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NEW APPROACHES

Validation of Two Independent Photogrammetric Techniques for Determining Body Measurements of Gorillas

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The ability to accurately measure morphological characteristics of wild primates in the field is challenging, yet critical for understanding fundamental aspects of their biology and behavior. Recent studies have shown that digital photogrammetry can be used to non-invasively measure morphological traits of wild primates, as it allows for the determination of geometric properties of objects remotely from photographic images. We report here on a rare opportunity to test this methodology by comparing measurements obtained directly from living great apes to those obtained from photographs. We test the accuracy and precision of two independent photogrammetric techniques, employing the use of parallel lasers and a distance meter, respectively, for obtaining measurements of static objects and captive western lowland gorillas (*Gorilla gorilla gorilla*) ($n = 4$) at Zoo Atlanta. For static objects, the mean percent error between corresponding measurements collected by the same observer directly versus using photogrammetry was 0.49–0.74% for the parallel laser method and 0.62–0.76% for the distance meter method. For gorillas, mean percent error between corresponding direct and remote measurements was 2.72–5.20% for the parallel laser method and 2.20–7.51% for the distance meter method. Correlations between direct measurements and corresponding parallel laser and distance meter measurements of gorillas were highly significant with R^2 values and slopes approaching 1.0 (parallel lasers: $R^2 = 0.9989$, $P < 0.0001$; distance-meter: $R^2 = 0.9990$, $P < 0.0001$). Further, variation between measurements of the same targets collected repeatedly by the same observer, and between different observers, was uniformly low across methods (CV, range = 0.003–0.013). While errors are slightly higher for the distance meter technique, both methods show great promise for addressing a wide range of questions requiring the non-invasive collection of morphological data from wild primates. Am. J. Primatol. 78:418–431, 2016.

Key words: photogrammetry; parallel laser; distance meter; gorilla

INTRODUCTION

The ability to accurately measure morphological traits of wild primates in the field is critical for understanding fundamental aspects of their biology, including developmental aspects of life history, sexual dimorphism, correlates of reproductive success, and health. However, as this can be logistically challenging and invasive, most available data comes either from captive primates or measurements of wild primates after death. Several studies have developed non-invasive approaches, such as the use of a weight scale, to allow for collection of body mass data from wild animals [e.g., Altmann & Alberts, 2005; Johnson, 2003; Pusey et al., 2005]. However,

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this is not possible in all settings, as it may interfere with the natural behavior of study animals.

Photogrammetry is a technology that allows for the determination of spatial measurements of objects indirectly, or remotely (i.e., without physical contact), from photographic images [Mikhail et al., 2001; Walker & Alspaugh, 2013]. Advancements in this field have been driven by the need to obtain reliable geospatial information from the earth's surface [McGlone, 2013], including more recent applications that entail geospatial mapping of archaeological or paleontological sites [Bates et al., 2008; Breithaupt & Matthews, 2001]. Photogrammetry provides a means of generating a permanent photographic record of morphology, whether of inanimate objects or biological specimens [Falkingham, 2012; Mallison & Wings, 2014], and for collecting measurements of study animals in the field [e.g., Bergeron, 2007; Brager and Chong, 1999; Deakos, 2010; Durban & Parsons, 2006; Ireland et al., 2006; Jaquet, 2006; Morgan & Lee, 2003; Shrader et al., 2006]. Photogrammetry has also been applied to humans [Gavan et al., 1952; Geoghegan, 1953; Tanner & Weiner, 1949] and to wild primates, the latter to measure features such as sexual swelling size [Deschner et al., 2004; Domb & Pagel, 2001; Emery & Whiten, 2003; Fitzpatrick et al., 2014], sagittal crest size and other cranial features [Breuer et al., 2007, 2012; Caillaud et al., 2008], tail length [Rothman et al., 2008], and body segment lengths [Barrickman et al., 2015; Berghänel et al., 2015; Brazeau et al., 2013; Breuer et al., 2007, 2009, 2012; Kurita et al., 2012; Lu et al., 2013].

Previous efforts to validate photogrammetric techniques applied to studies of primate morphology often incorporate comparisons of measurements obtained directly from static test objects against those obtained remotely from photographs [e.g., Barrickman et al., 2015; Breuer et al., 2007; Rothman et al., 2008]. However, there have been few opportunities to directly test the accuracy of photogrammetry for collecting linear measurements of living primate subjects. Rothman et al. [2008] tested the accuracy of a parallel laser method, in which paired lasers separated by a known distance are projected into the photographic imaging plane as a scale, for measuring tail length of red colobus monkeys in Kibale National Park, Uganda. The mean percent error between direct and photogrammetric measurements of tail length reported in the latter study was 1.7%, with a maximum error of 5.0% for any single measurement. Further, they found that direct and estimated tail lengths were highly correlated [See also Barrickman et al., 2015 for an application to howler monkeys].

These results suggest that photogrammetry is a promising method for obtaining body measurements from arboreal primates in field settings. However, opportunities to validate photogrammetric techniques using living great ape subjects, which are larger-bodied, often observed from the ground, and differ in their physical characteristics (e.g., length of body hair), are rare due to the invasive nature of such tests [but see Machanda et al., 2015].

In the current study, we test accuracy and precision of two independent photogrammetric methods, incorporating the use of a distance meter [following Breuer et al., 2007] and parallel-laser apparatus [following Rothman et al., 2008], implemented under the same conditions for collecting measurements of both static/inanimate objects and western lowland gorillas (*Gorilla gorilla gorilla*) housed at Zoo Atlanta. Since the Zoo Atlanta gorillas have been trained to present themselves for body measurements during veterinary examinations, this provides a rare opportunity to compare the quality of photogrammetric measurements to those collected directly from living great apes. Furthermore, if both techniques can be shown to produce accurate and precise estimates of body size in gorillas, this expands potential for future comparative studies across populations where logistical constraints (and thus the applicability of one method over another) may vary considerably.

DESCRIPTION

We tested the application of two independent methods for measuring the linear dimensions of static objects and living gorillas from photographs. These methods entail the use of a commercially available digital single-lens reflex (DSLR) camera system, and incorporation of a distance meter [following Breuer et al., 2007] or parallel laser apparatus [following Rothman et al., 2008], respectively. The general principles of these methods are reviewed below, followed by a discussion of sources of error.

Method 1: Distance Meter

We tested the distance meter method as described by Breuer et al. [2007] and applied to wild western gorillas observed at Mbeli Bai, Republic of Congo [also see Breuer et al., 2009, 2012; Caillaud et al., 2008]. This method relies on collecting accurate measurements of the distance between the target *object plane*, a plane that is oriented perpendicular to the optical axis and contains all target landmarks for measurement, and the lens (i.e., *object distance*). According to this method, the size of an object (o) is determined by the ratio of the *principal distance* of the lens and the object distance:

$$D/f = o/p; \qquad (1)$$

where f is the principal distance of the lens (termed *focal length* when the lens is focused at infinity); D is the object distance, measured from the camera lens to the target object; and p is the pixel size of the object in the photo. p represents the number of pixels comprising the linear distance of the object in the photo, multiplied by pixel length—an intrinsic parameter of the camera sensor itself.

In a single, thin lens system, the object distance can be modeled as the distance from the target object plane to a plane that is perpendicular to the optical axis and passes through the center of the lens. For a lens focused on an object at infinity, the principal distance (or focal length) is the distance from the center of the lens to the point at which light rays converge to form a focused image (i.e., the focal plane), calculated according to the lens maker's equation from the radius of curvature of both lens surfaces and the index of refraction [Fiete, 2013; Mikhail et al., 2001]. However, in reality, lenses typically used with commercially available DSLR camera systems have multiple elements inserted along the optical axis and cannot be appropriately modeled as a thin lens system [Bentley & Olson, 2012; Kingslake, 1992]. Thus, the lens system is redefined such that principal distance and object distance are measured in reference to two principal planes, each oriented perpendicular to the optical axis. Assuming the same index of refraction on both sides of the lens, the principal planes intersect the optical axis at nodal points; in the absence of lens distortion, a principal ray passing through the front (incident) node will emerge from the rear (emergent) node without changing its angle with respect to the optical axis, though it will be displaced. In this system, the object distance is defined in reference to the front principal plane (or incident node); when focused on an object at infinity, the principal distance is defined as that distance between the rear principal plane (or emergent node) and the focal plane [Greivenkamp, 2004; Kerr, 2004].

Method 2: Parallel Lasers

A second method relies on the projection of dual parallel lasers to calibrate photographic images, and has been applied to studies of red colobus monkeys [Rothman et al., 2008], howler monkeys [Barrickman et al., 2015], and to other mammals [e.g., Bergeron, 2007; Durban & Parsons, 2006]. Photographs are collected using a DSLR camera mounted to an aluminum base, configured with a housing structure that projects parallel lasers into the target object plane. This method is based on the principle that when laser beams are aligned parallel to one another, they project laser points onto a target that remain equidistant irrespective of changes in distance from their origin [Rothman et al., 2008]. If measurement landmarks on the target object are positioned in a plane (i.e., the object plane, as defined above) that is perpendicular to the projection plane of the laser beams, and the distance separating each of the lasers is known, this provides a scale that allows for calibration of photographs for measurement purposes.

Sources of Error

The quality of data obtained using photogrammetric methods is dependent upon different sources of error, which determine accuracy and precision [Butler et al., 1998; Cooper & Cross, 1988]. *Accuracy* can be defined as the degree of agreement between remote measurements and accepted reference values, which in this case are corresponding measurements obtained directly from the target object. Accuracy is dependent upon systematic errors generated as from the photogrammetric apparatus, image collection and/or measurement procedures. *Precision* is a function of random errors in the imaging and/or measurement procedure, and can be defined as the degree of agreement among repeated observations of the same object made under identical conditions.

Systematic error may be introduced as a result of the properties of the apparatus. The properties of the digital sensor itself, including pixel size, density, and sensor size, can all influence image quality, particularly under low light conditions, and the ability to resolve closely spaced landmarks on the target object [Butler et al., 1998; McGlone, 2013; for a helpful online resource, see https://photographylife.com/the-benefits-of-a-high-resolution-sensor]. Lens aberrations, or departures from the theoretical predictions of geometrical optics, can also significantly impact image quality [Bentley & Olson, 2012; Kingslake, 1992]. Though advances in photographic lens design may reduce aberrations, lens distortion remains a concern, as this may introduce error in measurements obtained from photographs [also see Fiete, 2013; Mikhail et al., 2001]. Lens distortion results from the curved geometry of lenses, such that points in the optical field are projected as being closer or farther from the center than their true distance. This can be detected as a deviation from rectilinear projection, whereby straight lines in the field of view are projected as straight lines in the photographic image. Radial distortion increases from the center of the optical field, and is greatest for objects located at the periphery. Available software packages (e.g., Adobe Photoshop CS6 Lens Correction filter) allow for post-acquisition algorithmic transformations of digital images to correct for lens distortions, though improvements in accuracy should be evaluated [Hugemann, 2010]. However, the degree of distortion can vary depending on lens construction, and should be a factor in choice of lenses for use in photogrammetry.

An additional source of systematic error arises from the problem of "focus breathing," which specifically impacts methods that rely on principal distance as a parameter in measurement calculations (i.e., the distance meter method above). In compound lenses with multiple optical elements, the positions of these optical elements “float” as the lens is focused, and this movement changes the principal distance of the lens in relation to the focal distance. Although this effect tends to be greater in zoom lenses compared to prime lenses, the latter are not free of this effect. The manufacturer specified “focal length” for prime lenses is the nominal principal distance for an object focused at infinity. However, principal distance is reduced as object distance is reduced [Tubbs & Ito, 2002].

Both the distance meter and parallel laser method are subject to systematic error due to improper alignment [e.g., Bergeron, 2007; Rothman et al., 2008]. If projection of the distance meter onto the target object is not oriented parallel to the ground (for terrestrial animals), distance will be overestimated (see Equation 1). Also, to ensure the accuracy of measurements derived using the laser method, it is critical that paired lasers are oriented parallel to one another. Otherwise, paired laser distance changes with increasing object distance, hence impacting calibration of acquired images for measurement. Finally, both methods require that the target object plane (i.e., defined by the landmarks selected for measurement) is positioned perpendicular to the optical axis of the camera. If the target object plane is rotated toward or away from the optical axis, this introduces cosine errors; the object distance derived from photogrammetry will underestimate the true distance, and this error will increase in magnitude with increasing rotation of the target [Bergeron, 2007]. In practice, however, rotations up to 10 degrees can be accommodated with a reduction in target object length of 1.5%. As target object rotation surpasses 25 degrees, error exceeds 10% [$1-\cos\alpha$; also see Barrickman et al., 2015; Jaquet, 2006].

Repeated measurements of the same target object can also generate different values as a result of random errors during the imaging and/or measurement procedure. These random errors may be observed when a single individual conducts repeated observations of the same target (i.e., intraobserver error), or in the variation observed among measurements of the same target object collected by multiple individuals (i.e., interobserver error). These random errors may result from variations in the alignment of the optical axis relative to the target object plane during imaging. Moreover, when the target (i.e., gorilla) is moving, the obtained distance may be also slightly different than the real object-distance. Finally, both random and systematic errors may also occur during subsequent digital photograph processing and analysis. One’s ability to clearly identify landmarks in the photographs, necessary to minimize intra- and inter-observer errors, may be impacted by properties of the camera sensor, including resolution, illumination of the subject, image compression generated by measurement software, and characteristics of the animal itself [Butler et al., 1998; McGlone, 2013].

EXAMPLE

Ethical Statement

Our protocols comply with the American Society of Primatologists Principles for the Ethical Treatment of Non-human Primates, and received exemption by the Institutional Animal Care and Use Committee of The George Washington University and Zoo Atlanta’s Scientific Advisory Committee.

Gorilla Study Subjects

We collected data over 14 days in August–September of 2013 at Zoo Atlanta in Atlanta, Georgia. Adult gorillas are trained to present themselves for examination by Zoo Atlanta staff. During these examinations, gorillas are separated from zoo staff by a vertical steel mesh partition; gorillas are trained to present designated parts of their body flat against the mesh, while staff on the opposite side of the partition collect measurements of these body parts as projected across the mesh, using a tape measure.

The current study incorporates data from three adult females (Lulu, Sukari, and Kuchi) and one silverback male (Charlie) from two different social groups, for whom both direct measurements and photogrammetric measurements could be obtained. As there is variation among individuals in their training for veterinary examinations, these individuals were also chosen as they performed most reliably during measurement procedures. Our four study subjects were housed in two separate enclosures characterized by naturalized environments that promote behaviors similar to those observed in the wild. Each provided opportunities for an observer standing outside the enclosure to view and collect photographs of the gorillas from a distance of ~7–13 m. We also collected direct and photogrammetric measurements of static objects, as described further below.

Gorilla Body Measurements

For photogrammetric measurements, individuals were photographed in lateral view (*norma lateralis*) while in their exhibit enclosures, from an observer distance (parameter D in Equation 1) of ~7–13 m. We examined three dimensions that could be reliably obtained during direct measurements (given the logistical constraints of obtaining measurements across a vertical mesh partition) and for which landmarks could be readily identified from photographs. Two of these measurements were obtained from the head in *norma lateralis* orientation: (1) distance from the skin overlying the most anterior margin of the external auditory meatus to the skin covering the anterior-most projection of the ipsilateral supraorbital torus (EAR-TORUS); and (2) distance from the skin overlying the most anterior margin of the external auditory meatus to the superior-most projection of the sagittal crest (EAR-CREST). The third measurement obtained was the arm segment length (ARM), measured in lateral view, as the distance from the top rounded contour of the shoulder to the most distal protuberance of the elbow (Fig. 1). We selected only those photos that showed subjects in *norma lateralis* orientation, with no apparent rotation of the subject in the coronal plane (i.e., towards or away from the camera).

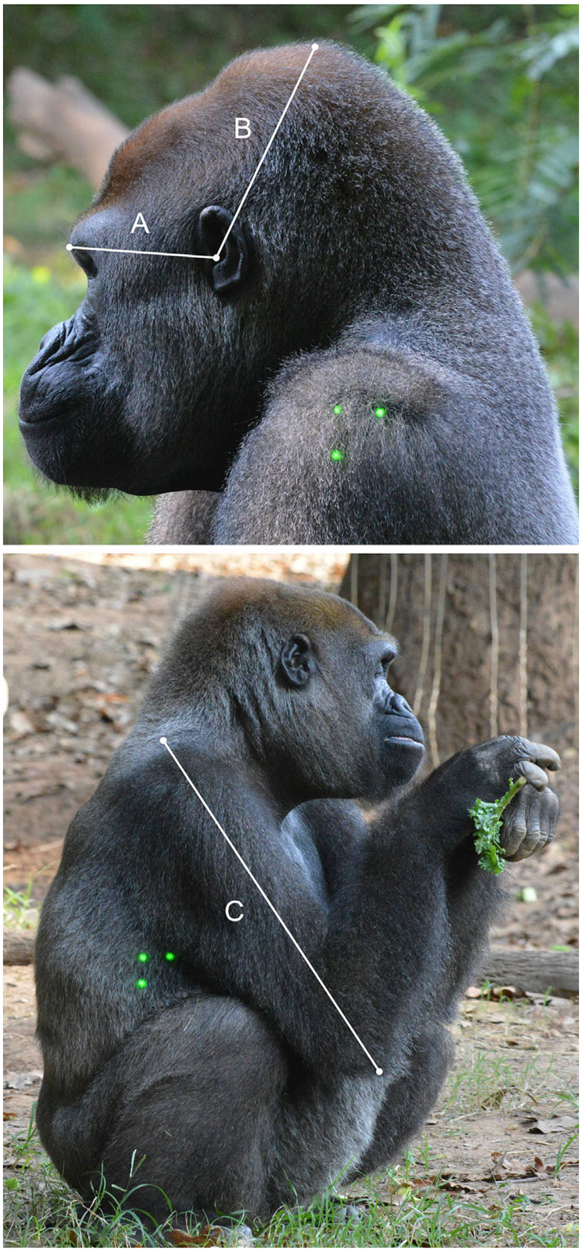

Fig. 1. Measurements considered: EAR-TORUS (**A**), EAR-CREST (**B**) and ARM (**C**). The gorilla IDs are Charlie (silverback male, top) and Kuchi (adult female, bottom).

The Apparatus

Digital photographs were collected using a full-format Nikon D800 digital SLR camera (36.3 MP resolution) with a Nikon AF Micro-Nikkor 200mm f/4 D IF-ED lens, a system with excellent marks in tests of low light performance, optical distortion and image sharpness (http://www.kenrockwell.com/nikon/200mm-micro.htm). A Leica Geosystems DISTO E7400× Laser Distance Meter (reported accuracy: ±1 mm at a range up to 80 m) was used to collect measurements of object distance.

The design of our parallel laser apparatus follows Rothman et al. [2008] and Bergeron [2007], with a few modifications (see Fig. 2). Like Rothman et al. [2008], we used AGLM2 green laser modules, which in our experience showed greatest contrast against the subject and were more easily visualized during daylight. The AGLM2 modules (wavelength 532 nm, maximum output power <5 mW) were produced by Apinex (Montreal, Canada), and are rated as Class IIIa according to the U.S. Food and Drug Administration's Center for Devices and Radiological Health.

We modified previously published designs for the laser apparatus in the following ways. First, the lasers were mounted in a vertical stainless steel plate rather than aluminum, allowing for thinner material to be used while still maintaining the structure and strength of the apparatus. We also added a housing behind the front plate to enclose and protect the laser hardware and wiring from exposure to the outside elements. The stainless steel housing was designed with an array of openings to allow for increased convective cooling of hardware and the overall housing. Each laser was connected to a battery pack that held two AA batteries and an on/off switch. The battery packs were mounted directly to the stainless steel housing to form a compact design.

As we found small-scale variation among lasers in the projection angle of the beam as it exits the module, each laser module was fixed into the vertical plate using aluminum collars that allowed minor adjustments in the orientation of each module using one set screw and three hex screws. Each hex screw was machined such that it formed a paired concave-convex joint with its aluminum collar. The base of each aluminum collar, and its corresponding surface on the vertical plate, was also machined to a paired concave–convex contour to allow for more range of motion in aligning the lasers to parallel orientation (see "Alignment of parallel lasers," below) (Fig. 2).

Second, our laser housing design allows for the mounting of three, rather than two, lasers—each separated by a distance of 4.0 cm and positioned at three corners of a square. The paired laser distance

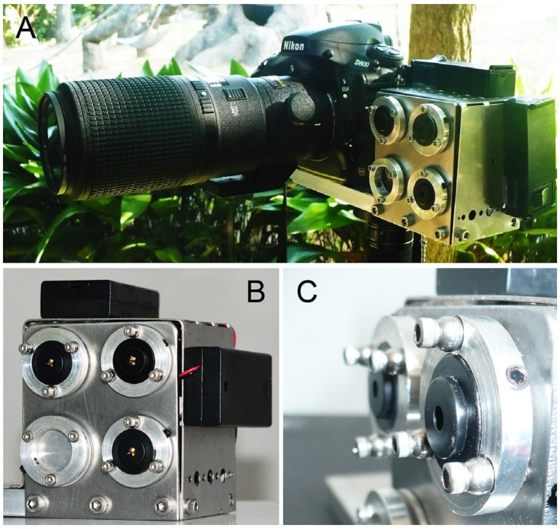

Fig. 2. Photogrammetric kit, including a digital SLR camera and housing for three parallel lasers mounted onto a steel base. Separate AA battery packs for each laser module are mounted on the outside of the laser housing (**A**). The parallel laser housing allows for positioning of four laser modules for flexibility. Only three modules are used here. (**B**). Close-up view of the aluminum collar surrounding each laser module (**C**).

represents a compromise. Extrapolation beyond this distance is required when measuring large objects, which can magnify any small errors in the calibration. However, if paired lasers are separated by too great a distance, this precludes our ability to measure small features (e.g., on the head of infants).

We designed our apparatus to accommodate parallel laser alignment in both x (horizontal) and y (vertical) axes to address the problem of parallax [Bergeron, 2007; Rothman et al., 2008]. As Rothman et al. [2008] noted, when two parallel lasers are positioned vertically with respect to one another and the apparatus is rotated upwards to photograph an arboreal target, difference in path length between the top and bottom laser beams alters the distance between laser points projected on the target itself [see Fig. 2 in Rothman et al., 2008]. Rothman et al. [2008] described a method to correct for parallax in such cases, where the angle formed between the projected laser beams and the horizontal is determined with use of a clinometer. However, if parallel lasers are aligned in a horizontal plane with respect to one another in such a scenario, there should be no difference in their path lengths and a correction factor is not needed, assuming there is no tilt toward or away from the target object plane. In our case, testing both parallel laser and distance meter methods in the field, it was logistically challenging to collect clinometer readings consistently in all cases. Thus, in an attempt to streamline the technique, designing the apparatus with three lasers allowed us to calibrate each photograph in both vertical and horizontal axes, as necessary, depending upon the orientation of the target object.

Procedure

Alignment of parallel lasers

Prior to each photography session, the position of the lasers was finely adjusted until vertical and horizontal pairs were each separated by a distance of 4.0 cm. A known size square-shape target (all four corners separated by a distance of 4.0 cm in vertical and horizontal planes) was positioned on a wall, and the lasers were projected onto the target from a distance of 13 m, parallel to each other and to the ground to avoid parallax. Each laser beam was finely adjusted by hand to each corner of the target and then secured in place. To determine the error in the alignment in both x and y axes, a photo of the target was then obtained with the three parallel lasers projected into the photographic image plane to serve as a scale.

Calculating object distance (D) and principal distance (f) for the distance meter method

Though we used a prime lens, our measurements may still be impacted by the phenomenon of focus breathing described above; as lens elements float to accommodate focusing on objects at different distance, both the position of principal planes and the principal distance also change. Here, it was necessary to define object distance using a fixed landmark. Thus, object distance in our protocol was defined as that distance from the target object plane to the front vertex of the lens. To determine principal distance at different object distances, we obtained seven photographs of a static object of known dimensions at different distances (6–16 m), and solved for principal distance using Equation 1, above. We then calculated a linear regression between the object distance and the estimated principal distance ($f = -0.0002 \times D + 204.3$; $R^2 = 0.891$). This equation was used to calculate the principal distance for all photographs measured here.

Criteria for selection of photographs

To minimize error described above, the following criteria determined selection of appropriate photographs for measurement. (1) Landmarks were in focus and could be easily identified; (2) Projected laser points were located on the body, in the same plane as the measurement landmarks; (3) The target object plane appeared from visual inspection to be perpendicular to the optical axis of the lens and projection path of the lasers, to minimize parallax error; (4) The gorilla was located in the center of the image (i.e., not at the periphery, where lens distortion effects are greatest) and photographed while sitting or standing still, as movement of the gorilla toward/away from the lens introduces error in object distance determination.

Collection of measurements from photographs

Photographs of static objects were collected by two observers (JG, DA) according to the procedures described above; only the first author had the opportunity to collect photographs of Zoo Atlanta gorillas. Pixel length measurements of targets were collected from digital photos by the first author for most calculations; a second observer (DA) collected repeated measurements from a subset of photos for determination of inter-observer error. All measurements were conducted using the "measure tool" in ImageJ 1.47v [Abramoff et al., 2004]; measurements were collected with single pixel resolution, using a mouse to identify target landmarks representing the start and end points of the measure line in ImageJ. For the laser method, the distances between horizontal and vertical paired lasers were measured; the average of these distances was used to set the scale in each photograph.

Testing Precision and Accuracy of Photogrammetric Methods

We tested the precision of our measurements, which is impacted by random errors in the imaging and/or measurement procedure. Intra-observer error was determined in two ways. Within-photo error was determined by collecting three repeated measurements from a subset of the photos (e.g., one photo for each gorilla) on three separate occasions. Further, each individual/target object was photographed four times per measurement for determination of between-photo measurement error. (All photographs and measurements of gorillas for calculations of intra-observer error were performed by the first author, JG). We also determined inter-observer error in two ways: (1) a second observer (DA) re-measured a subset of those gorilla and object photos described above to estimate within-photo error among observers; and (2) photographs of static objects were collected by two different observers (JG and DA) and measured by JG to estimate error associated with different photographers. We report coefficients of variation (CV), as previously used in Breuer et al. [2007], and performed Wilcoxon Tests to determine differences between measurements by the two observers.

Finally, to validate the method, we report here on the accuracy of photogrammetric measurements compared to measurements collected directly from the same structures—for both static objects and western gorillas observed at Zoo Atlanta. Static object measurements were collected with a measuring tape having a resolution of 0.1 cm. All direct measurements of gorillas were obtained by Zoo Atlanta staff using a flexible tape measure with 0.5 cm resolution, based on the Zoo's established measurement protocols and what has been deemed feasible during past veterinary examinations. To examine the relationship between direct and photogrammetric measurements, we calculated the percent of error between corresponding sets of measurements, and performed ordinary least squares linear regression analysis. Finally, we used regression analysis to determine whether error between direct and photogrammetric measurements is significantly biased by object distance.

Results: Measurements of Gorillas

The parallel lasers were aligned five different times during the period of photo acquisition from Zoo Atlanta gorillas; the average error between laser and direct measurements of the calibration target was 1.01% for the horizontal axis (range = 0.64–1.30%), and 1.04% for the vertical axis (range = 0.28–1.91%).

Repeated direct measurements of the gorillas collected by a single observer (Zoo Atlanta Primate Staff – RPG) yielded a mean CV = 0.02 (range = 0.01–0.03) for ARM, mean CV = 0.03 (range = 0.02–0.05) for EAR-CREST, and mean CV = 0.05 (range = 0.02–0.09) for EAR-TORUS (Table I).

Precision

To estimate between-photo error, target lengths were obtained by a single observer using photogrammetric methods from four different photos collected per individual gorilla. CVs were similar for the parallel-laser and distance meter methods, and also similar to CVs obtained in direct measurements (Table I).

Within-photo measurement error for the same observer was determined by re-measuring photos on three separate occasions. The mean CV for a total of three photos was 0.006 for EAR-TORUS, 0.005 for EAR-CREST, and 0.020 for ARM measurements, respectively. When two different observers collected measurements from the same photographs (n = 12), the mean CV was 0.051 (range = 0.027–0.069) (Table II). Measurements between observers were highly correlated, for laser ($R^2 = 0.9947, P < 0.00001$) and distance-meter ($R^2 = 0.9952, P < 0.00001$) techniques.

Accuracy

When comparing photogrammetric measurements to the mean of direct measurements for each target, results again demonstrated low errors (Table I). For repeated measurements obtained using the parallel laser technique, the average percent error with respect to direct measurements ranged between 2.72% and 5.20%; measurements collected using the distance meter method were on average 2.20–7.51% different from the corresponding direct measurements. The maximum error recorded for any single measurement, considering all body parts, was 9.63% and 11.00% using the parallel laser and distance meter techniques, respectively. Across all measures, and for both techniques, the percent error between photogrammetric and direct measurements showed no significant relationship with observer distance (Fig. 3).

Finally, when mean individual measurements across structures were combined, correlations between

TABLE I. Measurements of Gorillas Collected Directly (Top), Using the Parallel Laser Method (Middle), and Using the Distance Meter Method (Bottom), by a Single Observer (JG)

Measurement	ID	*N*	D range (cm)	Mean (cm)	SD	CV	% Error: Mean (min–max)
Direct							
EAR-CREST	Charlie	5	n/a	23.30	0.45	0.02	n/a
	Sukari	4		15.30	0.76	0.05	
	Kuchi	3		16.33	0.58	0.04	
	Lulu	3		15.33	0.29	0.02	
EAR-TORUS	Charlie	4	n/a	12.13	0.25	0.02	n/a
	Sukari	4		11.50	1.08	0.09	
	Kuchi	3		10.33	0.58	0.06	
	Lulu	3		9.67	0.29	0.03	
ARM	Charlie	2	n/a	56.75	0.35	0.01	n/a
	Sukari	4		40.40	0.89	0.02	
	Kuchi	4		46.75	1.44	0.03	
	Lulu	5		39.70	0.84	0.02	
Parallel lasers							
EAR-CREST	Charlie	4	824.1–1,293.9	22.93	0.69	0.03	2.72 (1.35–5.52)
	Sukari	4	838.6–1,229.8	15.88	0.49	0.03	4.33 (1.33–6.33)
	Kuchi	4	894.9–1,273.7	17.08	0.76	0.04	4.81 (0.61–9.63)
	Lulu	4	765.6–1,023.4	16.04	0.38	0.02	4.61 (2.00–7.40)
EAR-TORUS	Charlie	4	824.1–1,293.9	12.49	0.50	0.04	3.81 (0.40–7.72)
	Sukari	4	838.6–1,229.8	11.15	0.31	0.03	3.08 (0.07–6.58)
	Kuchi	4	894.9–1,273.7	10.87	0.18	0.02	5.20 (3.79–8.24)
	Lulu	4	765.6–1,023.4	9.67	0.46	0.05	3.59 (1.38–7.22)
ARM	Charlie	4	711.6–956.0	56.31	2.82	0.05	3.64 (0.39–7.15)
	Sukari	4	968.2–1,672.5	41.89	1.43	0.03	4.36 (1.66–7.98)
	Kuchi	4	894.9–1,273.7	47.05	2.92	0.06	4.98 (0.85–8.90)
	Lulu	4	765.6–1,364.2	40.05	1.93	0.05	3.74 (0.20–7.70)
Distance meter							
EAR-CREST	Charlie	4	824.1–1,293.9	22.16	0.73	0.03	4.88 (1.20–8.83)
	Sukari	4	838.6–1,229.8	15.36	0.69	0.04	3.01 (0.20–6.58)
	Kuchi	4	894.9–1,273.7	16.18	0.75	0.05	3.70 (1.38–7.01)
	Lulu	4	765.6–1,023.4	15.12	0.72	0.05	3.50 (0.22–7.84)
EAR-TORUS	Charlie	4	824.1–1,293.9	12.07	0.46	0.04	2.95 (0.25–5.73)
	Sukari	4	838.6–1,229.8	10.78	0.21	0.02	6.30 (3.82–8.30)
	Kuchi	4	894.9–1,273.7	10.30	0.28	0.03	2.20 (0.35–3.10)
	Lulu	4	765.6–1,023.4	9.10	0.17	0.02	5.82 (3.70–7.99)
ARM	Charlie	4	711.6–956.0	54.16	4.05	0.07	7.51 (3.98–11.00)
	Sukari	4	968.2–1,672.5	40.06	1.39	0.03	2.66 (0.21–5.60)
	Kuchi	4	894.9–1,273.7	44.55	2.16	0.05	6.07 (3.42–7.74)
	Lulu	4	765.6–1,364.2	38.08	1.69	0.05	4.86 (1.94–9.74)

% Error represents the percent difference between corresponding measurements obtained directly and those using photogrammetric methods, calculated for individual measurements as follows: % error = [(photogrammetric measurement − mean direct measurement)/mean direct measurement]*100. Here, the Mean % Error represents the average of errors calculated for each of 4 repeated measurements per individual. D refers to object distance. SD: standard deviation, CV: coefficients of variation.

direct measurements and corresponding parallel laser and distance meter measurements were highly significant with both R^2 values and slopes approaching 1.0 (parallel lasers – direct measurements: $R^2 = 0.9989$, $P < 0.0001$; distance-meter – direct measurements: $R^2 = 0.9990$, $P < 0.0001$) (Fig. 4).

Results: Measurements of Static Objects

Two static objects, one large and one small, were measured: (1) an interior office door (DOOR); and (2) an emergency exit sign frame (SIGN). For all laser alignments performed for these tests, the difference between direct measurements and photogrammetric-derived measurements of the target in both horizontal and vertical axes, respectively, was no greater than 1.25%.

Precision

Repeated measurements of static objects collected directly by a single observer (JG) showed uniformly low CVs. The mean sign length was 29.87 ± 0.12 cm (CV = 0.004), while the mean door length was 93.53 ± 0.25 cm (CV = 0.003). Using photogrammetry, tests of intraobserver between-photo measurement error demonstrated CVs that were similar for both methods, for DOOR (laser CV = 0.010; distance meter CV = 0.010) and SIGN length (laser

TABLE II. Parallel Laser and Distance Meter Photogrammetric Measurements Obtained by Two Different Observers (JG and DA) From the Same Photographs

			Charlie ARM				Lulu ARM	
Observer	PhotoID	D	L	DM	PhotoID	D	L	DM
JG	1	844.3	56.53	60.92	4	1,008.2	39.62	38.19
JG	2	711.6	53.48	51.95	5	1,023.4	41.23	40.47
JG	3	824.1	56.30	52.93	6	765.6	38.19	37.39
DA	1	844.3	57.60	60.62	4	1,008.2	43.31	41.35
DA	2	711.6	57.23	55.60	5	1,023.4	42.80	42.27
DA	3	824.1	57.39	54.10	6	765.6	38.22	38.03
Mean			56.42	56.02			40.56	39.62
SD			1.53	3.88			2.24	2.02
CV			0.027	0.069			0.055	0.051
			Charlie EAR-TORUS				Lulu EAR-TORUS	
	PhotoID	D	L	DM	PhotoID	D	L	DM
JG	7	711.6	12.95	12.50	10	1,008.2	9.53	9.07
JG	8	824.1	11.94	11.43	11	1,023.4	9.43	9.31
JG	9	1,022.4	13.06	12.52	12	1,014.9	10.36	9.23
DA	7	711.6	12.57	12.39	10	1,008.2	9.74	9.63
DA	8	824.1	11.22	11.07	11	1,023.4	9.84	9.73
DA	9	1,022.4	13.10	12.95	12	1,014.9	9.73	9.62
Mean			12.47	12.14			9.77	9.43
SD			0.75	0.73			0.33	0.26
CV			0.060	0.060			0.033	0.028
			Charlie EAR-CREST				Lulu EAR-CREST	
	PhotoID	D	L	DM	PhotoID	D	L	DM
JG	7	711.6	22.01	21.24	10	1,008.2	16.31	15.52
JG	8	824.1	22.74	21.77	11	1,023.4	16.13	15.93
JG	9	1,022.4	22.95	22.01	12	1,014.9	16.47	14.67
DA	7	711.6	21.72	21.41	10	1,008.2	16.28	16.10
DA	8	824.1	22.96	22.66	11	1,023.4	16.56	16.37
DA	9	1,022.4	19.68	19.39	12	1,014.9	15.48	15.30
Mean			22.00	21.41			16.20	15.65
SD			1.28	1.11			0.39	0.62
CV			0.058	0.052			0.024	0.039

EAR-TORUS and EAR-CREST were measured from the same photographs. D refers to object distance in centimeters. Parallel laser (L) and distance meter (DM).

CV = 0.010; distance meter CV = 0.005) (Table III). For within-photo measurement error, the mean CV for a total of six photos (three for the SIGN and three for the DOOR) was 0.0011 (range = 0.0004–0.0019) using the parallel laser method and 0.0012 (range = 0.0004–0.0019) using distance meter.

Results of inter-observer error tests are also reported in Table III. When two observers (JG, DA) collected measurements from the same photographs, measurements were not significantly different for SIGN (Wilcoxon Test, $z = 0.3145$, $P = 0.7532$) and for DOOR (Wilcoxon Test, $z = 0.5345$, $P = 0.5930$). Finally, when images were collected by two different photographers (JG, DA) and measured by JG, the results were not significantly different (Wilcoxon Test, $z = 0.1048$, $P = 0.9165$; and $z = 0.5241$, $P = 0.6002$).

Accuracy

When comparing measurements obtained directly to those obtained using photogrammetry by a single observer (JG), the mean percent error of repeated parallel laser measurements was 0.49% (0.15 ± 0.11 cm) for SIGN and 0.74% (0.69 ± 0.72 cm) for DOOR; for distance meter measurements, the mean percent error was 0.62% (0.18 ± 0.16 cm) for SIGN and 0.76% ($0.71 + 0.24$ cm) for DOOR (Table III).

COMPARISON AND CRITIQUE

In a rare opportunity to compare measurements obtained directly from living great apes to measurements estimated remotely, we found that two independent photogrammetric methods, employing

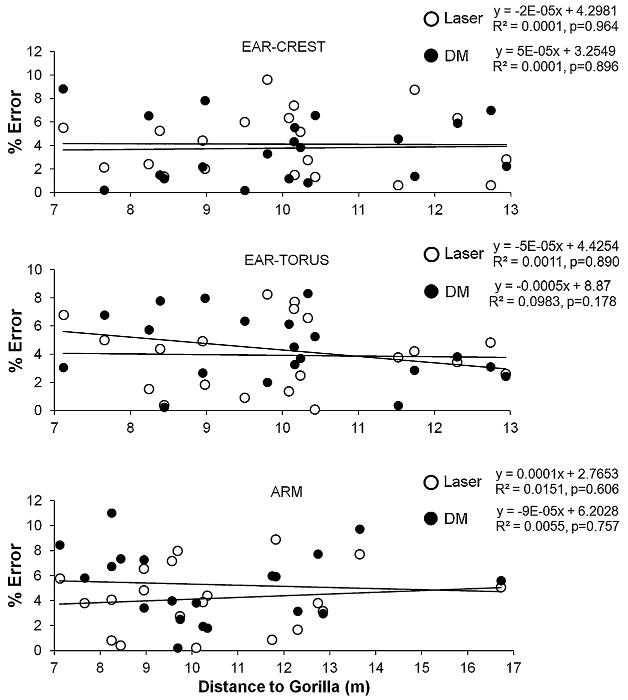

Fig. 3. OLS regressions of percent error of photogrammetric measurements on observer distance for EAR-CREST, EAR-TORUS, and ARM length, plotted separately for laser and distance meter (DM) methods.

the use of parallel lasers [following Rothman et al., 2008] and distance meter [following Breuer et al., 2007], respectively, produce similar levels of accuracy and precision. For measurements of captive western lowland gorillas observed at Zoo Atlanta, mean systematic errors ranged between 2.72% and 5.20% using parallel lasers, and between 2.20% and 7.51% when using the distance meter method. The maximum error recorded for any single measurement of gorillas was 9.63% and 11.00% using the parallel laser and distance meter techniques, respectively. Moreover, direct and photogrammetric measurements of gorillas were highly correlated, with R^2 values and slopes approaching 1.0. In static object tests, mean error was 0.76% or less, across target objects and techniques. Thus, maximum errors in our gorilla measurements were slightly higher for the distance meter method. However, as suggested previously, both techniques show great promise for research applications requiring morphological data from primates, where inter-individual or inter-group differences being examined are greater than measurement errors reported here.

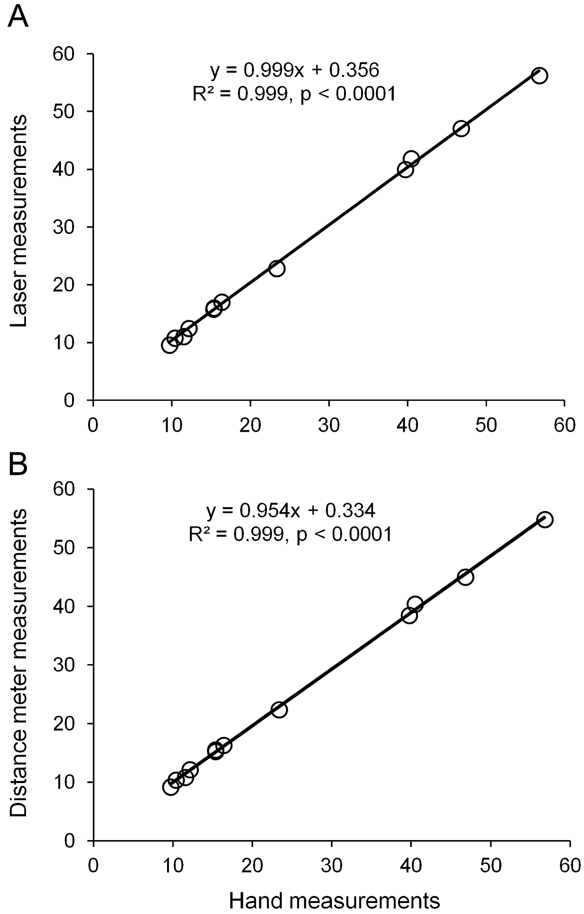

Fig. 4. OLS regressions of mean individual measurements obtained using (**A**) the parallel laser method and (**B**) the distance meter method, against measurements obtained directly (hand measurements).

Previous photogrammetric linear measurements of red colobus monkeys obtained using parallel lasers showed lower errors [mean error 1.7% and maximum error 5.0%; Rothman et al., 2008] compared to measurements obtained directly from living gorillas examined here. However, mean errors reported here are similar, or lower, than those reported for measurements obtained from howler monkeys using the parallel laser method [for the latter, reported mean error across all measurements = 3.62%, mean error for distal forelimb = 6.3%, and for distal hindlimb = 13.1%; Barrickman et al., 2015]. However, accuracy of measurements of static objects reported here are very similar, or lower, than that described in previous studies using the same photogrammetry techniques: 0.09% and 1.7%, respectively [Breuer et al., 2007; Rothman et al., 2008].

As noted by previous investigators [Bergeron, 2007; Rothman et al., 2008], accuracy of the parallel laser method is highly dependent upon proper alignment of the lasers. As we have now implemented this method in a field setting to study wild gorillas [Abavandimwe et al., 2015], we have found the apparatus to be very stable. Alignment of the lasers is checked daily before going into the field, according to the following criteria (based on results of our tests above): (1) the distance between paired vertical lasers and between paired horizontal lasers is 4.0 ± 0.05 cm (i.e., allows for ±1.25% error in the calibration); and (2) the difference (% error) between

TABLE III. Measurements of Static Objects Collected by a Single Observer (JG/JG) and Two Observers (JG/DA and DA/JG) Using Direct and Two Independent Photogrammetric Methods: Parallel Laser and Distance Meter

	Sign length									Door length								
		Photogrammetry									Photogrammetry							
Observer: photographer/ measurer	Direct	Object distance	Principal distance	Laser Msmt	Laser error	Laser % error	DM msmt	DM error	DM % error	Direct	Object distance	Principal distance	Laser Msmt	Laser error	Laser % error	DM msmt	DM error	DM % error
Intra-observer																		
JG/JG	29.80	723.4	202.85	29.61	−0.26	−0.86	29.50	−0.37	−1.24	93.80		202.79	92.93	−0.60	−0.65	94.45	0.91	0.98
JG/JG	29.80	1,037.0	202.23	29.91	0.04	0.15	29.75	−0.11	−0.38	93.50	1,037.8	202.22	93.51	−0.02	−0.02	93.09	−0.45	−0.48
JG/JG	30.00	1,379.5	201.54	29.73	−0.14	−0.46	29.79	−0.07	−0.24	93.30	1,323.3	201.65	94.98	1.45	1.55	92.77	−0.76	−0.81
Mean	29.87			29.75	0.15	0.49	29.68	0.18	−0.62	93.53			93.81	0.69	0.74	93.44	0.71	0.76
SD	0.12			0.15	0.11		0.16	0.16		0.25			1.06	0.72		0.89	0.24	
CV	0.004			0.010			0.005			0.003			0.010			0.010		
Inter-observer																		
JG/DA	29.80	723.4	202.85	29.61	−0.22	−0.75	29.38	−0.45	−1.52	93.80	754.2	202.79	93.64	−0.33	−0.35	94.54	0.57	0.61
JG/DA	29.80	1,037.0	202.23	30.26	0.43	1.43	29.63	−0.20	−0.68	94.00	1,037.8	202.22	93.88	−0.09	−0.09	93.16	−0.80	−0.86
JG/DA	29.90	1,379.5	201.54	29.61	−0.22	−0.75	29.79	−0.04	−0.15	94.10	1,323.3	201.65	94.32	0.35	0.38	93.25	−0.71	−0.76
Mean	29.83			29.83	0.29	0.98	29.60	0.23	−0.78	93.97			93.95	0.26	0.27	93.65	0.70	0.74
SD	0.06			0.38	0.12		0.21	0.21		0.15			0.34	0.15		0.77	0.12	
CV	0.004			0.010			0.007			0.004			0.004			0.010		
DA/JG	29.80	744.5	202.81	29.36	−0.51	−1.71	29.84	−0.02	−0.07	93.80	763.0	202.77	94.06	0.52	0.56	92.40	−1.13	−1.21
DA/JG	29.80	1,009.6	202.28	29.33	−0.53	−1.79	30.01	0.14	0.47	93.50	1,063.8	202.17	93.23	−0.30	−0.32	93.36	−0.17	−0.18
DA/JG	30.00	1,364.9	201.57	29.93	0.07	0.22	29.67	−0.19	−0.65	93.30	1,337.9	201.62	93.50	−0.04	−0.04	93.10	−0.44	−0.47
Mean	29.87			29.54	0.37	1.24	29.84	0.12	0.40	93.53			93.59	0.29	0.31	92.95	0.58	−0.62
SD	0.12			0.34	0.26		0.17	0.09		0.25			0.42	0.24		0.50	0.50	
CV	0.004			0.010			0.010			0.003			0.005			0.005		

All measurements are reported in centimeters. Parallel laser (Laser) and distance meter (DM). SD, standard deviation; CV, coefficients of variation.

direct measurements and photogrammetric-derived measurements of the target in both horizontal and vertical axes, respectively, is no greater than 1.25%. Despite carrying the apparatus over steep rugged terrain and long treks to our study groups, we find it necessary to realign the lasers very infrequently, on average only once a week. Further, addition of a third laser into the configuration offers a practical advantage in that the alignment can be easily checked both in the field and acquired photographs; if all three lasers have remained stable in their position, they should remain equidistant with horizontal and vertical pairs positioned at right angles from one another.

Although Rothman et al. [2008] reported that mean errors between direct and photogrammetric measurements were similar for tests of static/inanimate objects versus colobus monkey tail lengths, we found that accuracy in static object measurements was higher than that calculated for gorilla measurements. Several factors may account for this difference. Static objects present hard boundaries, unlike gorillas whose body surfaces are covered with long hair; this “fuzzy boundary” problem means that determining landmarks from photos, and also for direct measurements, is more challenging. Further, anatomical features having more three-dimensionally complex morphologies (e.g., head size or sagittal crest size) or whose surfaces may be curved present different challenges for reliably identifying landmarks for measurement in photographic images, although it is noted that direct measurements obtained across a mesh partition here are also affected by these kind of errors. These factors may also account for differences in percent error between the current study for gorilla measurements and the low errors reported by Rothman et al. [2008] for colobus tail lengths, which as comparatively linear structures have start and end points that may be more easily observed (e.g., when hanging downwards) and defined. Barrickman et al. [2015] also reported higher mean errors between direct and photogrammetric measurements of fore- and hindlimb lengths in howler monkeys. For all of these reasons, validation tests of photogrammetric techniques that incorporate measurements obtained directly from study animals are likely to yield more realistic assessments of measurement error, compared to tests using static objects. Choice of body dimensions and species to be measured may also contribute to differences in error, depending on the three-dimensional complexity of those features and the ease with which landmarks can be identified [also see Barrickman et al., 2015].

Moreover, due to problems associated with parallax, any deviation in the target measurement plane away from or towards the camera can contribute to measurement error. Although only those photos of individuals in *norma lateralis* orientation were selected, minor deviations from this plane may be difficult to detect and thus may have impacted the results reported here. In this latter respect, Bergeron [2007] and Rothman et al. [2008] suggested that in those instances in which the measured surface is tilted, the maximum measurement from a set of measurements is probably closest to the true value. However, in our results this was not the case; the mean of independent measurements was closer to the direct measurement, while the maximum of independent measurements was higher. Linear correlations between the direct and the mean photogrammetric measurements, both by laser and distance meter techniques, were very significant and presented a slope close to 1.0. This finding may be influenced by error in our direct body measurements, given necessary challenges associated with the Zoo Atlanta measurement protocol. Where error is random or non-biased, using the average of a set of repeated measurements should allow for better discrimination between individuals [Pérez-Pérez et al., 1990].

Another source of error to consider in the parallel laser method is that small errors in the calibration could be magnified considerably when large objects are measured, for example the arm. An ideal solution to this problem would be to increase the distance between paired lasers, thus eliminating the need to extrapolate beyond the calibration scale. However, given the nature of our study subjects and their target dimensions to be measured, this is not feasible.

Finally, our results are promising for future comparative studies across species and study sites, where field logistics and/or the behavior of study animals dictate the use of one technique over another. Results produced from the two photogrammetric methods were broadly similar when compared to direct measurements and in our intra- and inter-observer error tests. In fact, mean direct measurements presented a very strong linear correlation with mean measurements obtained from both photogrammetric techniques. However, there were some minor differences in the results generated using these two methods. In our tests, error was often slightly higher using the distance meter method. While our analyses showed no relationship between observer distance and percent error with respect to direct measurements for either technique, the distance meter method may introduce additional sources of error that should be considered in field applications. For instance, calculations of object length using this method may be impacted by errors in principal distance estimation using the prediction equation generated above. Further, errors in distance meter measurements may have a greater impact on object length at short observer distances. It may also be the case, however, that measurement accuracy may decrease at longer distances, if the projection path of the distance meter from observer to target is not horizontal [Elhassan & Ali, 2011].

By testing the accuracy and precision of two independent photogrammetric techniques using living great ape subjects, our results demonstrate the potential of these approaches for collecting morphological data at sites where subjects are observed at close range and measurement conditions are consistent with those described here. Error associated with these methods, particularly for the parallel laser method in which mean % error was 5.2% or less, is broadly similar to that reported for a range of primate morphology studies [e.g., Bailey, 2004; Galbany et al., 2005; Kimura & Hamada, 1996; Sherwood et al., 2004; Spoor & Zonneveld, 1995]. Thus, these techniques may be of great value to primatological investigations, allowing researchers to address a wide range of previously intractable questions requiring the collection of morphological data from wild primates, and thus show promise to contribute to research on a variety of topics. Three-dimensional photogrammetry, as employed in a range of other applications [e.g., McGlone, 2013], also represent an exciting new direction. Particularly, 3D approaches would address some of the above limitations of 2D photogrammetric techniques, including the requirement that target landmarks lie in a plane perpendicular to the optical axis, thus expanding the range of measures that could be accurately estimated. Though, since this requires incorporation of multiple camera systems collecting simultaneous images from different vantage points, the logistics of implementing a 3D approach in forested habitats with high vegetation density represents a challenge that would need to be overcome.

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