Savannah elephant foot metrics

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Introduction

The lengths and circumferences of all four feet in a sample of 162 (85 female and 77 male) elephants are presented. From these datasets, 159 had corresponding shoulder heights and 160 had estimated live weights. The results confirm constant relationships between foot metrics and shoulder height for East African elephants, and the load that elephant weight places on the ground in kg/cm^2 to be calculated.

Trophy hunters' and Asian elephant handlers' lore holds that front feet metrics are reliable indices of an elephant's height for both savannah elephants (*Loxodonta africana*) and Asian elephants (*Elephas maximus*). Biologists have examined this position, and Sukumar et al. (1988) methodically tested it for Asian elephants, concluding that forefoot circumference x 2.03 gave an accurate measurement for shoulder height. Western et al. (1983) tested hind foot length as an indicator of size and age in the African elephant (*Loxodonta africana*). Chapman et al. (2016) used footprints to estimate body size in Asian elephants indirectly. Wijanto et al. (2021) correlated foot circumference with body length, shoulder height, and pelvic width in Sumatran elephants (*E. m. sumatranus*). All the foregoing research indicated a close correlation between the foot metrics and shoulder heights. We add our findings to this body of information by presenting data sets of all four feet from 77 male and 85 female / East African savannah elephants across a wide age range.

In this field note, the authors seek answers to the following questions: 1) Do the lengths and circumferences of the savannah elephant fore and hind feet differ between left and right; and is there any change with age? 2) Do these metrics differ between males and females? 3) Do these metrics show any evidence of lateralisation analogous to right/left-handedness in humans or other animals? 4) Do these metrics show sufficiently consistent relationships to shoulder heights to be reliable guides to an elephant's size and sex?

Methodology and data analysis

Data for the analyses were obtained from elephants culled to reduce numbers on the north bank of the Victoria Nile in Uganda's Murchison Falls National Park (NP) in 1965, as described by Laws and Parker (1968). All measurements were taken in cm using a steel tape immediately post-mortem. Lengths were a straight line across the sole of the foremost and hindmost point on each foot. On field data sheets, the length data were recorded as diameters. This error persists in the archived material held in the University of Florida[1]. Lateral widths were not recorded. Circumferences were the distances around the edge of the sole, including toenails. Live weights in kg were routinely calculated (Laws et al.1967) and shoulder heights in cm taken from the locked foreleg of all elephants culled. The latter was used as the standard measure of an elephant's size as described in Laws et al. (1975). Ages were estimated using the molar key provided by Laws (1966).

To compare variability in the foot length and circumference measurements, we used the left and right of each forefoot and hindfoot length and circumference as pairs of measurements. We

[1]https://ufdc.ufl.edu/IR0001446

calculated the absolute difference between each pair and the mean of the pair for each elephant, (from the left and right forefoot and hindfoot length and circumference) and then averaged these values across all elephants for each metric.

For analyses including age as an effect, we first created annual classes by standardising ages into year classes 0.5, 1.5, 2.5 ... where 0.5 = 0–0.9, 1.5 = 1.0–1.9 etc. For statistical analysis requiring age as a categorical variable, we grouped these into five categories (five age categories): ages 0–5, 5–10, 10–18, 18–28 and 28–61.

Permutational ANOVAs were performed in the Permanova add-on (Anderson et al. 2008) to Primer v6 (Clarke and Gorley 2006). We used Euclidean distance, Type III (partial) sums of squares, fixed effects summing to zero for mixed terms, and 9,999 permutations of residuals under a reduced model.

To examine the relationship between age and foot dimensions, we evaluated four PERMANOVA models, one for each of the mean within individuals of forefoot length, hindfoot length, forefoot circumference and hindfoot circumference. Fixed terms in the analyses were sex and five age categories, and we considered their interaction. We then fitted exponential rise-to-maximum equations with a y-intercept to each dimension for each sex; the y-intercept expresses size at birth.

To examine the role of sex and foot dimensions in predicting shoulder height, we used hindfoot and forefoot circumference and divided it into five approximately equal classes: 50–75, >75–90, >90–100, >100–110 and >110 cm. Shoulder height was then modelled as a PERMANOVA with sex, hindfoot circumference class and the interaction between them as factors.

We calculated the ratio of circumference to length for each foot to examine the variation in foot shape, as expressed by the relationship between foot length and circumference. This was then modelled as a PERMANOVA with fixed effects of sex, age5cat, side (left, right), and front/rear. Individuals (nested in sex and five age categories) were included as a random effect because the feet of an individual may not be regarded as independent. Second-order interactions involving sex and age were included in our calculations, but no other interaction terms were included.

To estimate weight loading, we need the cross-sectional area of each foot. Elephant's feet are elliptical in cross-section. In the following calculations:

A = area
a = length/2
b = width/2
C = circumference.

The area of an ellipse is:

$$A = \pi * a * b.$$

As we have data for length but not width, width was approximated from circumference and length as follows, using the simple first approximation:

C = 2 * π * square root ((a2 + b2)/2)

https://www.mathsisfun.com/geometry/ellipse-perimeter.html, viewed 27 May 2025. This approximation is accurate within 5% for the relatively rounded feet of elephants.

This was resolved for half-width as:

b = square root (2 * (C/(2π))2 – a2)

We calculated b and hence A for each elephant foot. We summed A across all four feet and, using weights for each individual, calculated weight loading. We then modelled weight loading in a PERMANOVA with sex and age5cat as fixed effects.

Results

The absolute difference between left and right pairs for measurements of foot length and circumference was zero for just over one-third (35.5%) of pairs. Mean absolute differences were similar but somewhat lower for hindfeet and circumference (Table 1). This is inconsistent with the notion that length is the more accurate measurement, though alternative explanations relating to foot shape are possible.

Table 1. Comparison of mean absolute difference as ratios in measurements between left-right pairs of foot measurements of African savannah elephants.

	Forefeet	Hindfeet
Length	0.01176	0.00698
Circumference	0.00557	0.00411

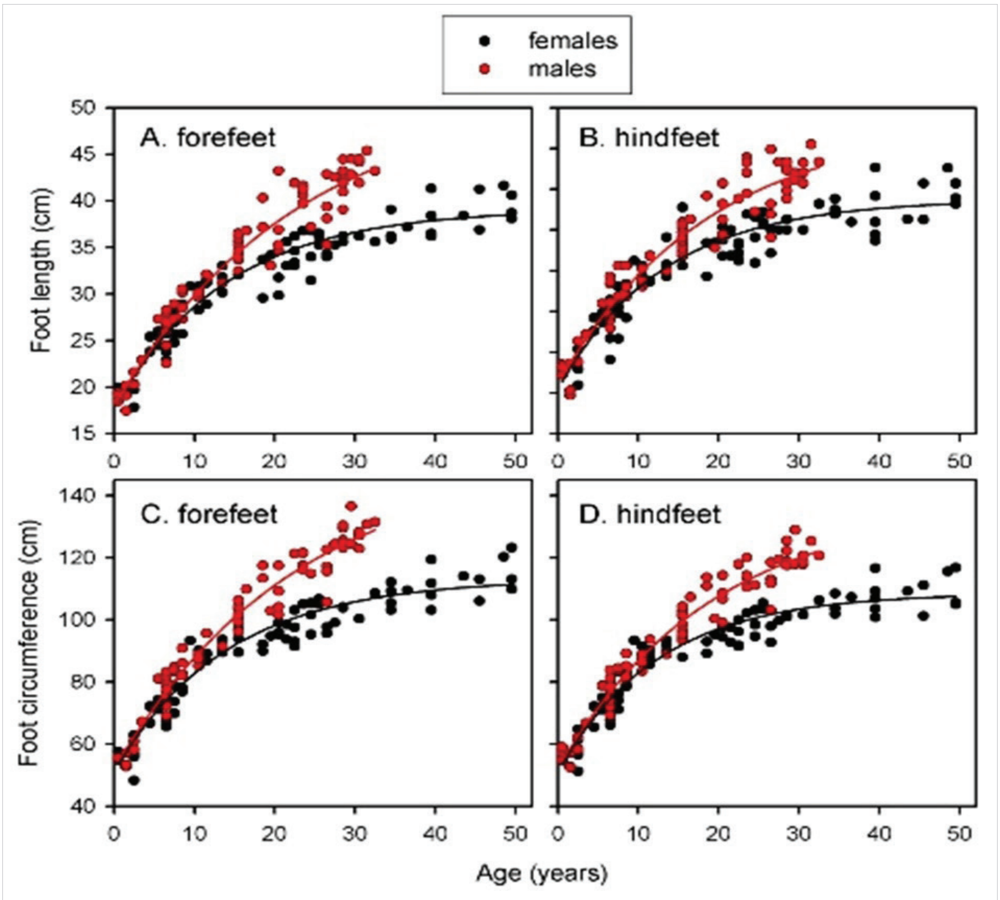

Figure 1 Growth of feet metrics with age in African savannah elephants. See Table 2 for regression equations.

Table 2. Exponential rise-to-maximum regression equations for the growth of feet in African savannah elephants (from Fig. 1).

Metric	Intercept	a constant	b exponent	Adjusted R^2 (%)	p
Female forefeet length	17.657	21.445	0.0718	90.5	< 0.0001
Female hindfeet length	20.466	23.248	0.0764	87.7	< 0.0001
Female forefeet circumference	51.091	62.087	0.0712	90.5	< 0.0001
Female hindfeet circumference	50.922	57.629	0.0808	90.8	< 0.0001
Male forefeet length	17.909	33.832	0.0434	93.4	< 0.0001
Male hindfeet length	21.149	32.262	0.0532	91.6	< 0.0001
Male forefeet circumference	51.763	101.703	0.0438	95.7	< 0.0001
Male hindfeet circumference	52.040	86.015	0.0520	95.0	< 0.0001

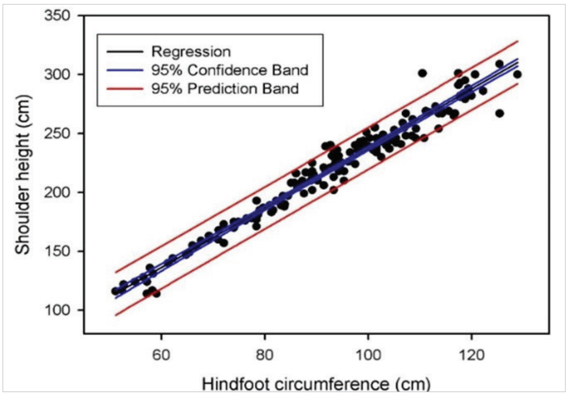

Figure 2. Hindfoot and forefoot circumferences as predictors of shoulder height in 159 African savannah elephants. The regressions are: shoulder height (in cm) = 2.524*hindfoot circumference – 15.1521 (R^2 = 96.3%; F1,155 = 4114.4, p<0001). Shoulder height (in cm) = 2.287* Forefoot circumference (in cm) + 2.6955 (R^2 = 96.4%; F 1.155 = 4182.5, p<0.0001.

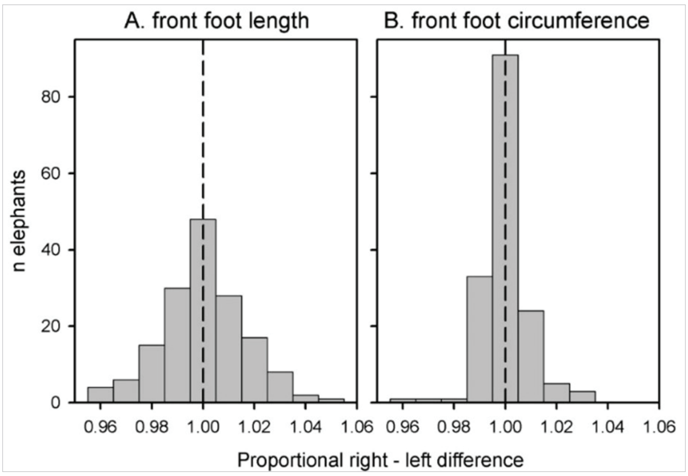

Figure 3. Proportional differences between left and right front feet dimensions in 161 African savannah elephants. The dashed lines indicate perfect symmetry.

Growth

Fore- and hind-feet lengths and circumferences varied significantly with sex and age and the interaction between the two (p = < 0.001). For all four parameters, males grew quicker and larger than females (Fig. 1).

Shoulder height differed strongly among hindfoot circumference classes (p = 0.0001), but not between the sexes (p = 0.778), though the interaction term was significant (p = 0.018). The relationship between shoulder height and hindfoot circumference was strongly linear, even when the sexes were combined (Fig. 2).

Laterality

The length of left and right forefeet of 30.2% of elephants were within 0.5% of equal, whilst the equivalent figure for circumference was 57.2%, with no indication that more had larger left than right feet or vice versa (Fig. 3).

Foot shape

In cross-section, elephant feet are elliptical and slightly to markedly elongate (indicated by circumference: length < π), rarely marginally wider than long (Fig. 4). Foot shape varied between individuals, between front and rear feet, and less strongly between the

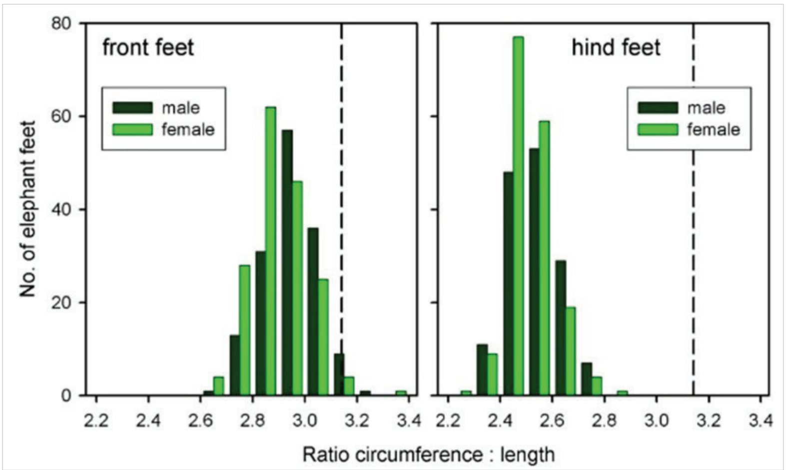

Figure 4. The shape of the front and hind feet of male and female African savannah elephants is indicated by the ratio of circumference to length. Mean ratios are: male front 2.95; female front 2.89; male hind 2.53; female hind 2.51. The dashed line is π, the value at which feet would be as wide as long.

Table 3. Significance of terms in a PERMANANOVA model of foot shape (the ratio of foot circumference to length) of African savannah elephants. Significant terms are highlighted.

Term	Probability
Sex	**0.003**
Age	0.252
Side of feet	0.942
Front/rear feet	**0.0001**
Individual (nested in Sex and Age)	**0.0001**
Sex x Age	0.460
Sex x Side of feet	0.775
Sex x front/rear feet	**0.007**
Age x Side of feet	0.160
Age x Front/rear feet	0.804

sexes (Table 3). Neither age nor any interactions involving it were significant, and there was no suggestion of consistent laterality—the side of the foot term. Hind feet are markedly more elongate than front feet, and females have a little more elongate feet than males, more so on the front than hind feet (the interaction term 'Sex x front/rear feet' in Table 3).

Weight loading

The area of all elephant feet (four feet summed for the individual) ranged from 660.6 cm^2 in a 2-yr-old female to 5,476.2 cm^2 in a 29-year-old male. Estimated weight loads of elephants ranged from 0.280 to 1.092 kg/cm^2. Loads varied between the sexes (p=0.0004) and age classes (p=0.0001), and the interaction between sex and age class was also very highly significant (p=0.0001). Weight load increased with age, with males and females having similar loadings up to approximately 10 years of age, males developing heavier loadings thereafter (Fig. 5). In the age range available for the analysis, males showed no asymptotic weight load, but females did, with those aged 50 years having an estimated weight load of 0.81 kg/cm^2.

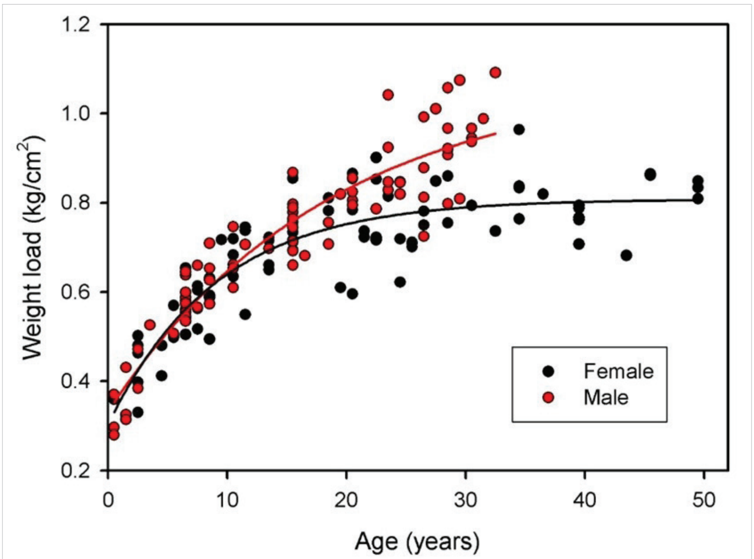

Figure 5. Weight loadings (mass/area of feet) in African savanna elephants. Model parameters are:
males: 0.7518(1–e^(-0.0542*age))+0.3321; R2 = 87.2%, p<0.0001; and
females: 0.5046(1–e^(-0.1102*age))+0.3031; R2 = 76.3%, p<0.0001.

Discussion

Answers to questions asked in the introduction follow. Do the lengths and circumferences of the savannah elephant fore and hind feet differ between right and left, and is there any change with age? They do not differ significantly between the right and left, and there is no noticeable change in the ratios of one to the other with age.

Both hindfoot and forefoot circumferences are strong predictors of shoulder height regardless of age and sex, and regression equations are provided for this. Do these metrics differ between males and females? Yes, they do, and this is in accordance with the other morphological data (e.g. shoulder heights) recorded, for example, in Laws et al. (1975).

Do these metrics show any evidence of lateralisation analogous to right/left-handedness in humans or other animals? In keeping with the similar finding on tusk use (Parker 2024), there is no obvious evidence of lateralisation. However, this does not eliminate the possibility of innate lateral bias. Proof of its existence now rests on observing behaviour rather than upon morphological features.

It is an assumption that an elephant's footprint will exactly mirror the sole that made it. Self-evidently, they must be more or less the same. Pedantic perhaps, but this assumption has not been objectively verified. From IP's experience tracking elephants, their footprints are strongly influenced by the hardness or softness of the substrate was (i.e. compacted earth, sand or mud) onto which their feet were placed, as well as the pace at which the imprinters (elephants) were travelling. If running, the central toenail at the front of an elephant's foot digs into the ground, leaving a small mound inside the anterior aspect of the imprint, and upon withdrawal forward, will extend the print length. The print of a walking or standing elephant will be close to the size of the imprinting sole, but where it is soft, as in sand or mud, this precision is less likely. Beyond giving a general idea of the imprinting elephant's size, the overlap between male and female lengths makes determining sex uncertain. Consequently, beyond providing a general idea of size, and until footprints have been objectively contrasted to foot soles, their relationship remains a subjective assumption. We conclude that while footprints are guides to an elephant's size, they are not precise indices and should be treated as such.

We have confirmed that in shape savannah elephant's forefeet are not circular, but slightly elliptical, whereas the rear feet are strongly elliptical. An elephant's gait and the broad soles of its feet spread its live weight load on the ground more widely than the gaits of equines and bovids, whose hooves concentrate their weights on more restricted areas. While self-evident and somewhat esoteric, it is an aspect to consider when comparing the influences of elephants on their environments with those of other large animals, for example, in their respective roles on soil erosion.

Acknowledgements

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