collection at the CMNH. Sample sizes are listed below the talar wedging graph. Original fossil tali were studied at the School of Anatomical Sciences and the Institute for Human Evolution (now Evolutionary Studies Institute), Johannesburg, Transvaal (now Ditsong) Museum in Pretoria, South Africa, Kenya National Museum (Nairobi). Casts of Ethiopian fossils were studied at the University of Michigan Anthropology Department.

**Talar angles.** The horizontal angle of the head/neck, angle of torsion of the head/neck and angle of declination of the head/neck were compared with published measurements from Day and Wood\(^14\) (Note: Although Day and Wood\(^14\) call the plantar angulation of the talar neck and head an angle of ‘inclination’, we prefer the term ‘declination’ and use it throughout).

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\(^{25}\) cinema 3D company has been using this technology to create highly realistic digital models of animals, as described in their website. No specific references are necessary as the description is based on the technology and its applications in various fields.”

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**Figure 4 | First two principal component scores of a generalized Procrustes analysis of medial cuneiform 3D landmark coordinates.** Humans and the fossil hominins are separated from the great apes because of their flat, forward-facing hallucial facet. Dinaledi, along with OH 8 and StW 573 fall just within the *H. sapiens* range, and well outside that of the extant great apes.
Calcaneal robusticity. Calcaneal robusticity was measured as detailed in Latimer and Lovejoy21 and modified slightly in Zipfel et al.23. There is plantar damage to UW 101–1322 and the minimum area of the calcaneal tuber was estimated from a digital cross-section (using DeskArtes) of a surface scan of the original fossil. Tuber volume was then calculated as the product of the mimimum cross-sectional area of the tuber times the length of the tuber (from the midpoint of the proximal talar facet to the most proximal point of the calcaneal tuber). Calcaneal robusticity was calculated as the tuber volume divided by body mass. Body mass for the Foot 1 individual was calculated from regression-based equations of McHenry33 based on the talar trochlea width of the associated talus UW 101–1417. Comparative values were generated from data provided in Latimer and Lovejoy21 on modern apes and humans, with modified body masses in the apes from Smith and Jungers34. Data on calcaneal robusticity in Au. afarensis were from Latimer and Lovejoy21 and modified with a body mass generated from the regression-based equations of McHenry33 for talus trochlea width of A.L. 333-147—a not necessarily associated talus, but from a similarly sized individual as A.L. 333-8 and A.L. 333-55. Data on A.L. 333-147 are taken from Ward et al.35. Data for Au. sediba are taken from Zipfel et al.23.

Tarsal elongation. Tarsal elongation was assessed as the maximum PD length of the bone divided by the maximum ML width of the bone in both the lateral cuneiform and the intermediate cuneiform. Chimpanzee, gorilla and orangutan measurements were obtained at the AMNH, MCZ and CMNH. Humans were from the Merida (Mexico) and Mithi (Montenegro) populations housed at the Harvard Peabody Museum of Archaeology and Ethnology (PMAE). Sample sizes are reported in the graphs themselves. Original fossils SW 273 (Anastraelaphotherium sp.) and UW 88–139 (Au. sediba) were measured at the School of Anatomical Sciences and the Institute for Human Evolution (now Evolutionary Studies Institute), Johannesburg, respectively. The OH 8 original fossil was studied at the Tanzania National Museum and House of Culture. A cast of the Hadar lateral cuneiform A.L. 333-79 was studied at the PMAE.

Metatarsal proportions. Measures of the maximum PD lengths of G. gorilla (n = 20), P. troglodytes (n = 32), H. sapiens (n = 97; all housed at the National Museum of Natural History, Washington DC), Metatarsal (MT) 1–3 lengths, were taken with digital calipers; measurements from LB1 were taken from the original specimen, and Skhul IV was taken from a cast. MT1/MT2 × 100 was found by dividing the length of MT1 by MT2 and multiplying the quotient by 100. MT1/MT3 × 100 was found by dividing the length of MT1 by MT3 and multiplying the quotient by 100. These data were plotted using PAST 3.0 (ref. 36).

Metatarsal head dimensions. Relative metatarsal head dimensions were measured as described in the study by Latimer and Lovejoy21, in which the plantar cornua of the first metatarsal head did not factor into the PD height measurement. Because of ML erosion to the Dinaledi hominins, only the PD height of the first and second metatarsals were compared. Comparative data were generated from African ape specimens measured at the CMNH and humans measured at the PMAE. A cast of A.L. 333-115 was measured at the PMAE and results were comparable to those reported in the study by Latimer and Lovejoy21.

**Figure 5** | Torsion of metatarsals I–V for *H. naledi*. Darkened bars represent the median, boxes represent the 50% percentile limits and whiskers represent the highest and lowest values, excluding outliers. The values for the Dinaledi sample fall within the *H. sapiens* ranges of variation for all five metatarsals. Total sample sizes: *H. sapiens*: 50; *P. troglodytes*: 38; *G. gorilla*: 48; *P. pygmaeus*: 27; Colobines: 12; Cercopithecines: 25. Note: Sample sizes subtly vary per element according to the completeness of each skeletal specimen.
Metatarsal torsion. The methods used are described in Drapeau and Harmon. Surface laser scans were made of the complete metatarsals, using ScanStudio software and a NextEngine laser scanner (NextEngine Inc.). Scans were imported into Geomagic, where four landmarks were placed, two delineating the mid-shaft of the metatarsal head and two delineating the major axis of the base. The angle created by these two lines in the coronal plane represents the lateral torsion of the metatarsal. Torsion and intermetatarsal articular facet orientation were used to align the metatarsals in virtual space and model the shape of the transverse arch. Comparative specimens were measured at the Cleveland Museum of Natural History, National Museum of Natural History, Washington, DC, Anthropological Institute of the University of Zurich and the Canadian Museum of Civilization, Gatineau, QC, Canada. All measurements on fossils were taken from the original specimens, except for the Dinaledi specimens, which were taken from laser surface scans.

Metatarsal robusticity. This has been carried out using the method of Archibald in which the metatarsal robusticity index is defined as [(mid-shaft diameter + 100)/length]. The metatarsal dimensions used are defined as follows:

- **Metatarsal 1.** Length is measured from the most distal point on the upper part of the proximal articular surface to the most distal point on the distal articular surface. Circumference of the mid-shaft is measured at a point mid-way between the most distal point on the proximal articular surface to the most distal point on the distal articular surface.
- **Metatarsals 2–4.** Length is measured from the most dorsolateral point on the posterior articular surface to the most distal point on the distal articular surface. Circumference of the mid-shaft is measured at a point mid-way between the most dorsomedial point of the proximal articular surface to the most distal point of the distal articular surface.
- **Metatarsal 5.** Length is measured from the most lateral point on the proximal articular surface to the most distal point of the distal articular surface. Circumference of the mid-shaft is measured at a point mid-way between the most medial point on the proximal articular surface to the most distal point of the distal articular surface.

Phalangeal curvature. All phalangeal curvatures were quantified using high-resolution polynomial curve fitting (HR-PCF) methods. Unlike traditional curvature quantification techniques (that is, included angle, normalized curvature moment arm) that model curvature as an imaginary circular line passing through the center of the bone, HR-PCF models the surface curvature of the bone and can fit a polynomial function to either the dorsal or ventral surface of a phalanx. In the case of the Dinaledi pedal phalanges, the ventral surfaces of many phalanges were interrupted by flexor sheath ridges that create irregularities in the outline of shaft curvature, so the more regular dorsal margin of the outline was chosen for polynomial fitting. Although it could be argued that the dorsal and ventral curvatures are responses to different loading regimes, they are highly interdependent and associated with the same positional behaviour; the dorsal curvature is also simpler. Elements were photographed in a lateral and standardized orientation. JASC PSP (Cored Corporation, 1600 Carling Avenue, Ottawa, Ontario KIZ 8R7, Canada) image editing software was used to convert the resulting 2D images into simple digitized outlines. These digitized outlines contain thousands of individual pixels, each having its own, paired coordinates. End points were selected for each element based on the limits of a discrete 2nd order polynomial curve and the co-ordinates of the individual pixels comprising the selected portion of the dorsal contour were used as data points to generate a best-fit 2nd order polynomial function with three coefficients defined as \( y = Ax^2 + Bx + C \). The three resulting coefficients \( A, B, C \) can be used as the raw data in a statistical analysis. Sample sizes for the talus 3D coordinates are: H. sapiens: 15; G. gorilla: 77; P. troglodytes: 44; H. sapiens 89; P. pygmaeus: 43. For the medial cuneiform 3D coordinates, they are H. sapiens: 77; P. troglodytes: 40; P. pygmaeus: 15; G. gorilla: 42; P. pygmaeus: 43.

### Three-dimensional (3D) measurements.

x,y,z homologous landmark configurations for the talus and medial cuneiform were collected according to protocols defined in Harcourt-Smith. All landmarks were collected with a Microscribe digitizer by W.E.H.H. Coordinate date was superimposed using generalized Procrustes alignment, which controls for translational and rotational differences and adjusts for size. Aligned coordinates were subjected to a principal components analysis. All generalized Procrustes alignments and principal components analyses were done in morphologika 2.5 (ref. 40). Angulation between articular facets and other anatomical structures on the talus and calcaneus were collected using laser surface scans of the fossils and the software Geomagic Control 2014 (Geomagic Solutions), which allows a best-fit plane to be fitted to a selected area, or an axis to be determined using two landmark points.

All non-human extant samples for the 3D analyses are wild shot adults housed at AMNH, CMNH, MCZ, National Museum of Natural History (Smithsonian), Natural History Museum (London), Powell-Cotton Museum (Kent, UK) and the Royal African Museum (Tervuren, Belgium). Human samples were collected at the AMNH and the Dart Collection, University of the Witwatersrand. Original fossils were studied at the School of Anatomical Sciences and the Institute for Human Evolution (now Evolutionary Studies Institute), Johannesburg, the Transvaal (now Ditsong) Museum (Pretoria, South Africa) and the Kenya National Museum (Nairobi). Primary casts of Ethiopian fossils were studied at the Institute of Human Origins (Arizona State University) and at the Musée de l’Homme, Paris. Primary casts of Tanzanian fossils were measured at the National History Museum, London. Sample sizes for the talus 3D coordinates are: H. sapiens: 89; P. troglodytes: 44; P. pygmaeus: 43. For the medial cuneiform 3D coordinates, they are H. sapiens: 77; P. troglodytes: 40; P. pygmaeus: 15; G. gorilla: 42; P. pygmaeus: 43.
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Author contributions

W.E.H.-S., Z.T., K.A.C., J.M.D. and B.Z. designed the study and wrote the paper. M.S.M.D analysed the metatarsal torsion and A.S.D. analysed the phalangeal curvature. W.E.H.H.-S, Z.T., K.A.C., J.M.D. and B.Z. designed the study and wrote the paper. Acknowledgements

Additional information

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