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Brief Communication: A Midtarsal (Midfoot) Break in the Human Foot

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ABSTRACT The absence of a midtarsal break has long been regarded as a derived feature of the human foot. Humans possess a rigid midfoot that acts as an efficient lever during the propulsive phase of bipedal gait. Non-human primates, in contrast, have a more mobile midfoot that is adaptive for tree climbing. Here, we report plantar pressure and video evidence that a small percentage of modern humans (n = 32/398) possess both elevated lateral midfoot pressures and even exhibit midfoot dorsiflexion characteristic of a midtarsal break. Those humans with a midtarsal break had on average a significantly flatter foot than those without. Midtarsal breakers also had significantly more medial weight transfer (pronation) during the stance phase of gait than those without this midfoot mobility. These data are in accordance with Elftman (Clin Orthop 16 (1960) 41–45) who suggested that pronation aligns the axes of the transverse tarsal joint, permitting elevated midfoot mobility. Am J Phys Anthropol 151:495–499, 2013. © 2013 Wiley Periodicals, Inc.

During the stance phase of walking, the human foot is flexible, permitting it to absorb ground reaction forces and to conform to the substrate. However, during the propulsive phase of gait, the foot becomes rigid and acts as an efficient lever. This rigidity of the midfoot is a product of many anatomical factors, including stiff plantar ligaments (Gomberg, 1985), a well-developed plantar aponeurosis (Hicks, 1954), interlocking tarsal joints (Bojsen-Møller, 1979), and the oblique translation of the peroneus longus tendon under the foot (Lovejoy et al., 2009). Non-human primates, in contrast, have a more mobile midfoot which allows them to mold their midfoot around arboreal substrates. A more mobile midfoot in non-human primates results in what is called the "midtarsal break" or the midfoot break (DeSilva, 2010). When non-human primates lift their heel off the substrate, they establish a temporary fulcrum in the midfoot region (Elftman and Manter, 1935; DeSilva, 2010). This motion was first recognized by Elftman and Manter (1935) during terrestrial locomotion in chimpanzees, and subsequent studies have yet to identify a non-human primate without a midtarsal break (Meldrum, 1991; Gebo, 1992; Schmitt and Larson, 1995). Though suggested for years to be a motion at the midtarsal joint, the midtarsal break is actually a more complex motion involving dorsiflexion at both the calcaneocuboid and lateral (4th and 5th) tarsometatarsal joints (DeSilva, 2010), and also involves a strong rotational component (Thompson et al., 2012).

Studies of the midtarsal break have generally dichotomized this character: humans do not have a midtarsal break while non-human primates do. However, several studies from both the orthopedic and paleoanthropological literature have found considerable variation in human midfoot mobility. For example, cadaver studies indicate that flexion in the sagittal plane can be quite high in the human foot (Ouzounian and Shereff, 1989; Whittaker et al., 2011), and there is some evidence for midfoot dorsiflexion particularly in cases of limited ankle dorsiflexion (Karas and Hoy, 2002), and developmental pathologies (Maurer et al., in press). An in vivo study of joint motion in the feet of six male subjects also found considerable variation in midfoot rigidity (Lundgren et al., 2008). However, these studies have all been performed on a small sample of individuals. There are also occasional anecdotal reports of a midtarsal break in some humans (Vereecke et al., 2003; Crompton et al., 2010, 2012), though no video evidence has documented whether any humans truly possess a midtarsal break. Here, we present the first clear evidence, using both plantar pressure and video documentation, for a midtarsal break in a small percentage of modern humans.

MATERIALS AND METHODS

Data were collected on adult, non-pathological, humans at the Boston Museum of Science as part of their *Living Laboratory* collaboration with local researchers. The study design was approved by the Institutional Review Boards at both Boston University and the Boston Museum of Science. We collected data on 398 adult subjects from June 2011 to August 2012 (Table 1). Age was self-reported and height and weight data were collected on study participants. Most of our participants were well enough to walk around the Museum of Science, though those few individuals with injuries affecting their gait, or neuropathic conditions, were not included in the study. Participants walked barefoot, at their normal gait speed, down a 6.1-m long mechanized gait carpet (Gaitrite Inc., NJ) which was used to collect spatiotemporal data including velocity, step length, step width, foot rotation,

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TABLE 1. Descriptive statistics of foot anatomy and spatiotemporal gait parameters in humans with and without a midtarsal break

	Midtarsal break absent	Midtarsal break present	Statistical significance
N	366 (92% of subjects)	32 (8% of subjects)	
Sex	121 males 245 females	16 males 16 females	
Age	37.9 ± 15.1	39.4 ± 15.1	$P = 0.57$
BMI	24.4 ± 5.1	26.7 ± 6.5	$P = 0.03$
Maximum lateral midfoot pressure (kPa)	62.5 ± 53.3	251.4 ± 46.0	$P < 0.0001$
Midfoot dorsiflexion angle (°)	4.38 ± 3.44	11.1 ± 2.4	$P < 0.0001$
Arch height (CSI)	0.19 ± 0.15	0.35 ± 0.09	$P < 0.0001$
Arch height (CSI: only >0 included)	0.26 ± 0.12	0.35 ± 0.09	$P < 0.0001$
Medial weight transfer (CPEI)	13.7 ± 7.7	20.4 ± 7.1	$P < 0.0001$
Velocity (cm/sec)	117.19 ± 16.15	115.92 ± 15.02	$P = 0.69$
Step length (cm)	64.35 ± 6.43	64.08 ± 6.31	$P = 0.83$
Step width (cm)	9.98 ± 2.83	10.06 ± 3.79	$P = 0.89$
Foot rotation (°)	3.74 ± 5.56	3.74 ± 5.85	$P = 0.99$
Cadence (steps/min)	109.05 ± 9.24	108.48 ± 9.41	$P = 0.76$
Step time (sec)	0.55 ± 0.05	0.56 ± 0.05	$P = 0.76$
Swing time (sec)	0.41 ± 0.03	0.41 ± 0.03	$P = 0.52$
Stance time (sec)	0.69 ± 0.07	0.70 ± 0.07	$P = 0.47$
Single support time (sec)	0.41 ± 0.03	0.41 ± 0.03	$P = 0.52$
Double support time (sec)	0.27 ± 0.06	0.29 ± 0.05	$P = 0.26$

CSI: Chippaux–Smirak Index; CPEI: Center of Pressure Excursion Index.

cadence, step time, swing time, stance time, single support time, and double support time (Table 1). The study participants continued walking onto a High Resolution (HR) Mat VersaTek, a plantar pressure measuring system (Tekscan Inc., MA). The HR Mat is a roughly square plate measuring 487.7 mm × 447.0 mm and consisting of 8,448 sensing elements, collecting data at 185 Hz. The HR Mat is too small to collect multiple footprints, and we therefore have mixed data from both the left and right foot of our study participants. Two trials were performed with the first serving to calibrate the HR Mat to each individual using the walk calibration protocol of the Tekscan software. When it became clear that we would require kinematic data to test whether elevated lateral midfoot plantar pressure was in part a product of dorsiflexion in the midfoot, we added a video camera (Sony DCR-TRV280 Digital 8 Handycam) to our experimental apparatus. The video camera was placed to the right side of the VersaTek digital force plate, which allowed it to capture the lateral side of the right foot of our participants. The video data are coordinated with the plantar pressure data using Tekscan's video synch software package and were analyzed at 30 frames/s. Video data were collected on 141 of the 398 subjects studied. Of these, video of the right foot, in clear lateral view, was captured and quantified for 75 participants.

Peak plantar pressures and the center of force trajectory were calculated using the research foot software module (HR Mat Research 6.51). A present midtarsal break was defined as a region of pressure along the lateral midfoot that was in excess of 200 kPa. This value (200 kPa) is a standard pressure used by the podiatric community for identifying regions of interest (e.g., Bus et al., 2011), and was thus employed in this study. We simultaneously examined frame-by-frame video data using the Tekscan video synch software package to test whether those with elevated lateral midfoot pressure also exhibited midfoot dorsiflexion. Stills of the lateral midfoot in maximum dorsiflexion were captured and imported into ImageJ (NIH). Dorsiflexion was quantified as the angle formed between the plantar part of the forefoot and a line drawn along the plantar heel to the tuberosity of the 5th metatarsal as described in DeSilva (2010). Arches were quantified using the Chippaux–Smirak Index (CSI) (Chippaux, 1947; Smirak, 1960), which is a measure of the minimum width of the midfoot divided by the maximum width of the forefoot. A CSI of 0 signifies an arch high enough that at least a portion of the midfoot does not contact the ground at all. Medial weight transfer was measured using the center of pressure excursion index (CPEI) developed by Song et al. (1996). To calculate the CPEI, the center of force trajectory was mapped onto a participant's footprint using the Tekscan software. A straight line was drawn from the initial center of force point (typically on the heel), to the final center of force point (typically under the big toe). To calculate the CPEI, the distance from this line to the point along the center of force trajectory, that is the most laterally deviate, was measured and divided by the length of the line connecting the initial and final center of force points. Statistical significance was assessed using a Mann–Whitney *U* test since many of the parameters (e.g., CSI, CPEI) failed a Shapiro–Wilk test for normality. The gait parameters were all normally distributed and were assessed with a Student's *t*-test.

RESULTS

Eight percent of the subjects in our study had peak pressures in excess of 200 kPa in the lateral midfoot ($n = 32$ out of 398), and are regarded throughout the remainder of the paper as "midtarsal breakers." These included 16 females (6.5% of the total number of females) and 16 males (13.2% of the total number of males). Video data confirm that elevated midfoot pressure at the tarsometatarsal joint is present in individuals with excessive midfoot dorsiflexion, or a midtarsal break (Fig. 1). The angular magnitude of the midtarsal break (flexion in the sagittal plane) was 11.1° ± 2.4° ($n = 12$ midtarsal breakers with quantifiable video);

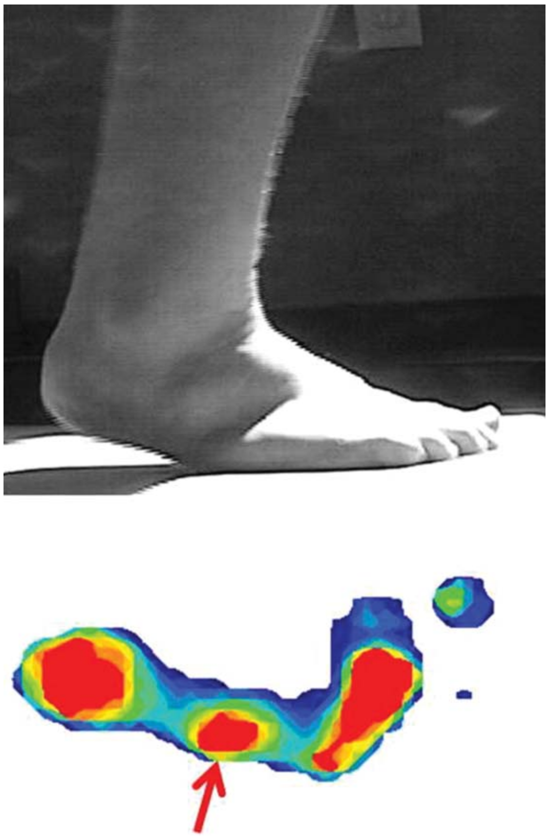

Fig. 1. A midtarsal break in a human foot (top image). This is the most extreme midtarsal break found in any of our participants ($\sim$20°). Below, notice the corresponding high pressure region (arrow) in the lateral midfoot. This plantar pressure signature has previously been only found in ape footprints (e.g., Crompton et al., 2010), but was found in 8% of the human footprints examined in this study.

significantly greater than the range of motion at the tarsometatarsal joint in non-midtarsal breakers (Table 1). Age ($P = 0.57$) did not differ between those with and without a midtarsal break.

BMI was statistically higher in those with a midtarsal break ($P = 0.03$). Almost a third ($n = 10/32$) of those with a midtarsal break had a BMI > 30, considered "obese" by the Center for Disease Control and Prevention. Nine were "overweight," twelve were normal weight, and one was "underweight" with a BMI <18.5, indicating that, while an important factor, weight alone does not explain midfoot mobility.

Those with a midtarsal break also had on average a higher CSI ($P < 0.0001$), and therefore a flatter foot, than those without a midtarsal break. Because the lateral midfoot is arched off the ground in individuals with high enough arches to have a CSI of 0, lateral midfoot pressure in these individuals is non-existent. We therefore tested the relationship between arch height and a midtarsal break in those with a CSI value >0 and found this too was strongly significant ($P < 0.001$). It is notable, however, that the average CSI of those with a midtarsal break is 0.35, considered intermediate by the podiatric community and biomechanists alike (e.g., Riddiford-Harland et al., 2000). Only five individuals had CSI values low enough to be considered "lowered" and only three had CSI values considered "flatfooted." Eleven individuals are in the "normal" range, while the majority ($n = 13/32$) are intermediate. These data indicate that although midtarsal breakers have on average a lower arch than the general population, those with so-called "normal" arches can still exhibit considerable midfoot mobility.

We performed a *post hoc* study examining whether the individuals with a midtarsal break differed from those with a rigid foot in measures related to foot function or overall walking performance. There were no significant differences between midtarsal breakers and others for any gait parameters measured (velocity, step length, step width, foot rotation, cadence, step time, swing time, stance time, single support time, double support time) (all $P > 0.1$). However, we found that those with a midtarsal break did have a statistically higher CPEI, compared with those without a midtarsal break ($P = 0.0001$) (Table 1). CSI and CPEI were correlated in our participants, though the CPEI explained only 4.5% of the variation in CSI, suggesting that both can independently contribute to midtarsal mobility in the human foot.

DISCUSSION

Though previous studies have presented anecdotal evidence that a midtarsal break can occur in humans (Vereecke et al., 2003; Crompton et al., 2010, 2012), this is the first study to document a frequency and to provide visual evidence for midfoot dorsiflexion in some human feet. Roughly 8% of the 398 humans examined in this study had a midtarsal break as defined by elevated pressure under the lateral midfoot, making it no longer accurate to argue that the midtarsal (or midfoot) break is entirely absent in humans, though it still remains unusual. However, in studying these plantar pressure maps, it became clear that the midtarsal break is a continuous, rather than dichotomous character, and we intend to examine these subtle differences in midfoot mobility in more detail in future studies.

Though 92% of humans do not have a midtarsal break (as defined in this study), it is of considerable interest that those with this midfoot mobility have a higher CPEI. Though this index is not a direct measure of midtarsal pronation, it was designed as a proxy for foot pronation (Song et al., 1996), and has been used by others as a pressure-based measure of foot pronation (Yoon et al., 2010; Hillstrom et al., 2013). Pronation of the subtalar joint results in an alignment of the transverse tarsal joints (Elftman, 1960; Close et al., 1967; Phillips and Phillips, 1983), making the midfoot mobile during stance phase, allowing it to adapt to its substrate and act as a shock absorber. A more recent cadaver study found that tarsometatarsal dorsiflexion is greatest during hindfoot eversion (a component of triplanar pronation) (Blackwood et al., 2005). The data presented in this current study suggest that humans with elevated medial weight transfer not only have a mobile midfoot, but have a mobile enough midfoot to produce a discernible midtarsal break. Furthermore, our finding that the arch is lower on average in midtarsal breakers is consistent with the role of the plantar ligaments (e.g., long plantar ligament) in stiffening the lateral midfoot.

It is therefore predicted that excessive pronators and low arched individuals might possess some anatomical correlates of a midtarsal break. For instance, though humans possess a dorsoplantarly flatter base of the fourth metatarsal compared to the other primates, there is considerable variation in this character (DeSilva, 2010), and we hypothesize that those with more convex lateral metatarsal bases also might exhibit the kind of midfoot dorsiflexion found in this study. The recent announcement of a convex base of a fourth metatarsal in *Australopithecus sediba* suggests that this species of early hominin possessed midfoot mobility (DeSilva et al., 2013), in contrast to the midfoot rigidity found in *Au. afarensis* (Ward et al., 2011) and *Au. africanus* (DeSilva, 2010). The data reported in this current study indicate that midfoot mobility in *Au. sediba* could have been caused by flatfootedness and/or excessive pronation, the latter of which is consistent with the postcranial fossils from Malapa cave (DeSilva et al., 2013).

It is important to recognize that the foot is exceptionally complex, making pronation and low arches just two of many possible contributing factors to midfoot flexibility. For instance, Crompton et al. (2010) present plantar pressure data on an individual with a midtarsal break who appears to have reduced medial weight transfer, and may simply have lax plantar ligaments, a thin plantar aponeurosis, or a weakly developed calcaneocuboid locking mechanism. In addition, excessive pronation is probably not the primary cause of the midtarsal break in non-human primates. Langdon et al. (1991) demonstrated that the transverse tarsal joint is aligned in both supination and pronation in apes. Furthermore, apes lack both the long plantar ligament and a robust plantar aponeurosis that help stabilize the plantar aspect of the foot in humans. Given that this study could not examine the calcaneocuboid joint morphology, or the anatomy of the plantar ligaments or plantar aponeurosis in the participants with a midtarsal break, we cannot yet speculate on how the variation in those structures may impact the variation in midfoot mobility. Nevertheless, our study indicates that a low arch and excessive medial weight transfer during stance phase can render the human midfoot flexible enough to produce a midtarsal break.

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