Measuring body dimensions of leopards (*Panthera pardus*) from camera trap photographs

Allan Tarugara[1,2], Bruce W. Clegg[1], Edson Gandiwa[2], Victor K. Muposhi[2] and Colin M. Wenham[1]

[1] Malilangwe Wildlife Reserve, Chiredzi, Masvingo, Zimbabwe
[2] School of Wildlife, Ecology and Conservation, Chinhoyi University of Technology, Chinhoyi, Mashonaland West, Zimbabwe

ABSTRACT

Measurement of body dimensions of carnivores usually requires the chemical immobilization of subjects. This process can be dangerous, costly and potentially harmful to the target individuals. Development of an alternative, inexpensive, and non-invasive method therefore warrants attention. The objective of this study was to test whether it is possible to obtain accurate measurements of body dimensions of leopards from camera trap photographs. A total of 10 leopards (*Panthera pardus*) were captured and collared at Malilangwe Wildlife Reserve, Zimbabwe from May 7 to June 20, 2017 and four body measurements namely shoulder height, head-to-tail, body, and tail length were recorded. The same measurements were taken from 101 scaled photographs of the leopards recorded during a baited-camera trapping (BCT) survey conducted from July 1 to October 22, 2017 and differences from the actual measurements calculated. Generalized Linear Mixed Effects Models were used to determine the effect of type of body measurement, photographic scale, posture, and sex on the accuracy of the photograph-based measurements. Type of body measurement and posture had a significant influence on accuracy. Least squares means of absolute differences between actual and photographic measurements showed that body length in the level back-straight forelimb-parallel tail posture was measured most accurately from photographs (2.0 cm, 95% CI [1.5–2.7 cm]), while head-to-tail dimensions in the arched back-bent forelimb-parallel tail posture were least accurate (8.3 cm, 95% CI [6.1–11.2 cm]). Using the BCT design, we conclude that it is possible to collect accurate morphometric data of leopards from camera trap photographs. Repeat measurements over time can provide researchers with vital body size and growth rate information which may help improve the monitoring and management of species of conservation concern, such as leopards.

Subjects Animal Behavior, Conservation Biology, Ecology
Keywords Accuracy, Bait, Morphometrics, Non-invasive, Posture

INTRODUCTION

Body size is an important variable in carnivore biology. Within populations, individuals of the same species often exhibit variation in body size (*Hamilton, 1961*; *McNab, 2010*; *Nwaogu et al., 2018*). Investigation of the driving factors behind this ecological

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Corresponding author
Allan Tarugara,
allantarugara@gmail.com

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phenomenon is of conservation and management relevance and consequently, body size has been used to gauge important ecological effects. For example, how body size varies across subjects exposed to different weather conditions (*East, 1984*; *Klein, 1986*; *Carbone et al., 2014*), food resources (*Radloff & Du Toit, 2004*; *Hayward & Kerley, 2008*; *Owen-Smith & Mills, 2008*; *Carbone, Pettorelli & Stephens, 2011*) and time periods (*Jablonski, Erwin & Lipps, 1996*; *Yom-Tov, 2001*; *Van Buskirk, Mulvihill & Leberman, 2010*). While evaluation of body size may be relatively easy for captive individuals it is more difficult for free-ranging animals. It is especially challenging when subjects are dangerous, for example, leopards (*Panthera pardus*). Under these circumstances, target individuals are usually captured and chemically immobilized. However, this is intrusive, costly and can be potentially harmful to the animals or the handlers (*Chinnadurai et al., 2016*; *Najera et al., 2017*). Consequently, it is often difficult to obtain an adequate sample size of body measurements (*Fukuda et al., 2013*; *Law, De Kort & Van Weerd, 2016*; *Turner et al., 2016*; *Rothe-Groleau, Rauter & Fawcett, 2018*). Body dimensions are routinely measured during collaring exercises but the proportion of collared individuals in each age and sex class is generally low which brings into question the representativity of the morphological data for the different groups (*Cichoń, Dubiec & Chadzińska, 2001*). Devising a method of remotely obtaining body measurements would improve the resolution of the data because a large proportion of the population could be measured without the need for immobilization.

Little information is available on measuring body dimensions of carnivores from photographs. *Ferreira & Funston (2010)* and *Shumba et al. (2017)* successfully measured body dimensions of lions (*Panthera leo*) and wild dogs (*Lycaon pictus*) from photographs collected using hand-held digital cameras. While useful, the method may not be effectively applied to leopards due to their secretive nature. Camera trapping has emerged as a powerful tool for monitoring leopards and similarly marked carnivores in their natural habitats (*Karanth & Nichols, 2011*; *Sollmann, Mohamed & Kelly, 2013*; *Burton et al., 2015*) and the technique could provide a means of addressing this problem. However, measurement of body dimensions of leopards from camera trap photographs has not been attempted. This study seeks to fill this gap.

Here we test a simple method of collecting morphometric data on free-ranging leopards from photographs collected using camera traps in a savanna ecosystem. In this study, baits were used as a means of attracting leopards to camera stations. The main objective of the study was to establish whether it is possible to collect accurate body measurements of leopards from camera trap photographs. The findings may broaden the presently available knowledge on carnivore morphometrics, possibly influencing policy and management, especially where species of interest are hunted. To the best of our knowledge, this is the first study to report on collecting morphometric data of leopards from camera trap photographs in a savanna ecosystem.

MATERIALS AND METHODS

The study was carried out using a sample of leopards from Malilangwe Wildlife Reserve (MWR), a medium-sized (490 km^2), fenced, protected area in the semi-arid savanna of

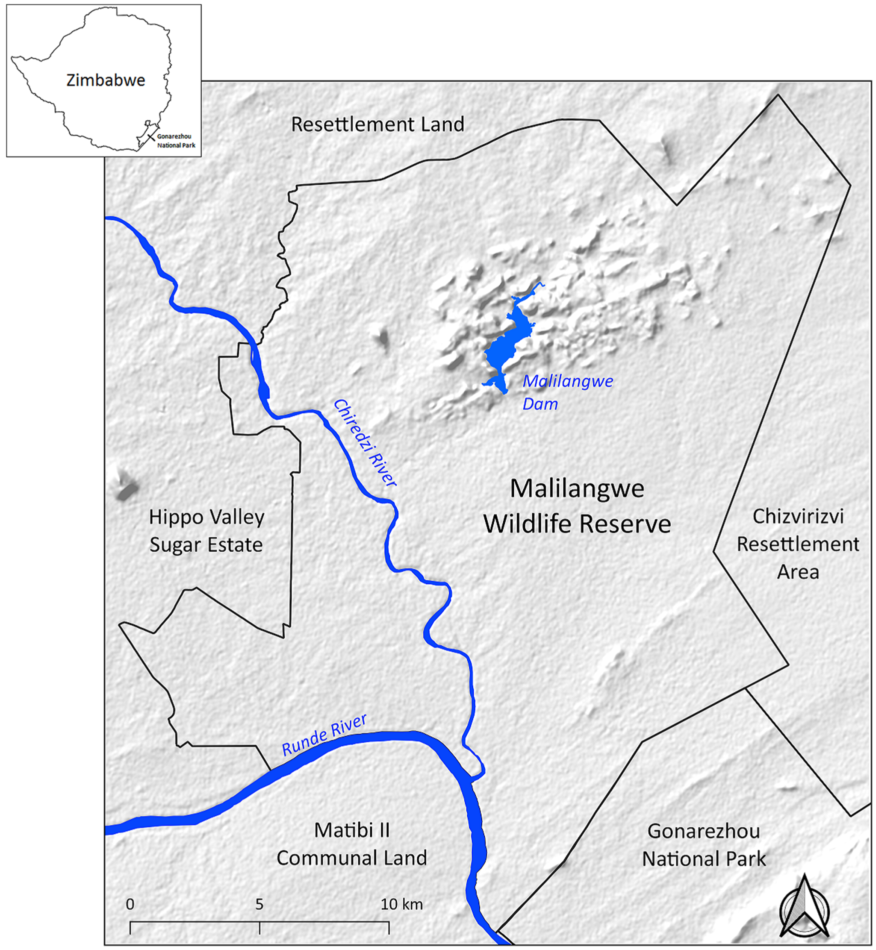

Figure 1 **Location of Malilangwe Wildlife Reserve in Zimbabwe.**
Full-size DOI: 10.7717/peerj.7630/fig-1

south-eastern Zimbabwe (20°58′ and 21°15′S and 31°47′, and 32°01′E) (Fig. 1). MWR is a non-hunting property whose main objectives are conservation and community development. Rainfall (mean ≈ 560 mm per annum, n = 66 years, CV = 34%) is seasonal with approximately 84% of precipitation occurring between November and March. The average minimum and maximum monthly temperatures range from 13.4 °C (July) to 23.7 °C (December) and 23.2 °C (June) to 33.9 °C (November), respectively (*Clegg & O'Connor, 2017*). Altitude ranges from 290 m, in river systems, to 500 m above sea level on sandstone hills (*Traill & Bigalke, 2007*).

Malilangwe Wildlife Reserve is generally characterized by open savanna woodland dominated by *Colophospermum mopane*. Vegetation cover is diverse, ranging from grassland to dry deciduous woodland, with 38 vegetation types occurring on soils ranging from 90% sand to 40% clay (*Clegg & O'Connor, 2012*). The leopard population at MWR is estimated at 61 (61–67) individuals (*Tarugara et al., 2019*) and the main prey species (density in parentheses) are impala (*Aepyceros melampus*, 13.6 km^{-2}), nyala (*Tragelaphus angasii*, 0.38 km^{-2}) and bushbuck (*T. sylvaticus*, 0.22 km^{-2}) (*Clegg, 2017*). Competing

Table 1 Morphometric measurements recorded for sample leopards.

Measurement	Description
Body length	From the most posterior point of the head along the contour of the body to the proximal base of the tail
Shoulder height	Perpendicular distance between point of shoulder blade to heel of foot
Tail length	From the proximal base to the tip of the last tail vertebra
Head-to-tail length	From the tip of the nose, tracing between the eyes over the head and along the contour of the body to the tip of the tail's last vertebra

predators include lion (0.1 km^{-2}), spotted hyena (*Crocuta crocuta*, 0.12 km^{-2}), wild dog (0.06 km^{-2}), and cheetah (*Acinonyx jubatus*, 0.02 km^{-2}) (*Clegg, 2017*).

Research design

In this study, morphometric data were collected in two stages. First, actual dimensions were physically recorded from target individuals chemically immobilized for collaring and second, a set of body measurements from the same collared leopards were obtained from camera trap photographs. Measurements recorded on the leopards themselves served as a baseline upon which comparison with photograph-based measurements could be made. Because it was not logistically possible to obtain reference measurements of the entire leopard population at MWR, photograph-based measurements were limited to sample collared individuals. The dataset comprised measurements taken from multiple photographs of each collared leopard and consequently analysis followed a repeated measures design (*Fitt & Lancaster, 2017*; *Christiansen et al., 2018*).

Data collection

Actual body dimensions

Reference measurements were obtained during a leopard collaring exercise conducted at MWR between May 7 and June 20, 2017. Walk in, fall-door traps were used to capture five male and five female leopards for fitting with Followit Global Positioning System collars (Followit, Lindesberg, Sweden). Subjects were chemically immobilized with a combination of Zoletil-Medetomidine (1.0–0.03 mg/kg body mass), with the anesthetic being darted into the muscular region of the hindquarters. Reversal was achieved by injection of Antisedan (at 2.5 mg/mg of Medetomidine) or Yohimbine (at one ml/50 kg of body weight). All handling procedures were performed by a licensed practitioner (with Zimbabwean Dangerous Drugs License number: 2017/25) following safe, professional and humane guidelines (*Sikes & Animal Care and Use Committee of the American Society of Mammalogists, 2016*). Ethical clearance for the study was granted by the Chinhoyi University of Technology Ethics Committee (clearance number: 01/17).

Following the protocols laid out in *De Waal, Combrinck & Borstlap (2004)* four morphometric measurements were taken to the nearest 0.1 cm from each anesthetized leopard (Table 1). A non-stretch tape was used to measure body, tail and head-to-tail length and a graduated wooden sliding caliper was devised to record shoulder height

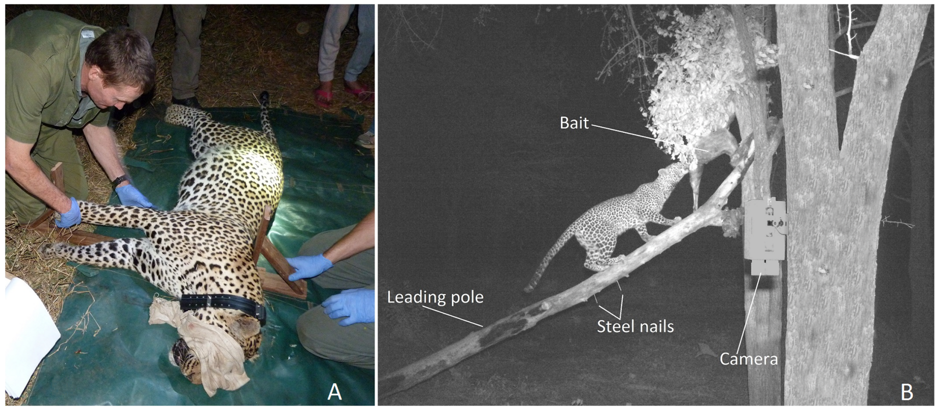

Figure 2 Actual and image-based data collection. (A) Researchers measure shoulder height with a sliding wooden caliper and (B) arrangement of bait, leading pole and camera at sampling stations. (Photo credit: Sarah Clegg). Full-size DOI: 10.7717/peerj.7630/fig-2

(Fig. 2A). A photograph of the right-side profile of each leopard was taken for identification (individual leopards have unique rosette patterns).

Camera trap data collection

Photographic data were collected as part of a baited-camera trapping (BCT) survey conducted in the study area from July 1 to October 22, 2017 (*Tarugara et al., 2019*). Camera trapping commenced 11 days after collaring so errors due to growth post collaring were negligible. A total of 210 BCT stations were distributed across the study area in a stratified random pattern to record presence data. At each sampling station, two trees spaced two to four m apart were chosen, one for the bait and the other for the camera. An impala carcass was secured to the bait-tree with wire and a leading pole was placed against the tree to provide easy access for leopards. A Cuddeback C2 infra-red camera (Cuddeback, Green Bay, WI, USA) was secured to the camera-tree to the right of each bait. In this way, only the right-side profile of a leopard was photographed. Two stainless steel nails were driven 20 cm apart into the leading pole and cameras set such that photographs included this detail in their frame (Fig. 2B). Hyenas, lions, and elephants (*Loxodonta africana*) visit baited sampling stations, sometimes moving the nails and the leading pole. Photographs without the nails or leading pole were not usable because they could not be scaled. To remedy any interference, sampling stations were monitored every third day and the set-up refreshed.

Data analyses

Photograph-based measurements

Collared individuals were uniquely identified from the rosette patterns on their right flanks. Data for eight of the 10 collared individuals were used in the analyses; one male shrugged off its collar and one female left the reserve early in the study. Photographs containing leopards that were not positioned correctly for measuring were discarded from the dataset before analysis. Data were analyzed using ImageJ software (*Schneider, Rasband & Eliceiri, 2012*), an image processing program that facilitates scaling and measuring of distances on photographs. A reference measurement was made between the

Table 2 Posture categories used in the study.

Posture	Description
Level back-straight forelimb-inward tail	Back flat, forelimb extended, tail curved away from observer
Level back-straight forelimb-outward tail	Back flat, forelimb extended, tail curved toward observer
Level back-straight forelimb-parallel tail	Back flat, forelimb extended, tail parallel to leading pole
Level back-bent forelimb-inward tail	Back flat, forelimb angled, tail curved away from observer
Level back-bent forelimb-outward tail	Back flat, forelimb angled, tail curved toward observer
Level back-bent forelimb-parallel tail	Back flat, forelimb angled, tail parallel to leading pole
Arched back-straight forelimb-inward tail	Back contorted, forelimb extended, tail curved away from observer
Arched back-straight forelimb-outward tail	Back contorted, forelimb extended, tail curved toward observer
Arched back-straight forelimb-parallel tail	Back contorted, forelimb extended, tail parallel to leading pole
Arched back-bent forelimb-inward tail	Back contorted, forelimb angled, tail curved away from observer
Arched back-bent forelimb-outward tail	Back contorted, forelimb angled tail curved toward observer
Arched back-bent forelimb-parallel tail	Back contorted, forelimb angled, tail parallel to leading pole

steel nails visible in the photograph. The measurement was taken at the base of the nails (point of entry into the pole) to minimize error resulting from splaying should nails be bumped by animals. By default, ImageJ measures this distance in pixels. The *Set Scale* function of the program was used to define the spatial scale of the photographs such that measurements could be made in calibrated units, for example, centimeters. Because the distance between the camera and the bait-tree could not be standardized, the relative measurement represented by the scaling standard varied between photographs. The known distance (20 cm) between the nails was therefore assigned to the reference measurement and the program calculated a scaling factor (pixels cm^{-1}) which was recorded for each photograph. The four body dimensions (shoulder height, head-to-tail, body, and tail length) were measured from the photographs using the same protocols applied when the reference dimensions were recorded. The absolute differences between the ImageJ measurements and the actual recorded during collaring were calculated.

Posture categorization

Posture was divided into 12 categories (Table 2) and each photograph was assigned the category that best described it (*Waite et al., 2007*; *Meise et al., 2014*). Posture categories that had few observations were dropped from the analysis as including them resulted in model convergence issues. The result was a posture variable with three categories (level back-straight forelimb-parallel tail (LB-SF-PT), level back-bent forelimb-parallel tail (LB-BF-PT), and arched back-bent forelimb-parallel tail (AB-BF-PT)) (Fig. 3).

Accuracy of measurements

We used the generalized linear mixed-effects model (GLMM) of the *glmer* function in the *lme4* package of R (*R Core Team, 2017*; *Bates et al., 2018*) to determine the fixed effects of *body measurement* (factor with four levels), *posture* (factor with three levels), *sex* (factor with two levels) and *scaling factor* on the accuracy of photographic measurements. Multiple measurements of the same leopard or from the same baiting station were not independent, therefore we used *sampling station ID* (spatial non-independence) and

Figure 3 Pictorial representation of three most common leopard postures used in the study. (A) level back-straight forelimb-parallel tail (with outline of shoulder height), (B) level back-bent forelimb-parallel tail (with outline of body length), and (C) arched back-bent forelimb-parallel tail (with outline of head-to-tail length measurement). Full-size DOI: 10.7717/peerj.7630/fig-3

leopard ID (within subject non-independence) as random effects in the GLMM and the absolute difference between photographic and field measurements as the dependent variable. Distributions plotted using the *ggplot2* package of R (*Wickham et al., 2018*) showed that data were right skewed and therefore models of the gamma family were constructed, with a loglink function specified to achieve homoscedasticity of residuals. The significance of each fixed effect was determined using a Type II analysis of variance by running the *Anova* function of the *car* package of R (*Fox & Weisberg, 2018*) on the model's output. A Type II analysis was chosen because interactions of fixed effects were not specified in the model. The fixed effects of *sex* and *scaling factor* were not significant therefore these were dropped and the model re-run. The *lsmeans* package of R (*Lenth, Love & Lenth, 2018*) was then used to calculate the least squares means (and 95% confidence intervals) of the absolute differences for the various body measurement and posture combinations. Pairwise comparisons were conducted on the means using Tukey's post hoc test. A compact letter display was constructed using the *cld* function of the *multcompView* package of R (*Piepho, 2004*) to show significant differences ($\alpha = 0.05$) between the least squares means.

RESULTS

A total of 422 camera trap photographs containing eight of the target leopards, recorded from 26 sampling stations, were retrieved from the global dataset. From these, 101 photographs were used to obtain 210 morphometric measurements (Table 3). All the target leopards used in this study were correctly identified from the photographs. Analysis of variance showed that *body measurement* and *posture* had a significant influence on the accuracy of measurements, while the effects of *sex* and *scaling factor* were not significant (Table 4). The results of the final model run in the GLMM (Absolute difference ~ *body measurement* + *posture* + (1|*leopard ID*) + (1|*sampling station ID*) are given in Table 5.

Accuracy of photograph-based measurements

Pairwise comparisons of least square means of absolute differences (Table 6) showed that body length was measured most accurately from the photographs followed by shoulder

Table 3 Data for fixed effects used in the GLMM. Figures indicate the number of observations per combination of fixed effects and acronyms LB-SF-PT, LB-BF-PT, and AB-BF-PT represent the level back-straight forelimb-parallel tail, level back-bent forelimb-parallel tail and arched back-bent forelimb-parallel tail posture categories, respectively.

Leopard ID	Sex	Body length			Head to tail length			Tail length			Shoulder height	
		LB-SF-PT	LB-BF-PT	AB-BF-PT	LB-SF-PT	LB-BF-PT	AB-BF-PT	LB-SF-PT	LB-BF-PT	AB-BF-PT	LB-SF-PT	LB-BF-PT
Hunyugwe	M	3	3	2	–	1	2	–	1	2	6	2
Mubangweni	M	4	3	4	2	3	4	2	3	4	6	2
Safari camp	M	2	3	–	–	2	–	–	2	–	2	3
Nduna	M	–	2	–	1	1	–	3	2	–	3	3
Chipinyuluzi	F	2	2	1	2	–	2	2	–	1	1	2
Banyini	F	2	9	–	2	10	–	2	9	–	6	4
Swamps	F	1	–	3	1	–	3	1	–	3	1	–
Mamhande	F	5	4	2	4	3	2	4	3	2	14	7

Table 4 Analysis of variance for the model: Absolute difference ~ *body measurement* + *scaling factor* + *posture* + *sex* + (1|*leopard ID*) + (1|*sampling station ID*).

Fixed effect	df	chisq	Pr (>chisq)
Body measurement	3	38.82	<0.001
Posture	2	32.61	<0.001
Sex	1	1.05	0.306
Scaling factor	1	0.12	0.730

Note:
Fixed effects with Pr (>chisq) values <0.05 were considered significant.

Table 5 GLMM results of the model: Absolute difference ~ *body measurement* + *posture* + (1|*leopard ID*) + (1|*sampling station ID*). LB-BF-PT and LB-SF-PT represent the level back-bent forelimb-parallel tail and level back-straight forelimb-parallel tail posture categories, respectively.

A. Fixed effects	Estimate	Std. Error	*t* value	Pr (>|z|)
Body measurement				
Body length (intercept)	1.239	0.167	7.399	<0.001
Head-to-tail length	0.804	0.139	5.787	<0.001
Shoulder height	0.448	0.130	3.439	<0.001
Tail length	0.605	0.138	4.394	<0.001
Posture				
LB-BF-PT	0.071	0.160	0.442	0.659
LB-SF-PT	−0.528	0.152	−3.464	<0.001
B. Random effects		**Variance**		**Std.Dev**
Sampling station ID		0.028		0.169
Leopard ID		0.017		0.132
Residual		0.463		0.680

Table 6 Least squares means and confidence intervals across body measurement and posture categories. Values represent least square means of absolute differences (cm) and 95% confidence intervals (in parentheses). LB-SF-PT, LB-BF-PT, and AB-BF-PT represent the level back-straight forelimb-parallel tail, level back-bent forelimb-parallel tail and arched back-bent forelimb-parallel tail posture categories, respectively.

	LB-SF-PT	LB-BF-PT	AB-BF-PT
Body length	2.0 (1.5–2.7)	3.7 (2.8–4.9)	3.5 (2.5–4.8)
Shoulder height	3.2 (2.5–4.1)	5.8 (4.5–7.5)	5.4 (3.8–7.8)
Tail length	3.7 (2.8–5.0)	6.8 (5.0–9.1)	6.3 (4.5–8.9)
Head-to-tail length	4.5 (3.4–6.1)	7.7 (5.5–10.8)	8.3 (6.1–11.2)

height, tail length, and head- to- tail length respectively (Fig 4). Of the three postures, LB-SF-PT produced the most accurate measurements followed by LB-BF-PT and AB-BF-PT respectively. The range of error across the different types of body measurements and postures was 1.5–11.2 cm and the mean scaling factor was 10.4 pixels cm^{-1}. Overall, body length measured from the LB-SF-PT posture was most accurate.

DISCUSSION

This study demonstrated that it is possible to obtain accurate body measurements of leopards from camera trap photographs in savanna ecosystems. Measurement of body length from the LB-SF-PT posture was the most accurate. The arrangement of material at BCT stations made measurement from photographs possible. Photograph-based measurement of body dimensions has been successfully carried out for primates (Infraorder: *Similiformes*) (*Rothman et al., 2008*; *Barrickman, Schreier & Glander, 2015*), sea lions (*Zalophus wollebaeki*) (*Meise et al., 2014*), western fence lizards (*Sceloporus occidentalis*) (*Lambert, Yasuda & Todd, 2012*), fish (classes: *Chondrichthyes* and *Osteichthyes*) (*Rochet, Cadiou & Trenkel, 2006*; *Deakos, 2010*), horses (*Equus ferus caballus*) (*Weisgerber, Medill & McLoughlin, 2015*), sheep (*Ovis aries*) (*Zhang et al., 2018*), and cattle (*Bos taurus*) (*Tasdemir et al., 2008*; *Tasdemir, Urkmez & Inal, 2011*).
The method described here is best suited for marked carnivores that readily take baits and can climb up the leading pole. With careful consideration, the technique may be modified for studying other carnivore species (e.g., lions, cheetah, and hyenas), viverrids and ungulates provided there is a means of attracting subjects to the site, fixing a scaling standard and ensuring animals are positioned at right angles to the camera's field of view.

The posture of a leopard in the photograph significantly influenced the accuracy of measurements. Of the three postures, measurements taken from the LB-SF-PT category were the most accurate. This may be because this posture was most consistent with the way in which a leopard was aligned when reference measurements were taken during collaring. A study by *Zhang et al. (2018)* in China also showed that posture was the main factor influencing accuracy in image-based measurements of sheep. Their study however used a more sophisticated 3-camera design and subjects were photographed in a specialized alleyway. Within postures, measurements of body length were the most accurate followed

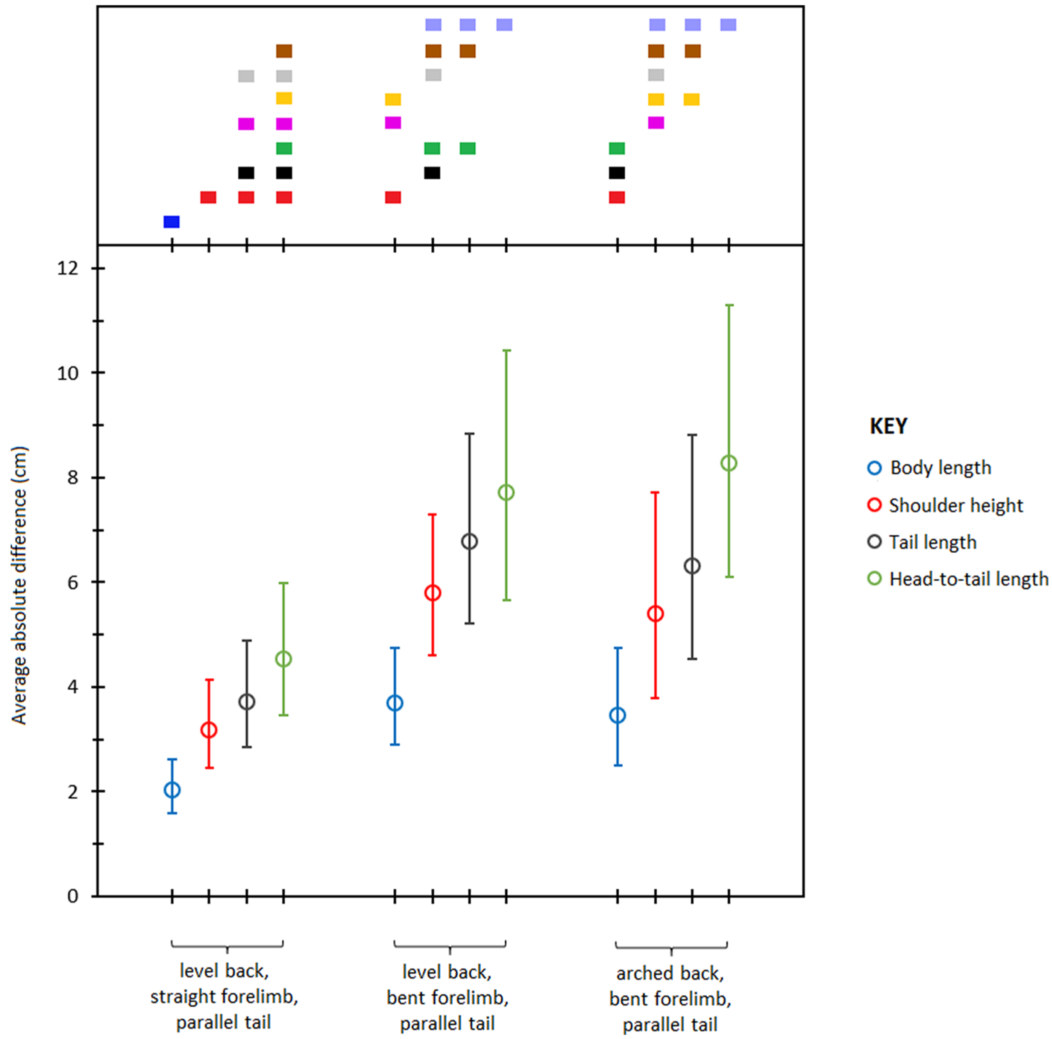

Figure 4 Average absolute differences (least squares means) between photographic and actual dimensions across different body type measurements and postures. Bars represent 95% confidence intervals (back transformed from log scale). The color display (top) depicts the results of pairwise comparisons conducted using Tukey's post hoc test. Measurements with colors in common were not significantly different ($p > 0.05$). Full-size DOI: 10.7717/peerj.7630/fig-4

by shoulder height. This finding was consistent with the work of *Tasdemir, Urkmez & Inal (2011)* in Turkey and *Meise et al. (2014)* in the Galapagos Islands who also measured body length accurately in cattle and sea lions using image analysis. Body length provided the most accurate results probably because reference and photograph-based dimensions were taken following the contour of the back (*De Waal, Combrinck & Borstlap, 2004*) and as such there were no significant differences between the measurements when the back of the leopard was either level or arched. Where leopards are hunted, body measurements of trophy individuals are taken in a straight line that is, placing a taut tape between two pegs marking the extents of a fully stretched out animal (*Safari Club International (SCI), 2016*). If reference dimensions for this study were taken in this way, variances from the actual may have been larger since leopards seldom assume this posture in photographs.

Compared to body length, the margin of error was greater when measuring shoulder height. This is probably because measurements recorded from the sliding wooden caliper during collaring were taken at 90° to the spinal axis of the leopard. Consequently, deviations from the straight forelimb position would likely affect the accuracy of image-based measurements. This is a limitation of our method since leopards standing on an angled pole may not always align their forelimbs perpendicularly. This may also explain why shoulder height measurements were less accurate than body length. In contrast, shoulder height of lions (*Ferreira & Funston, 2010*) and wild dogs (*Shumba et al., 2017*) standing on level ground was measured accurately from photographs.

Across all postures, tail length and head-to-tail length measurements were the least accurate. This may be because the tail and head can articulate independently of the body. The body of a leopard standing on a leading pole was consistently at right angles to the camera's field of view but the tail and head assumed different angles from photograph to photograph and therefore were not parallel to the leading pole leading to inaccuracies in measurement. Contrary to our findings, *Rothman et al. (2008)* accurately measured tail length of red colobus monkeys (*Procolobus rufomitratus*) in Uganda from photographs. The greater accuracy in their case might be because the pair of laser points used to calibrate the photographs were projected specifically onto the subjects' tails, likely reducing the degree of error.

The study showed that sex and scaling factor did not have a significant influence on the accuracy of the image-based measurements. Because multiple photographs recorded at the same station are on a single scale, no significant differences are expected whether male or female leopards are recorded, despite the size difference. The same applies where the same leopard was recorded at various sampling stations and the scaling factors were different. Scaling factor varied from site to site relative to how close or far the subject was in the frame thereby adjusting for measurement error associated with distance from the camera. Similarly, a study conducted in California, USA (*Lambert, Yasuda & Todd, 2012*) also found that body size or distance of subjects from the camera did not influence the accuracy of morphometric measurements on photographs of western fence lizards collected using a digital camera.

Obtaining full body shots of leopards is crucial for performing measurements. The role of the leading pole at camera stations was central to our study design. The pole ensured that a leopard was positioned at right angles to the camera's field of view, thus enabling its full body profile to be captured. In conventional (unbaited) camera trapping, unsuspecting leopards are photographed as they pass in front of a camera and as a result the dataset often contains many photographs with frontal, backside and half-body shots (*Negroes et al., 2012*). In addition, subjects are seldom at right angles to the camera thereby making measurement impossible for such photographs. The pole also ensured that feeding leopards were consistently aligned broadside in a photograph, thus revealing the presence or absence of male external genitalia (*Du Preez, Loveridge & Macdonald, 2014*). In this way the sex of each individual could easily be determined. If, on the other hand, sex was to be judged based on morphological development, some large females may be mistaken for sub-adult males or vice-versa (*Balme, Hunter & Braczkowski, 2012*).

To measure distances from a photograph a scaling standard in the frame is required. The leading pole facilitated the easy fixing of steel nails which were visible in the photographs. Other researchers have addressed this issue by modifying digital cameras to project a pair of laser beams onto the subject or objects in the field of view (*Rothman et al., 2008*; *Deakos, 2010*; *Barrickman, Schreier & Glander, 2015*). The distance between the beams is the used to scale the photographs. However, laser products can be potentially harmful to the eyes of animals (*Rothman et al., 2008*) such that rigging camera sites with lasers may have detrimental effects especially where subjects are likely to stay longer around trapping stations, which is the case with BCT. Furthermore, lasers have been used elsewhere in animal deterrent systems (*Gorenzel et al., 2002*; *Bishop et al., 2003*; *Akula et al., 2016*) and their influence on leopard behavior is not known. Leopards are sometimes startled by shutter sound (A. Tarugara, 2017, personal observation on Moultrie I60 camera traps) and if wary, they might avoid laser-emitting camera traps.

Our findings have demonstrated that photographic measurements of body length recorded from the LB-SF-PT posture can be confidently used to inform on leopard morphometrics. The lowest mean error (2.0 cm for body length in the LB-SF-PT posture) was higher than reported in previous studies (0.2 cm—*Bergeron (2007)*, 1.1 cm—*Rothman et al. (2008)*, 0.75 cm—*Willisch, Marreros & Neuhaus (2013)*) but was similar to that of distal hindlimb measurements (1.9 cm) in *Barrickman, Schreier & Glander (2015)*. Observed differences between actual and photographic measurements may arise because muscles of immobilized subjects are relaxed while those of active animals are often tensed (Z. Jewell, 2019, personal communication). The ecological significance of this error depends on the intended application. Researchers need to decide whether an estimate of a body measurement and the realized degree of error is sufficiently accurate for their needs or not. For example, a variance of two cm in our case may be sufficiently accurate for monitoring growth over time but may not be sufficiently accurate for individual identification (as two subjects might have similar body sizes).

Morphometric data are important as they broaden our understanding of a species' biology (*Carbone et al., 2014*; *Codron et al., 2018*). Although body measurements can be obtained relatively easily from captive individuals, these data may not be relevant to wild populations due to differences in diet and activity budgets (*Altmann & Alberts, 2005*; *Turner et al., 2016*). Body dimensions of wild animals can be measured through capture and chemical immobilization but this often disrupts natural activities and stresses the subjects (*Deka et al., 2012*). During operations such as collaring and veterinary work, morphometric data are usually collected but these are often ancillary. As a result, sample sizes are usually small and with low representativity. Where remote acquisition of these data is possible, populations can be studied in more detail.

By arranging sampling stations as described above, it is possible to take repeated measurements of individuals non-invasively. The above approach may provide information that can directly inform on growth rates and indirectly on food and habitat quality. Methods that offer accurate and repeatable measurements can be used to monitor growth rates of sample individuals (*Rothman et al., 2008*) or to model the size structure of populations (*Cole, 1994*). Where remote collection of morphometric data is possible this enables easier investigation of body size parameters within or among populations (*Vindis et al., 2010*; *Boast et al., 2013*; *Shumba et al., 2017*). For dangerous or shy species, for example, leopards, remote collection of data can be convenient for researchers and subjects alike. In addition, remote measurement is generally less expensive and can likely investigate more subjects compared to physical methods (*Bergeron, 2007*; *Weisgerber, Medill & McLoughlin, 2015*). Furthermore, these data can be useful in differentiating sexes in species where size dimorphism is apparent (*Marker & Dickman, 2003*; *Balme, Hunter & Braczkowski, 2012*; *Farhadinia et al., 2014*). Also, where size-minimum harvesting regulations must be observed, morphometric data may have policy and management relevance.

Future research

Given that morphological development is a function of age (*Hilderbrand et al., 2018*; *Nadal, Ponz & Margalida, 2018*), we suggest exploring the possibility of using morphometrics to estimate age of leopards as a next step. This may augment the presently available criteria for aging leopards from photographs developed by *Balme, Hunter & Braczkowski (2012)* which uses dewlap size, ear condition, facial scarring and nose color as indices. Image analysis has been used elsewhere to estimate body mass in pigs (*Brandl & Jørgensen, 1996*), cattle (*Vindis et al., 2010*; *Pradana, Hidayat & Darana, 2016*) and sea lions (*Meise et al., 2014*). If software developers could incorporate length, age and weight determination functionalities in camera traps, the range of collectable data would be expanded. For future studies, we suggest fastening the poles and substituting nails with reflective tape or paint as nails are easily bumped by animals.

CONCLUSIONS

Our findings indicate that it is possible to measure morphometric dimensions of leopards from camera trap photographs but the type of body measurement and posture of the target animal are important considerations. We conclude that body length and the LB-SF-PT posture is the combination of choice for accurate measurements. To maximize on the capital investment, we recommend that researchers take advantage of BCT surveys to collect morphometric data for species that are poorly understood.

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Allan Tarugara, Bruce W. Clegg and Colin Wenham are employed by Malilangwe Wildlife Reserve.

Author Contributions

- Allan Tarugara conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, prepared figures and/or tables, authored or reviewed drafts of the paper, approved the final draft.
- Bruce W. Clegg conceived and designed the experiments, performed the experiments, analyzed the data, contributed reagents/materials/analysis tools, authored or reviewed drafts of the paper, approved the final draft.
- Edson Gandiwa authored or reviewed drafts of the paper, approved the final draft.
- Victor K. Muposhi authored or reviewed drafts of the paper, approved the final draft.
- Colin M. Wenham contributed reagents/materials/analysis tools, approved the final draft.

Animal Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

The Chinhoyi University of Technology Ethics Committee provided full approval for this research (clearance number 01/17).

Data Availability

The following information was supplied regarding data availability:

The raw measurements and the R script used are available in the Supplemental Files.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.7630#supplemental-information.

REFERENCES

Akula A, Deshmane P, Thorat S, Bagbande A, Pawar M. 2016. A comparative study and analysis of approaches towards agricultural supervision. In: *Global Trends in Signal Processing, Information Computing and Communication.* Piscataway: IEEE, 510–515.

Altmann J, Alberts SC. 2005. Growth rates in a wild primate population: ecological influences and maternal effects. *Behavioral Ecology and Sociobiology* **57(5)**:490–501 DOI 10.1007/s00265-004-0870-x.

Balme GA, Hunter L, Braczkowski AR. 2012. Applicability of age-based hunting regulations for African leopards. *PLOS ONE* **7(4)**:e35209 DOI 10.1371/journal.pone.0035209.

Barrickman NL, Schreier AL, Glander KE. 2015. Testing parallel laser image scaling for remotely measuring body dimensions on mantled howling monkeys (*Alouatta palliata*). *American Journal of Primatology* **77(8)**:823–832 DOI 10.1002/ajp.22416.

Bates D, Mächler M, Bolker B, Walker S. 2018. Fitting linear mixed-effects models using lme4. *arXiv preprint. Available at http://arxiv.org/abs/14065823*.

Bergeron P. 2007. Parallel lasers for remote measurements of morphological traits. *Journal of Wildlife Management* **71(1)**:289–292 DOI 10.2193/2006-290.

Bishop J, McKay H, Parrott D, Allan J. 2003. Review of international research literature regarding the effectiveness of auditory bird scaring techniques and potential alternatives. In: *Produced by Central Science Laboratories for the Department for Environmental Food and Rural Affairs, London*.

Boast LK, Houser AN, Good K, Gusset M. 2013. Regional variation in body size of the cheetah (*Acinonyx jubatus*). *Journal of Mammalogy* **94(6)**:1293–1297 DOI 10.1644/13-MAMM-A-076.1.

Brandl N, Jørgensen E. 1996. Determination of live weight of pigs from dimensions measured using image analysis. *Computers and Electronics in Agriculture* **15(1)**:57–72 DOI 10.1016/0168-1699(96)00003-8.

Burton AC, Neilson E, Moreira D, Ladle A, Steenweg R, Fisher JT, Bayne E, Boutin S. 2015. REVIEW: Wildlife camera trapping: a review and recommendations for linking surveys to ecological processes. *Journal of Applied Ecology* **52(3)**:675–685 DOI 10.1111/1365-2664.12432.

Carbone C, Codron D, Scofield C, Clauss M, Bielby J. 2014. Geometric factors influencing the diet of vertebrate predators in marine and terrestrial environments. *Ecology Letters* **17(12)**:1553–1559 DOI 10.1111/ele.12375.

Carbone C, Pettorelli N, Stephens PA. 2011. The bigger they come, the harder they fall: body size and prey abundance influence predator–prey ratios. *Biology Letters* **7(2)**:312–315 DOI 10.1098/rsbl.2010.0996.

Chinnadurai SK, Strahl-Heldreth D, Fiorello CV, Harms CA. 2016. Best practice guidelines for field-based surgery and anaesthesia of free-ranging wildlife I. anaesthesia and analgesia. *Journal of Wildlife Diseases* **52**:S14–S27.

Christiansen F, Vivier F, Charlton C, Ward R, Amerson A, Burnell S, Bejder L. 2018. Maternal body size and condition determine calf growth rates in southern right whales. *Marine Ecology Progress Series* **592**:267–281 DOI 10.3354/meps12522.

Cichoń M, Dubiec A, Chadzińska M. 2001. The effect of elevated reproductive effort onhumoral immune function in collared flycatcher females. *Acta Oecologica* **22(1)**:71–76 DOI 10.1016/S1146-609X(00)01094-8.

Clegg BW. 2017. Large mammal population estimates for Malilangwe Wildlife Reserve: 5th–14th October 2017. Internal management report for The Malilangwe Trust, 41.

Clegg B, O'Connor TG. 2012. The vegetation of Malilangwe wildlife reserve, south-eastern Zimbabwe. *African Journal of Range & Forage Science* **29(3)**:109–131 DOI 10.2989/10220119.2012.744352.

Clegg BW, O'Connor TG. 2017. Determinants of seasonal changes in availability of food patches for elephants (*Loxodonta africana*) in a semi-arid African savanna. *PeerJ* **5**:e3453 DOI 10.7717/peerj.3453.

Codron J, Avenant NL, Wigley-Coetsee C, Codron D. 2018. Carnivore stable carbon isotope niches reflect predator-prey size relationships in African savannas. *Integrative Zoology* **13(2)**:166–179 DOI 10.1111/1749-4877.12290.

Cole RG. 1994. Abundance, size structure, and diver-oriented behaviour of three large benthic carnivorous fishes in a marine reserve in northeastern New Zealand. *Biological Conservation* **70(2)**:93–99 DOI 10.1016/0006-3207(94)90276-3.

De Waal H, Combrinck W, Borstlap D. 2004. A comprehensive procedure to measure the body dimensions of large African predators with comments on the repeatability of measurements taken from an immobilized African lion (*Panthera leo*). *Journal of Zoology* **262(4)**:393–398 DOI 10.1017/S095283690300476X.

Deakos MH. 2010. Paired-laser photogrammetry as a simple and accurate system for measuring the body size of free-ranging manta rays *Manta alfredi*. *Aquatic Biology* **10(1)**:1–10 DOI 10.3354/ab00258.

Deka K, Athreya V, Odden M, Linnell J. 2012. Chemical immobilization of Leopard *Panthera pardus* in the wild for collaring in Maharashtra, India. *Journal of the Bombay Natural History Society* **109**:153–157.

Du Preez BD, Loveridge AJ, Macdonald DW. 2014. To bait or not to bait: a comparison of camera-trapping methods for estimating leopard *Panthera pardus* density. *Biological Conservation* **176**:153–161 DOI 10.1016/j.biocon.2014.05.021.

East R. 1984. Rainfall, soil nutrient status and biomass of large African savanna mammals. *African Journal of Ecology* **22(4)**:245–270 DOI 10.1111/j.1365-2028.1984.tb00700.x.

Farhadinia MS, Kaboli M, Karami M, Farahmand H. 2014. Patterns of sexual dimorphism in the Persian leopard (*Panthera pardus saxicolor*) and implications for sex differentiation. *Zoology in the Middle East* **60(3)**:195–207 DOI 10.1080/09397140.2014.939813.

Ferreira S, Funston PJ. 2010. Age assignment to individual African lions. *South African Journal of Wildlife Research* **40(1)**:1–9 DOI 10.3957/056.040.0103.

Fitt RN, Lancaster LT. 2017. Range shifting species reduce phylogenetic diversity in high latitude communities via competition. *Journal of Animal Ecology* **86(3)**:543–555 DOI 10.1111/1365-2656.12655.

Fox J, Weisberg S. 2018. *An R companion to applied regression*. Third edition. Los Angeles: Sage Publications. *Available at http://socserv.socsci.mcmaster.ca/jfox/Books/Companion*.

Fukuda Y, Saalfeld K, Lindner G, Nichols T. 2013. Estimation of total length from head length of saltwater crocodiles (*Crocodylus porosus*) in the Northern Territory, Australia. *Journal of Herpetology* **47(1)**:34–40 DOI 10.1670/11-094.

Gorenzel W, Blackwell B, Simmons G, Salmon T, Dolbeer R. 2002. Evaluation of lasers to disperse American crows, *Corvus brachyrhynchos*, from urban night roosts. *International Journal of Pest Management* **48(4)**:327–331 DOI 10.1080/09670870210151689.

Hamilton T. 1961. The adaptive significances of intraspecific trends of variation in wing length and body size among bird species. *Evolution* **15(2)**:180–195 DOI 10.1111/j.1558-5646.1961.tb03142.x.

Hayward MW, Kerley GI. 2008. Prey preferences and dietary overlap amongst Africa's large predators. *South African Journal of Wildlife Research* **38(2)**:93–108 DOI 10.3957/0379-4369-38.2.93.

Hilderbrand GV, Gustine DD, Mangipane BA, Joly K, Leacock W, Mangipane LS, Erlenbach J, Sorum MS, Cameron MD, Belant JL, Cambier T. 2018. Body size and lean mass of brown bears across and within four diverse ecosystems. *Journal of Zoology* **305(1)**:53–62 DOI 10.1111/jzo.12536.

Jablonski D, Erwin D, Lipps J. 1996. Body size and macroevolution. In: Jablonski D, Erwin D, Lipps J, eds. *Evolutionary Paleobiology*. Chicago: University of Chicago Press, 256–289.

Karanth KU, Nichols JD. 2011. Estimating tiger abundance from camera trap data: field surveys and analytical issues. In: O'Connell AF, Karanth KU, Nichols JD, eds. *Camera Traps in Animal Ecology*. New York: Springer, 97–117.

Klein RG. 1986. Carnivore size and Quaternary climatic change in Southern Africa. *Quaternary Research* **26(1)**:153–170 DOI 10.1016/0033-5894(86)90089-X.

Lambert MR, Yasuda CM, Todd BD. 2012. Evaluation of a photographic technique for estimating body size in lizards from a distance. *Herpetological Conservation and Biology* **7**:83–88.

Law SJ, De Kort SR, Van Weerd M. 2016. Morphology, activity area, and movement patterns of the frugivorous monitor lizard *Varanus bitatawa*. *Herpetological Conservation and Biology* **11**:467–475.

Lenth R, Love J, Lenth MR. 2018. Package 'lsmeans'. *American Statistician* **34**:216–221.

Marker LL, Dickman AJ. 2003. Morphology, physical condition, and growth of the cheetah (*Acinonyx jubatus jubatus*). *Journal of Mammalogy* **84(3)**:840–850 DOI 10.1644/BRB-036.

McNab BK. 2010. Geographic and temporal correlations of mammalian size reconsidered: a resource rule. *Oecologia* **164(1)**:13–23 DOI 10.1007/s00442-010-1621-5.

Meise K, Mueller B, Zein B, Trillmich F. 2014. Applicability of single-camera photogrammetry to determine body dimensions of pinnipeds: Galapagos sea lions as an example. *PLOS ONE* **9(7)**:e101197 DOI 10.1371/journal.pone.0101197.

Nadal J, Ponz C, Margalida A. 2018. The effects of scaling on age, sex and size relationships in Red-legged Partridges. *Scientific Reports* **8(1)**:1–7 DOI 10.1038/s41598-018-20576-x.

Najera F, Hearn AJ, Ross J, Saldivar DAR, Evans MN, Guerrero-Sanchez S, Nathan SKSS, De Gaspar Simón I, Macdonald DW, Goossens B, Rueda LR. 2017. Chemical immobilization of free-ranging and captive Sunda clouded leopards (*Neofelis diardi*) with two anesthetic protocols: medetomidine-ketamine and tiletamine-zolazepam. *Journal of Veterinary Medical Science* **79(11)**:1892–1898 DOI 10.1292/jvms.17-0259.

Negroes N, Sollmann R, Fonseca C, Jacomo AT, Revilla E, Silveira L. 2012. One or two cameras per station? Monitoring jaguars and other mammals in the Amazon. *Ecological Research* **27(3)**:639–648 DOI 10.1007/s11284-012-0938-4.

Nwaogu CJ, Tieleman BI, Bitrus K, Cresswell W. 2018. Temperature and aridity determine body size conformity to Bergmann's rule independent of latitudinal differences in a tropical environment. *Journal of Ornithology* **159(4)**:1053–1062 DOI 10.1007/s10336-018-1574-8.

Owen-Smith N, Mills MG. 2008. Predator-prey size relationships in an African large-mammal food web. *Journal of Animal Ecology* **77(1)**:173–183 DOI 10.1111/j.1365-2656.2007.01314.x.

Piepho H-P. 2004. An algorithm for a letter-based representation of all pairwise comparisons. *Journal of Computational and Graphical Statistics* **13(2)**:456–466 DOI 10.1198/1061860043515.

Pradana ZH, Hidayat B, Darana S. 2016. Beef cattle weight determine by using digital image processing. In: *2016 International Conference on Control, Electronics, Renewable Energy and Communications*. Piscataway: IEEE, 179–184.

R Core Team. 2017. *R: a language and environment for statistical computing*. Version 3.4.3. Vienna: The R Foundation for Statistical Computing. *Available at http://www.R-project.org/*.

Radloff FG, Du Toit JT. 2004. Large predators and their prey in a southern African savanna: a predator's size determines its prey size range. *Journal of Animal Ecology* **73(3)**:410–423 DOI 10.1111/j.0021-8790.2004.00817.x.

Rochet M-J, Cadiou J-F, Trenkel VM. 2006. Precision and accuracy of fish length measurements obtained with two visual underwater methods. *Fishery Bulletin* **104**:1–9.

Rothe-Groleau C, Rauter CM, Fawcett JD. 2018. Morphological traits as indicators of sexual dimorphism in Prairie Rattlesnakes (*Crotalus viridis*). *Transactions of the Nebraska Academy of Sciences and Affiliated Societies* **38**:10–18.

Rothman JM, Chapman CA, Twinomugisha D, Wasserman MD, Lambert JE, Goldberg TL. 2008. Measuring physical traits of primates remotely: the use of parallel lasers. *American Journal of Primatology* **70(12)**:1191–1195 DOI 10.1002/ajp.20611.

Safari Club International (SCI). 2016. Methods for body measurements. Method 16-D for darted carnivores. In: Schwabland J, Barnhart LI, eds. *Official Measurer's Manual.* Tucson: Safari Club International, 147.

Schneider CA, Rasband WS, Eliceiri KW. 2012. NIH image to ImageJ: 25 years of image analysis. *Nature Methods* **9(7)**:671–675 DOI 10.1038/nmeth.2089.

Shumba T, Montgomery RA, Sillero-Zubiri C, Rasmussen GS. 2017. Morphological variation of wild dogs across Africa. *International Journal of Zoology and Applied Biosciences* **2**:145–154.

Sikes RS, Animal Care and Use Committee of the American Society of Mammalogists. 2016. 2016 Guidelines of the American Society of Mammalogists for the use of wild mammals in research and education. *Journal of Mammalogy* **97**:663–688 DOI 10.1093/jmammal/gyw078.

Sollmann R, Mohamed A, Kelly MJ. 2013. Camera trapping for the study and conservation of tropical carnivores. *Raffles Bulletin of Zoology* **28**:21–42.

Tarugara A, Clegg BW, Gandiwa E, Muposhi VK. 2019. Cost-benefit analysis of increasing sampling effort in a baited-camera trap survey of an African leopard (*Panthera pardus*) population. *Global Ecology and Conservation* **18**:e00627 DOI 10.1016/j.gecco.2019.e00627.

Tasdemir S, Urkmez A, Inal S. 2011. Determination of body measurements on the Holstein cows using digital image analysis and estimation of live weight with regression analysis. *Computers and Electronics in Agriculture* **76(2)**:189–197 DOI 10.1016/j.compag.2011.02.001.

Tasdemir S, Yakar M, Ürkmez A, İnal S. 2008. Determination of body measurements of a cow by image analysis. In: *Proceedings of the 9th International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing.* New York: ACM, 70.

Traill LW, Bigalke RC. 2007. A presence-only habitat suitability model for large grazing African ungulates and its utility for wildlife management. *African Journal of Ecology* **45(3)**:347–354 DOI 10.1111/j.1365-2028.2006.00717.x.

Turner TR, Cramer JD, Nisbett A, Gray JP. 2016. A comparison of adult body size between captive and wild vervet monkeys (*Chlorocebus aethiops sabaeus)* on the island of St. Kitts. *Primates* **57(2)**:211–220 DOI 10.1007/s10329-015-0509-8.

Van Buskirk J, Mulvihill RS, Leberman RC. 2010. Declining body sizes in North American birds associated with climate change. *Oikos* **119(6)**:1047–1055 DOI 10.1111/j.1600-0706.2009.18349.x.

Vindis P, Brus M, Stajnko D, Janzekovic M. 2010. Non-invasive weighing of live cattle by thermal image analysis. In: Er MJ, ed. *New Trends in Technologies: Control, Management, Computational Intelligence and Network Systems*. Sciyo, 243–256.

Waite JN, Schrader WJ, Mellish J-AE, Horning M. 2007. Three-dimensional photogrammetry as a tool for estimating morphometrics and body mass of Steller sea lions (*Eumetopias jubatus*). *Canadian Journal of Fisheries and Aquatic Sciences* **64(2)**:296–303 DOI 10.1139/f07-014.

Weisgerber JN, Medill SA, McLoughlin PD. 2015. Parallel-laser photogrammetry to estimate body size in free-ranging mammals. *Wildlife Society Bulletin* **39(2)**:422–428 DOI 10.1002/wsb.541.

Wickham H, Chang W, Lionel H, Lin Pedersen T, Takahashi K, Wilke C, Kara W. 2018. *ggplot2: create elegant data visualisations using the grammar of graphics*. R Package Version 3.0.0. *Available at https://ggplot2.tidyverse.org*.

Willisch C, Marreros N, Neuhaus P. 2013. Long-distance photogrammetric trait estimation in free-ranging animals: a new approach. *Mammalian Biology* **78(5)**:351–355 DOI 10.1016/j.mambio.2013.02.004.

Yom-Tov Y. 2001. Global warming and body mass decline in Israeli passerine birds. *Proceedings of the Royal Society of London. Series B: Biological Sciences* **268(1470)**:947–952 DOI 10.1098/rspb.2001.1592.

Zhang ALN, Wu BP, Jiang CXH, Xuan DCZ, Ma EYH, Zhang FYA. 2018. Development and validation of a visual image analysis for monitoring the body size of sheep. *Journal of Applied Animal Research* **46(1)**:1004–1015 DOI 10.1080/09712119.2018.1450257.