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Morphometric study of humpback whale mother-calf pairs in the Sainte Marie channel, Madagascar, using a simple drone-based photogrammetric method

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Abstract

Morphometric studies of humpback whales (*Megaptera novaeangliae*) occurring in the Indian Ocean area have been limited by the technology currently available. In the Sainte Marie channel, Madagascar, straightforward aerial single-camera photogrammetry was tested on mother-calf pairs that combines standard Unoccupied Aerial Vehicle (UAV) with free, easy-to-access, and user-friendly software. The goals of the study were to estimate mother and calf body measurements and to investigate the effect of maternal parity (primiparous versus multiparous, based on length) on calf size. A mean length of 12.4 ± 1.2 m for mothers ($N = 16$) and 5 ± 0.9 m for calves ($N = 16$) was estimated. The size of calves did not depend significantly on maternal parity. The photogrammetry method used was simple and cost-effective, yet produced convincing morphometric measurements with acceptable precision and accuracy. The coefficients of variation (CVs) of repeated estimates and the level of error were relatively low (CV = 2.31 % for a known-sized object and average CV = 2.52 % for individual whales; average error = 1.8 % for a known-sized object). These results will encourage more teams to study the morphometry of large marine mammals despite limitations in terms of resources.

Keywords: aerial photogrammetry, breeding grounds, parity, Unoccupied Aerial Vehicle (UAV)

Introduction

Morphometric data is the numerical expression of an animal's morphological characteristics that can be used to address various biological questions (Schmidt-Nielsen and Knut, 1984). Previous studies have demonstrated the efficiency of using body length for determining growth rate, age-structures, and population demographics in cetaceans (Chittleborough, 1965; Perryman and Lynn, 1993). At the individual level, morphometric data can be examined to assess body condition and reproductive capacity (Perryman and Lynn, 2002; Miller *et al.*, 2012; Christiansen *et al.*, 2016; Fearnbach *et al.*, 2018). In addition, a time series

of morphometric data can be used to assess population responses to environmental and anthropogenic changes (Hanks, 1981). For example, long-term changes in size distribution can provide a signal of overexploitation of a population (Stevens *et al.*, 2000).

Live capture-release schemes are generally not applicable to large whales due to their size. Hence in the past, morphometric studies of large whales relied mainly on direct measurements on stranded or commercially harvested specimens (e.g., Chittleborough, 1955, 1958, 1965; Omura, 1955; Nishiwaki, 1959, 1962). Later, the development of photogrammetry for

studying whales allowed for the extension of morphometric studies to live animals. Known as the science of measuring objects using photographs, photogrammetry is better than direct measurements as it does not require physical capture of animals and is thus non-invasive and less opportunistic. Photogrammetry used in whale studies can be divided into two main approaches; either stereo-photogrammetry or single-camera photogrammetry. Stereo-photogrammetry uses overlapping photographs to estimate length (Cubbage and Calambokidis, 1987; Dawson *et al.*, 1995). It allows for accurate measurements of whales since the measurements are done in 3-dimensions. However, it requires a complex pre-configuration such as a precise and controlled stereo-camera mounting and synchronization. On the other hand, single-camera photogrammetry requires only a single photograph and uses either a known-size object in the frame for scale (Christiansen *et al.*, 2016) or a measurement of the range to the individual (Best and Rüther, 1992; Perryman and Lynn, 2002; Jaquet, 2006; Fearnbach *et al.*, 2011; Miller *et al.*, 2012; Durban *et al.*, 2015; Dawson *et al.*, 2017; Christiansen *et al.*, 2018; Burnett *et al.*, 2019). To achieve accurate measurements from single photographs while optimizing the cost, a variety of combinations of tools, detailed in Table 1, has been used in the field. One of the most notable advances is the use of Unoccupied Aerial Vehicles (UAVs) or small aerial drones to perform aerial photogrammetry.

UAVs have facilitated an array of methods for monitoring wildlife and studying spatial ecology. They provide an ideal solution if the studied animals are scared by the presence of humans in the area or if the animals are dangerous for human observers (Linchant *et al.*, 2015). UAVs allow researchers to observe animals in their environment from above, are less invasive than Occupied Aircrafts (OA), and are significantly much more cost-effective. UAVs have therefore been used for a number of marine mammal research applications (Goebel *et al.*, 2015; Fiori *et al.*, 2017), including measuring individual animals (Christiansen *et al.*, 2016, 2018; Durban *et al.*, 2016; Dawson *et al.*, 2017; Burnett *et al.*, 2019).

The models of UAVs commonly used in aerial photogrammetry of whales vary from standard UAVs, such as DJI Phantom 3, to the more expensive UAVs specifically designed for scientific research and/or above-water operations. To obtain an approximation of the range between the camera on the UAV and the whale,

researchers generally rely on an altimeter, i.e., an altitude measurements tool (as mentioned in Table 1). The altimeter can be a barometric one (Durban *et al.*, 2015, 2016; Burnett *et al.*, 2019) or an external customized tool such as Light Detection and Ranging technology or LIDAR (Dawson *et al.*, 2017; Christiansen *et al.*, 2018). LIDAR can provide very accurate and precise altitude measurements (Dawson *et al.*, 2017). However, the deployment of LIDAR on an UAV can incur additional cost. Therefore, although barometric altimeters are less accurate and less precise than LIDAR, they are still suitably reliable for photogrammetric purposes and are commonly integrated into most UAVs (Durban *et al.*, 2015, 2016; Burnett *et al.*, 2019). It should be noted that since the lens of the UAVs camera often distorts the images, some photogrammetric studies incorporate prior image correction to improve photo accuracy during the image processing step (Dawson *et al.*, 2017; Burnett *et al.*, 2019). Alternatively, other studies follow a set of specific framing rules in order to minimize the distortion effects on the image (Durban *et al.*, 2015, 2016; Christiansen *et al.*, 2016, 2018).

The logistical challenges in utilizing advanced research tools for studying whales may offer an explanation as to why comprehensive surveys on humpback whale morphometry in some regions is lacking. Adding elements to an existing UAV or designing a new UAV can be for example a complex task for teams lacking a Research & Development or electronics department. In this paper, the performance of a simple and cost-efficient single-camera photogrammetry approach is established and validated that combines a standard UAV (here a DJI Phantom 4) with open-source software to target mother-calf pairs from the Sainte Marie channel, Madagascar.

Humpback whales are a highly migratory species. They spend the majority of the summer in their mid- or high-latitude feeding grounds. In winter, they breed and give birth in warm tropical waters (Clapham, 2018). The Sainte Marie channel, located on the eastern coast of Madagascar, is part of the humpback whale's breeding grounds in the South Western Indian Ocean. It is an important breeding ground in terms of the presence of mother-calf pairs as the channel is relatively calm and shallow (Trudelle *et al.*, 2018). Humpback whales arrive here between June and September.

Female humpback whales start to calve between 5 to 9-years old (Clapham, 1992; Gabriele *et al.*, 2007) where they give birth to a single calf, approximately

Table 1. Non-exhaustive list of photogrammetric approaches used for measuring whales at sea. For Aerial vehicle: (***) expensive, time and resource consuming aerial vehicle. (**) efficient/specialized but expensive aerial vehicle. (*) Low price/standard vehicle. (.) Aerial vehicle not required. For Range measurement tool: (***) Efficient/specialized but expensive tool. (**) Moderate price/standard tool or pre-integrated in the vehicle. For Image measurement tool: (***) highly specialized scientific tool. (**) Paid software/Script available for free but requiring paid software. (*) Free software/Script and software available for free. (a) Based on linear measurements of a known-sized object. (b) Based on linear measurements of individual adult whales. (c) Based on measurements of the surface area of individual whales.

Reference	Aerial vehicle	Type	Range measurement tool	Scale basis	Lens distortion correction	Image measurement tool	CV (%)	Error (%)
Cubbage & Calambokidis (1987)	Airplane (OA) ***	Stereo-photogrammetry	Radar altimeter **	Independent reference object	No	Stereoplotter ***	1.7 (a)	0.5 (a)
Best and Rüther (1992)	Helicopter (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Independent reference object	No	Stereoplotter ***	1.3 (b)	-
Dawson et al. (1995)	(Not required) .	Stereo-photogrammetry	(Not required)	Camera characteristics (obtained from calibration)	No	Stereoplotter ***	4.4 (b)	< 2.5 (a)
Spitz et al. (2000)	(Not required) .	Single-camera-photogrammetry	Sonar **	Camera characteristics (obtained from calibration)	Yes	Adobe Photoshop software (Adobe) **	4.3 (a)	4.6 (a)
Perryman & Lynn (2002)	Airplane (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Camera characteristics (factory specifications)	No	Image Image Pro Plus (Media Cybernetics) **	2 (b)	1 (a)
Jaquet (2006)	(Not required)	Single-camera-photogrammetry	Laser range finder **	Independent reference object	No	Adobe Photoshop software (Adobe) **	1.3 (b)	0.27 (a)
Fearnbach et al. (2011)	Helicopter (OA) ***	Single-camera-photogrammetry	GPS ***	Camera characteristics (factory specifications)	No	ImageJ software (NIH) *	-	< 3.2 (a)
Miller et al.(2012)	Airplane (OA) ***	Single-camera-photogrammetry	Radar altimeter **	Independent reference object	No	Image Pro Plus (Media Cybernetics) **	1.7 (b)	-
Durban et al. (2015, 2016)	APH-22 hexacopter (UAV) **	Single-camera-photogrammetry	High precision barometer **	Camera characteristics (factory specifications)	No	-	-	< 1 (a)
Christiansen et al. (2016)	Splashdrone quadcopter (UAV) **	Single-camera-photogrammetry	(Not required)	Reference object in the same frame as the target animal	No	Custom-written script in R *	< 12 (c)	-
Dawson et al. (2017)	DJI Inspire Pro (UAV) **	Single-camera-photogrammetry	LIDAR ***	Camera characteristics, (obtained from calibration)	Yes	Custom-written script in MATLAB **	1.2 (b)	1 (a)
Christiansen et al (2018)	DJI Inspire Pro (UAV) **	Single-camera-photogrammetry	LIDAR ***	Camera characteristics (factory specifications)	No	Custom-written script in R *	0.3 (b)	4.75 (b)
Burnett et al. (2019)	DJI Phantom 3 Pro/4/4 Pro (UAV) *	Single-camera-photogrammetry	Barometer **	Independent reference object	Yes	Custom-written script in MATLAB **	< 5 (b)	-

every 2 years (Clapham, 2018). Humpback whale mothers are left with the responsibility of the survival of their young until the calf reach the age of approximately 1-year old (Clapham, 2018). The size of sexually mature females ranges between 11 m to 15 m (Omura, 1955; Nishiwaki, 1959, 1962). Christiansen *et al.* (2016) reported a mean length of 12 m for females accompanied by a calf off Australia. A similar measurement has been reported by Spitz *et al.* (2000) in Hawaii. The mean length of calves is about 4.2 m at birth (Chittleborough, 1965) and they have a growth rate of approximately 3 cm per day (Christiansen *et al.*, 2016).

In pinnipeds (Bowen, 2009) and some large whale species (Laws, 1961; Gambell, 1972; Best and Rüther, 1992), it has been found that primiparous mothers (females having their first young and thus inexperienced mothers) tend to produce smaller offspring compared to multiparous mothers (mothers that have previously calved and thus more experienced). This trend may be related to numerous factors, such as a physiological change in the mother following her first parturition that favours the development of future foetuses, a more favourable external environment for the mother, or a behavioural change in the mother gained through previous experiences (Ellis *et al.*, 2000). Female investment in offspring size can be considered as a form of maternal contribution to the survival of the offspring since larger offspring are known to have higher chances of survival in mammals (Ronget *et al.*, 2018). In humpback whales, the effect of the maternal parity on offspring size has not yet been investigated. Therefore, the goals of this study were to: 1) estimate mother and calf body measurements (standard length and maximum width), and 2) test whether the calf's size is related to the parity of the mother (primiparous or multiparous).

Materials and methods
Study site
Field studies were conducted in the Sainte Marie channel, in Madagascar (Indian Ocean). About 60 km long and 7 to 30 km wide (Trudelle *et al.*, 2018), the channel is located between Sainte Marie Island (between latitudes 17° 19' and 16° 42' South, and longitudes 49° 48' and 50° 01' East) and the East coast of Madagascar's mainland. The data collection, conducted in conjunction with an ongoing study on humpback whale mother-calf interactions, were completed between August and September 2018 under the national research permits #28/18 MRHP/SG/DGRHP.

UAV platform
The DJI Phantom 4 UAV is a quadcopter weighting 1380 g, with a diameter of 350 mm. It is equipped with a built-in barometer that provides real-time altitude measurements (in m), and a gimballed camera with a 3.61-mm focal length, infinite focus and 0.0015-mm pixel size. Within a centred radius equivalent to 60 % of the video frame height, the distortion-related displacement on an image from the camera is less than five pixels (Burnett *et al.*, 2019), which is low. In this study, the video resolution was set at 4096×2160-pixels (4K) with a framerate of 24 frames per seconds.

Whale visual searches protocol
All methods and approaches were carried out in accordance with relevant guidelines and regulations in force in Madagascar. Dedicated visual searches for humpback whale mother-calf pairs were conducted from a 6.40 m rigid motor boat during days with moderate weather conditions (Beaufort scale ≤ 3, corresponding to gentle breeze, wind speed less than 12 km h^{-1}, and wave height not exceeding 0.5 m) between 0630 and 1730 hours. The crew consisted of at least 3 trained observers (one on an elevated platform at the back of the boat and two covering the lateral view) and 1 or 2 experienced drone pilots. When a mother-calf pair was spotted, it was approached at idle speed to a distance between 100 and 200 m. All mother-calf pairs were photo-identified to ensure that there was no double-sampling during the study period. The ventral face of the tail fluke (visible when the whale is about to dive) and/or the dorsal fin of each individual was/were photographed using a Nikon digital camera (model D5600) fitted with a 50-300 mm lens. The photographs obtained within the season were then manually compared in order to check that indeed no double-sampling of mother-calf pairs occurred. Depending on the degree of dorsal furl, the relative age of each calf was also estimated (neonate versus non-neonate, Cartwright and Sullivan, 2009; Faria *et al.*, 2013, Saloma, 2018). All sighting data were integrated into the local dataset CETANET (www.cetanet.org, managed by Cétamada Association) that gathers all marine mammal sighting information recorded in Madagascar since 2009.

UAV flight protocol for whale images acquisition
The UAV was deployed from the boat to video-record the spotted mother-calf pair vertically overhead from an altitude around 15 m to 60 m, at a vertical speed of approximately 0.5 m s^{-1}. Sometimes the mother and the calf were not close to each other or were not
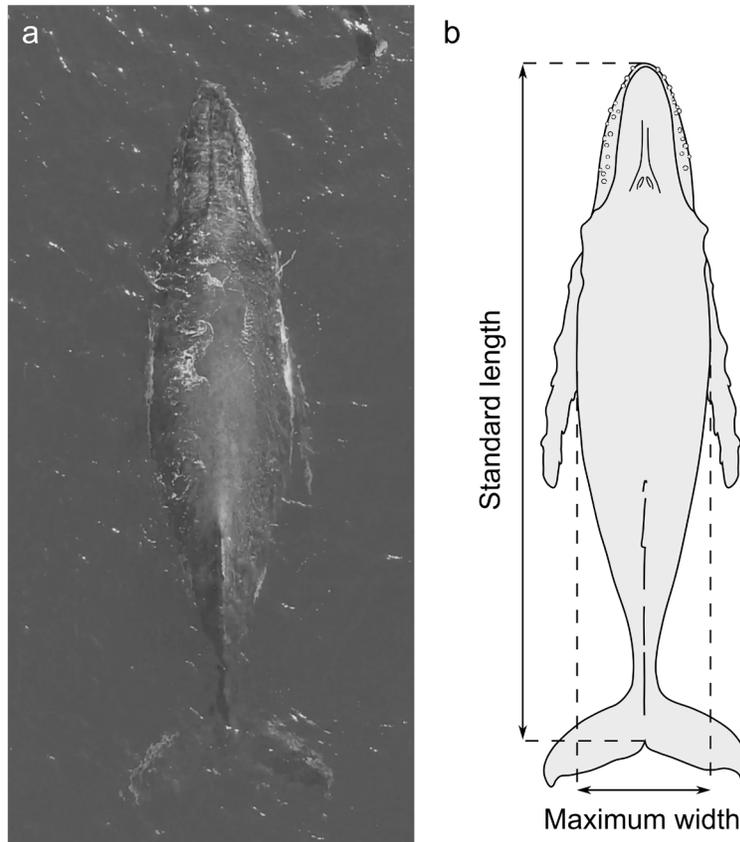
Figure 1. (a) Example of acceptable aerial photograph of humpback whale extracted from the video recording and used for photogrammetry. The original image was of 4096×2160-pixel but was cropped in this figure to highlight the fixed criteria. The whale must be flat at the surface, dorsal side facing up, emerged as much as possible, static or travelling at relatively slow speed, with a contour not masked by chops and with a non-arching body axis and peduncle. (b) Measurements in pixel recorded for each photograph.

at the surface at the same time. In these cases, they were filmed separately. The drone initialization (altitude zeroing) was performed before each flight on an on-boat platform 0.6 m above the sea level (the variation of the on-boat load between outings was fairly low and assumed to not have a very significant effect on this zeroing height). A maximum of two flight sessions was conducted for each pair (10-15 min duration per flight). Photographs were extracted afterward from the video recordings (see Images extraction and digitization).

Calibration images acquisition

To estimate the whales' dimension from photographs in the absence of known size scale markers in the frames and to account for systematic error in ranging, the camera needed to be calibrated. This can be done using images of an object with a known length taken at various distances between the object and the camera, i.e., ranges (Jaquet, 2006; Burnett *et al.*, 2019).

To perform calibration in this study, a static floating kayak of 2.75 m in length was video-recorded vertically overhead at altitudes between 5 m to 45 m at the end of the study period. In addition, for testing, a supplementary filming flight was performed to acquire video material that was independent to the one dedicated to the calibration. The equipment, settings used, and weather conditions present during calibration were consistent with the whale survey flights.

Image extraction and digitization

The photogrammetric method was based on 4096×2160-pixel photographs (no cropping) extracted from the collected nadir pointing video using the frame capture function in GOM Player v2.3.32.5292 (GOM & Company, www.gomlab.com). Video recordings were viewed frame by frame for the process. For each filmed individual, one photograph which was of the highest quality was extracted. A high quality

photograph is one which includes the whale lying flat at the surface, dorsal side facing up, emerged as much as possible, static or travelling at relatively slow speed, with contour not masked by chops, and with a non-arching body axis and peduncle (Fig. 1a). As the unadjusted lens is likely to distort images around the outside of the frame, a suitable high quality photograph was selected if the subject was positioned within the 60 % radius in the middle of the frame (see lens description in UAV platform). For each photograph, the standard length and the maximum width of the whale were measured in pixels using the software Inkscape v0.92 (www.inkscape.org) (Fig. 1b).

With respect to the kayak video dedicated to calibration, eight photographs were extracted at approximately 5 m altitude intervals (reference photographs). Only photos with clear, centred frames containing the entire kayak were selected. Additionally, from the supplementary independent kayak video, several photographs (tests hereafter) were taken at an altitude ranging from 5 to 45 m. The length of the kayak in all photographs was then measured in pixels.

Calibration process

For each of the reference photographs, the measured length from the photographs (in pixels) and the real length of the kayak (in m) were used to calculate the corresponding scale (in m pixel^{-1}):

$$\text{Scale} = \text{real length} / \text{length in pixels} \qquad (1)$$

Then, the scale was regressed against the altitude at which the reference photographs were taken (Fig. 2):

$$\text{Scale} = 0.0004197 \times \text{altitude} + 0.0001814 \qquad (2)$$

From (2), a formula was then derived with which the metric length could be estimated from vertical images taken at known altitudes:

$$\text{Estimated length} = \text{scale} \times \text{number of pixels} \qquad (3)$$

Barometric altimeter accuracy evaluation

The UAV model used did not have a suitable alternate altitude measurement for comparison. Therefore, the accuracy of the barometric altimeter was assessed directly using the optical properties of the camera. All of the test photographs were used to back-calculate the expected distance between the camera and the object (in m) as done by Krause *et al.* (2017):

$$\text{Expected camera-object distance} = (\text{Real length} \times \text{Focal length}) / (\text{Number of pixels} \times \text{Pixel size}) \qquad (4)$$

This was then compared with the barometric altitude reading while accounting for the zeroing height. To assess if the accuracy of the barometric altimeter varies with the expected altitude (expected camera-object distance minus zeroing height), a Spearman's correlation test was performed using the R statistical software v4.0.3 (R core team, www.R-project.org).

Measurement accuracy evaluation

It was not possible to directly address the accuracy of the measurements as it was impractical to include a scale object with a known size in each photograph of whales. However, as a proxy, the measurement error was evaluated based on the test photographs. From each photograph, the length of the kayak was estimated and the measurement error was then calculated as the percent difference as follows (Krause *et al.*, 2017):
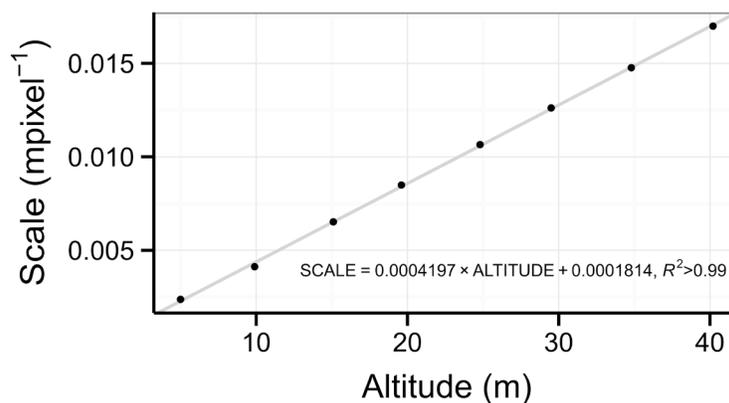
Figure 2. Relationship between photographic scale and height at which the photos were taken. Multiplied by the number of pixels, the regression equation gives length in meters.

% Error = | 1 - (real length / estimated length) × 100 | (5)

To investigate whether the error varies with the altitude at which the photographs were taken, a Spearman's correlation test and a Kruskal-Wallis test was used (using three altitude classes: 5 to 15 m, 15 to 25 m and > 25 m) in R.

Measurement precision evaluation
To indirectly assess the precision of the approach used, the coefficient of variation (CV) was calculated of the length estimations of the test object. Additionally, to address whether different observers consistently derive similar measurements, four independent observers estimated the length of the test object. The results were compared among observers using Kruskal-Wallis test in R.

Whale data analysis
The numbers of pixels of the whales were related to the estimated dimension in meters using the formula (2) and (3). Based on the estimated length and considering the life history of the humpback whale (Omura, 1955; Nishiwaki, 1959, 1962; Chittleborough, 1965; Clapham, 1992; Gabriele *et al.*, 2007; Clapham, 2018), the mothers were sorted into two categories: primiparous, i.e. likely accompanied by their first calf, for mothers < 13 m, and multiparous, likely already had previously one or more calves, for mothers ≥ 13 m. To assess if the body lengths of calves differ between the two parity categories of mothers, a Wilcoxon test was performed in R.

Age has previously been used to categorize females as primiparous or multiparous when complete birth records for each individual were not available (Ellis

et al., 2000). Such an approach is possible when the life history of the species is known. As mentioned previously, the age at which female humpback whales have their first calf is between 5-9-years old (Clapham, 1992; Gabriele *et al.*, 2007) and the birth interval is about 2 years (Clapham, 2018). Based on these data, it can be assumed that females < 9-years old whom are accompanied by a calf are likely to be primiparous mothers, while those that are ≥ 9 years old can be assumed to be multiparous. At age 9, a female humpback whale should reach 13 m (Chittleborough, 1965) and incidentally, this value is consistent with data obtained by whaling operations (i.e., data from direct measurements); the average size of sexually mature female humpback whales is 13 m (Omura, 1955; Nishiwaki, 1959, 1962). Therefore, 13 m was set as the threshold to define parity.

In some instances, it was possible to extract more than one suitable, high quality photograph of individual whales. Therefore, for these whales, it was possible to make additional length estimations. The CVs on individual whales was thus calculated as well to obtain a more direct precision assessment.

Results
Using a DJI Phantom 4, a total of 16 mother-calf pairs were photographed between August and September 2018. All calves had an unfurled dorsal fin, indicating that they were not neonates (yet aged less than 3 months). All photographs were obtained at an altitude ranging between 17 and 60 m (mean = 27±11 m); the majority (29 out of 32) being obtained at an altitude < 45 m. The empirical calibration formulas (2) and (3) allowed estimation of the standard length and the maximum width of mothers and calves from these photographs.
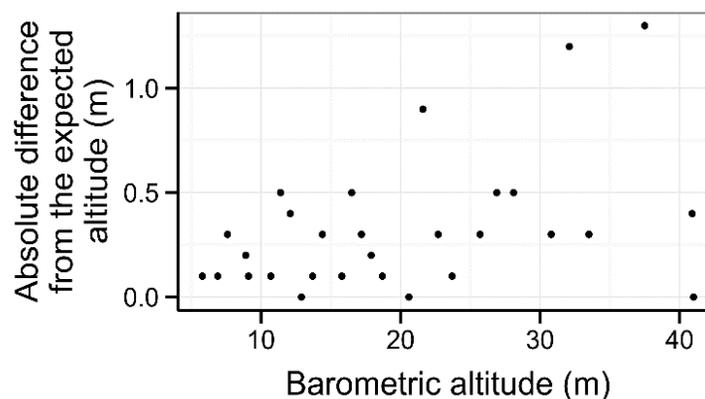
Figure 3. Barometric altitude reading versus its absolute difference from the expected altitude. The correlation was low and not statistically significant (Spearman's correlation test; rho = 0.354, *S* = 2624 and *p* = 0.06).
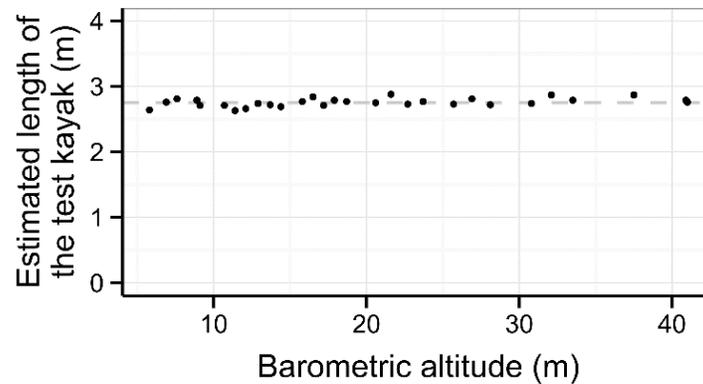
Figure 4. Repetitive estimation (N = 29) of the length of the test kayak at an altitude from 5.8 m to 40.9 m. The grey horizontal dashed line indicates the real length of the kayak (2.75 m). The coefficient of variation (CV) of the estimations was of 2.31 %.

Accuracy of the barometric altimeter

The absolute difference between the altitude reading provided by the barometric altimeter of the UAV and the expected altitude (expected camera-object distance minus zeroing height) was low (mean = 0.3±03 m, min = 0 m, max = 1.3 m, N = 29; Fig. 3). Furthermore, the correlation between this difference and the barometric altitude was low and not statistically significant (Spearman's correlation test; rho = 0.354, S = 2624 and p = 0.06).

Accuracy of the method using an object with a known size

The results of repetitive estimations of the length of an object with a known size, a 2.75-m test kayak, at an altitude between 5.8 and 40.9 m showed an average error of 1.8±1.41 % with respect to the real length (min = 0 %, max = 4.56 %, N = 29). The errors showed no statistically significant variation with respect to altitude (Spearman's correlation test; rho = -0.16,

S = 4711 and p = 0.406; Kruskal-Wallis test; χ^2 = 1.664, df = 2 and p = 0.435; Fig. 4).

Precision of the method using an object with a known size

The repeated estimations of the length of an object with a known size showed a CV of 2.31 %. No statistically significant differences were detected for the estimated length of the object among four independent observers (Kruskal-Wallis test; χ^2 = 0.511, df = 3 and p = 0.916; Fig. 5).

Morphometric measurements of whales

All estimations are presented in Table 2. The mothers showed a mean body length of 12.4±1.2 m (min = 10.2 m, max = 14.7 m, N = 16). Their average maximum width was 2.8±0.4 m (min = 2.1 m, max = 3.6 m, N = 16). The calves presented a mean body length of 5±0.9 m (min = 3.6 m, max = 7.2 m, N = 16) and a mean maximum width of 1±0.2 m (min = 0.7 m, max = 1.5 m, N = 16).
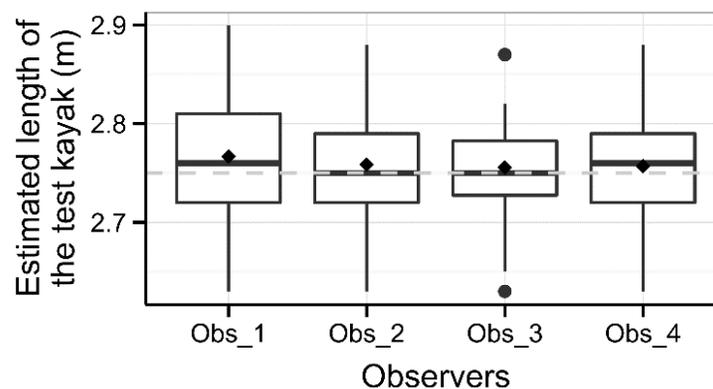
Figure 5. Repetitive estimation (N = 29) of the length of the test kayak compared between four independent observers. The grey horizontal dashed line indicates the real length of the kayak (2.75 m). The difference found was not statistically significant (Kruskal-Wallis test; χ^2 = 0.511, df = 3 and p = 0.916).

Table 2. Morphometric measurements of mothers and calves from photogrammetry and reproductive category of the mothers based on their estimated length. Length corresponds to standard length, i.e., length from the tip of the snout to the notch of the tail fluke. Width represents the maximum body width.

			Mother		Calf
Pair ID	Length (m)	Width (m)	Category	Length (m)	Width (m)
1	13.3	2.9	Multiparous	4.9	0.9
2	14	3.6	Multiparous	4.8	1.1
3	13.1	2.9	Multiparous	4.9	0.9
4	14.7	3.2	Multiparous	7.2	1.5
5	12.7	3.1	Primiparous	4.6	1
6	10.2	2.3	Primiparous	3.6	0.7
7	12.1	3	Primiparous	5	1.1
8	12.1	2.6	Primiparous	4.9	1
9	12.4	2.7	Primiparous	4.6	0.9
10	13.7	3	Multiparous	6.6	1.4
11	12.1	2.8	Primiparous	4.3	1
12	10.7	2.2	Primiparous	4.4	1
13	12.4	2.6	Primiparous	4.9	1
14	11.2	2.7	Primiparous	4.9	1
15	12.6	3	Primiparous	4.6	1
16	11	2.1	Primiparous	5.3	1

Relation between calf size and parity

The majority of the mothers (11 out of 16) were < 13 m in length and were classified into the primiparous category. The remaining 5 individuals were classified as multiparous mothers (≥ 13 m in length). The length of calves from primiparous mothers was smaller than those from multiparous ones on average (Fig. 6). However, there was no statistically significant difference (Wilcoxon test; $W = 12$ and $p = 0.084$).

Precision of the whale measurements

For most individual whales ($N = 24$), it was possible to extract supplementary photographs at different altitudes. Including the initial whale photographs, two length estimations for 23 individuals and three for one individual were obtained. With these estimations, an average CV of 2.52±1.65 % (min = 0.02 %, max = 5 %) was found.
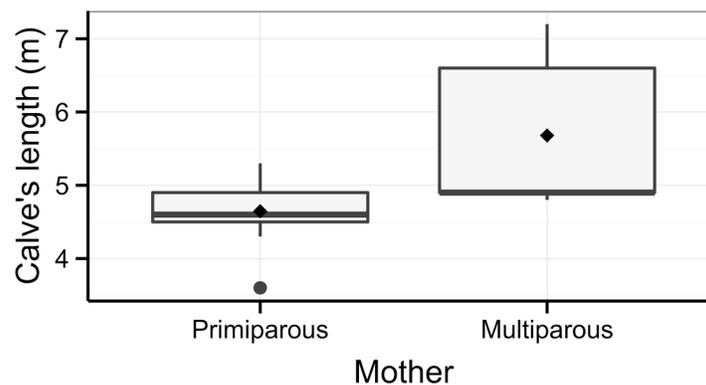
Figure 6. Calves' estimated standard body length according to the parity of their mother. The bold black lines represent the median and the diamonds represent the mean. The difference found was not statistically significant (Wilcoxon test; $W = 12$ and $p = 0.084$).

Discussion

The photogrammetric approach used relied on a formula which was based on several vertical-aerial photographs of a reference object with a known size (a 2.75-m kayak) placed on the sea surface. This empirical formula allowed assessment of morphometric data of both humpback whale mothers and their calves using nadir pointing aerial photographs taken at a known altitude with a DJI Phantom 4 UAV. In this method, errors are likely due to 1) the distortion of the lens, 2) the human error in the digitization process, 3) the accuracy of the UAV's barometric altimeter, and 4) the whales' body flex and varying submersion level. To minimise lens distortion, all the images were centred, with the targeted object avoiding the outer frames. With framing, the pixel displacement normally does not exceed 5 pixels (Burnett *et al.*, 2019). Thus, the associated error is likely to be relatively small. Also, the contribution of human error is likely to be negligible, as it was found that independent observers systematically derived similar estimations.

With the assumption that local environmental barometric pressure is relatively uniform within and between individual flights in a given site (Burnett *et al.*, 2019), the tests suggested that the measurements obtained with this method are relatively precise and accurate. Although higher than those reported by Dawson *et al.* (2017) and by Durban *et al.* (2015, 2016), the CVs of repeated estimates (2.31 % for an object with a known size and 2.52 % on average for individual whales) and the level of error (1.8 % on average, as calculated using an object with a known size) did not differ greatly from those reported in Christiansen *et al.* (2016) and in Burnett *et al.* (2019).

Regarding the barometric altimeter of the drone, the altitude it provided, used as a proxy for range, was accurate to within 1.3 m. Compared to the LIDAR altimeter like the one used by Dawson *et al.* (2017) which is accurate to < 0.06 m, the barometric altimeter of the drone was less accurate, which in turn, likely contributed greatly to the estimated errors and variation over repeated measurements.

With respect to the contribution of the body flex and varying body submersion of free-ranging whales, precise quantification is difficult as the true size of each individual is not known in advance for comparison. The dorso-ventral flexing of the body may result in underestimation of length if the method is based on nadir-pointing images (Cubbage and Calambokidis,

1987; Dawson *et al.*, 1995). Body submersion may also contribute to additional underestimation and variation because the altitude was used as a proxy for range (camera-object distance). As whales are always partially submerged (at least), the range is always slightly greater when photographing a whale than when photographing a kayak from the same altitude. Also, because the degree of submersion may vary slightly amongst photographs and individuals, there could be additional ranging imprecision which was not taken into account during this study. Incidentally, this may partially explain why the CV of repeated estimates is greater for whales than for the test kayak. Further studies involving this method and other alternatives at the same time that can take into account the whales' body flex and body submersion (e.g., stereo-photogrammetry, Cubbage and Calambokidis, 1987; Dawson *et al.*, 1995) would allow the quantification of these errors and are thus encouraged. In all cases, the method used in the present study ensured that only photographs of the whale lying flat at the surface, emerged as much as possible from the water, and with straight body axis and caudal peduncle were used. The authors are thus confident that these whale related issues were minimized.

The estimated standard lengths of the mothers were consistent with those obtained from underwater images by Spitz *et al.* (2000) in Hawaii and from aerial vertical photographs by Christiansen *et al.* (2016) off Australia. Using a threshold that was defined according to the known life history of humpback whales, the mothers were categorized as primiparous (< 13-m mothers) or multiparous (≥ 13-m mothers). The calves produced by mothers categorized as multiparous seemed larger than those produced by mothers categorized as primiparous. It has been reported that novice (primiparous) females generally produce smaller offspring (Clutton-Brock, 1991), while multiparous females are capable of producing larger offspring, as they are physically and physiologically more mature than primiparous females (Ellis *et al.*, 2000). For both fin whales (*Balaenoptera physalus*) and sperm whales (*Physeter macrocephalus*), it has been documented that the offspring of primiparous females are smaller than those of multiparous females examined at the same time (Laws, 1961; Gambell, 1972). For right whales (*Eubalaena australis*), calves from primiparous females have a smaller mean length than calves from older females (Best and Rüther, 1992). In this study, the difference in size between calves from multiparous mothers and primiparous mothers was however not statistically significant. It should be considered that

this study was conducted at the end of the breeding season, and all calves observed had an unfurled dorsal fin and were longer on average compared to the mean length at birth (4.3 m; Chittleborough, 1965). This means that the calves have already grown significantly since birth. The difference in size, while likely evident at birth, is likely less evident with time as calves may grow throughout the season at different rates depending on various external factors, as seen in pinnipeds (Bowen, 2009). Milk intake by humpback whale calves and the milk production from each mother may for example differ amongst mother-offspring pairs, meaning the postnatal growth rate may vary. Although the sample size was relatively small, the results provide a first assessment of the morphometry of the South Western Indian Ocean's female humpback whales and their calves.

In conclusion, this study allowed the estimation of the body measurements of humpback whale mother-calf pairs and the investigation of the effect of maternal parity on calf size using a relatively straightforward photogrammetric method that combined a standard UAV and free, easy-to-access, and user-friendly software. This method was not as precise and as accurate as methods involving more advanced equipment and tools such as drones equipped with an acute altimeter (Durban *et al.*, 2015, 2016; Dawson *et al.*, 2017) and paid software (Dawson *et al.*, 2017; Burnett *et al.*, 2019). However, it was demonstrated that the method presented in the present study produce convincing morphometric measurements with both satisfactory precision and accuracy. While the level of error limits the suitability of the method presented in the present study for comparing individuals, the method still has potential applications to study the global morphometric trend of a population. The method presented in the present study can be further adapted for studying population structures or for investigating population responses to a changing environment as has been done previously (Chittleborough, 1958; Hanks, 1981; Stevens *et al.*, 2000; Perryman and Lynn, 2002). It is hoped that this study will encourage more teams to study the morphometry of large marine mammals despite limitations in terms of resources. Such studies would especially help in conservation decision-making as it may help identifying environmental issues.

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