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USING LASER PHOTOGRAMMETRY TO MEASURE LONG-FINNED PILOT WHALES (*GLOBICEPHALA MELAS*)

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ABSTRACT

Knowledge of animal morphometry is important to understanding their ecology. By attaching two parallel lasers to a camera, known as laser photogrammetry (LP), a scale is projected onto photographed animals, allowing measurement of their body. Our primary aims were to test LP precision, and to estimate body length from dorsal-fin dimensions of *Globicephala melas*. Secondary aims involved demonstrating applications of LP, such as sex and leader determination. Using photographs taken over two-months, we measured dorsal base lengths (DBL) of 194 individuals individually-identified with natural markings. Results indicated 33 individuals were photographed in multiple encounters and eight matched previously-sexed whales. A mean difference of <2.1% between DBL's of 58% of repeatedly-sighted individuals was found, and whales closer to the boat (<22m) produced more precise measures. The length from the blowhole to anterior insertion of the dorsal fin (BAID) was a better predictor of total body length in stranded whales than DBL, and laser-estimated lengths fell almost all within known pilot whale size. Despite our small sample size, we showed two examples of how LP could be applied in research: (1) males and females had similar DBL (*n*=8), but large males could be distinguished using DBL; (2) leaders were not necessarily bigger than other individuals in the same cluster (*n*=4). The ease of use of LP makes it a valuable tool in collecting measurements of body features, especially when coupled with photo-identification.

Keywords: laser photogrammetry, morphometrics, measurement, length, *Globicephala melas*

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INTRODUCTION

In the study of animal biology, the ability to measure individuals is central to understanding an organism's life history and ecology. Linear measurements have long been used to quantify growth (Clark *et al*. 2000, Fearnbach *et al*. 2011, Busby *et al*. 2017), and to distinguish size classes (Meise *et al*. 2014), subspecies (Meijaard and Groves 2004), geographic forms (Jaquet 2006, Segura-García 2016), and sexes (Ramos *et al*. 2002, Martin and DaSilva 2006). Length estimates have been used to explain size-related social behaviours (Bergeron *et al*. 2010, Pack *et al*. 2012), as well as life history parameters such as pregnancy and age at maturity (Waters and Whitehead 1990). Morphometrics may easily be obtained from deceased animals or in certain circumstances, from live-captures. However, the capture of animals is often expensive, stressful to the animal, and dangerous (Pelletier *et al*. 2004, Meise *et al*. 2014), especially in the case of large aquatic animals, such as cetaceans (whales, dolphins, and porpoises). Historically, body lengths of whales and other large aquatic animals were estimated through visual observation. However, comparison of visual estimates to measured lengths from capture or stereo-video systems, indicates the discrepancy and bias of visual estimates (Gordon 1990, Rohner *et al*. 2015, Sequeira *et al*. 2016). For example, visual estimates of whale shark lengths were found to be underestimates of true lengths, with a 10% increase in the number of large individuals measured with stereo-video camera (Sequeira *et al*. 2016). As such, developing reliable methods to measure free-ranging animals has been an ongoing topic of research.

Photogrammetry involves obtaining morphometric measurements using photographs, such that disturbance to animals is minimized. Two methods of photogrammetry exist: stereo and single-camera. Stereo-photogrammetry involves photographing the individual from two angles, using two cameras, and overlapping the two images to create a three-dimensional optical model. Morphometrics may then be derived from the scale provided by the lens magnification and the distance between cameras (e.g. Dawson *et al*. 1995). Successful estimations of body size have been made for terrestrial and aquatic animals using this technique (e.g. bats, *Myotis daubentoni*, Jones and Rayner 1988; humpback whales, *Megaptera novaeangliae*, Spitz *et al*. 2000; sea lions, *Zalophus wollebaeki*, Meise *et al*. 2014; whale sharks, *Rhincodon typus*, Sequeira *et al*. 2016). However, despite its accuracy, the cumbersome nature of stereophotogrammetry setup may be impractical for use on research vessels that are limited in space and prone to movement (Bell *et al*. 1997, Spitz *et al*. 2000, Rowe and Dawson 2008). Such small research vessels are often the primary platform used to study marine mammals. Single-camera photogrammetry simplifies the equipment required by using an object of known size (Best and Rüther 1992, Flamm *et al*. 2000), or by using the distance from the individual to the camera for scale (Gordon 1991, Spitz *et al*. 2000, Jaquet 2006). Large terrestrial mammals have been measured this way (e.g. elephants, *Loxodonta africana*: Shrader *et al*. 2006, gorillas, *Gorilla gorilla*: Breuer *et al*. 2007). However, applications for use with cetaceans have been relatively limited (e.g. sperm whales, *Physeter macrocephalus*: Jaquet 2006, blue whales, *Balaenoptera musculus*: Durban *et al*. 2016) likely due to the challenges of taking measurements at sea, where only a small portion of the animal's body is briefly visible.

Laser photogrammetry is a recent advance to single-camera photogrammetry in which two parallel lasers are mounted to a digital camera, projecting dots of a known distance apart onto each photographed individual. Lasers may be used remotely from the study subject, as long as the target is perpendicular to the photographer, making data collection non-invasive for free-ranging animals. The setup itself is lightweight and operational by a single photographer, such that laser photogrammetry is gaining popularity. For example, laser photogrammetry has been used to measure the horn length of Alpine ibex *Capra ibex* (Bergeron 2007), total length of whale sharks *Rhincodon typus* (Rohner *et al*. 2015), and body size of manta ray *Manta alfredi* (Deakos 2010). In the study of cetaceans, laser photogrammetry has been used to measure dorsal fin dimensions of orca (*Orcinus orca*, Durban and Parsons 2006), bottlenose dolphins (*Tursiops truncatus*, Rowe and Dawson 2008, Rowe *et al*. 2010), and Hector's dolphins (*Cephalorhynchus hectori*, Webster *et al*. 2010). Knowledge of dorsal base lengths of Hector's dolphins was also used to estimate total body lengths (Webster *et al*. 2010). As such, the potential of laser photogrammetry to be applied to other marine mammal species is promising, and its continued use may be the best approach to non-invasively measure large animals in challenging field environments.

Long-finned pilot whales (*Globicephala melas*) are one of the largest members of the dolphin family (Delphinidae) and listed as *data* *deficient* under the International Union for Conservation of Nature (Taylor *et al.* 2008). Males are larger in size than females, ranging from 6-7 metres in length and 3 tons in weight, compared to the smaller 4-5 metre long and 1.5 ton females (NOAA Fisheries 2014). As other delphinids, pilot whales possess high cognitive capabilities (Herzing and Johnson 2015) and show social complexity in their established social units, with an average of 11-12 individuals travelling together (Ottensmeyer and Whitehead 2003). However, social bonds may also contribute to the high rate at which pilot whales mass strand, when healthy whales will beach themselves presumably to remain with other members of their group (Oremus *et al.* 2013, Whitehead and Rendell 2014).

Of the three recognized subspecies of long-finned pilot whales, one population, the North Atlantic (*Globicephala melas melas*), has long been known to summer off Cape Breton Island, Nova Scotia (Ottensmeyer and Whitehead 2003). For the communities of Pleasant Bay, Chéticamp, Bay St. Lawrence and Ingonish, Nova Scotia, whale-watching of this species represents an important part of the local economy (Fisheries and Oceans Canada 2006). As a result, providing new means to enhance our understanding of pilot whales in the region may be beneficial for species management.

The primary objective of this study was to assess the precision of a laser photogrammetry setup by measuring dorsal-fin dimensions, and estimating total body length of long-finned pilot whales residing off Pleasant Bay. Pilot whales are ideal candidates for testing this methodology as they travel in clusters and tend to surface more frequently relative to other species, thereby increasing the number of photographic opportunities. In addition, the appearance of natural marks on the dorsal fins and saddle patches of some pilot whales allows for photo-identification of up to 67% of individuals (Auger-Méthé and Whitehead 2007). Secondary objectives included testing applications of photogrammetry to demonstrate its use in a broad range of cetacean research areas. For our study, we tested two possibilities for application: whether dorsal fin base length differs between the sexes, or between leaders and followers. The distance between the blowhole and the dorsal fin was the focus, as this is the area most often seen and photographed when observing whales from a boat. Although laser photogrammetry has been used to measure cetaceans, for example, orca (*Orcinus orca*, Durban and Parsons 2006, Durban *et al*. 2017) and bottlenose dolphins (*Tursiops trunctus*, Rowe and Dawson 2008, Rowe *et al*. 2010), its use has been primarily restricted to measuring specific body regions, with few using linear regression to estimate total body length (Hector's dolphins, *Cephalorhynchus hectori*, Webster *et al*. 2010). Furthermore, despite the importance of measurement validation, few applications of laser photogrammetry have compared laser-estimated lengths to previously-recorded lengths of cetaceans (Durban and Parsons 2006, Webster *et al*. 2010). Thus, our study's estimation of total body length and validation of results using data on locally-stranded pilot whales is among the first to do so, and if shown to be precise, will strengthen the credibility of measurements obtained through these means.

MATERIALS AND METHODS

Field methods

Data were collected during July and August 2015 on the long-finned pilot whale population that summers off Pleasant Bay, Nova Scotia, Canada (46.8208° N, 60.8158° W), a population that has been studied since 1998 (Ottensmeyer and Whitehead 2003, Augusto *et al*. 2017). Three 2.5- to 3-hour trips were conducted per day, weather permitting, aboard a 12.8 m commercial whale-watch vessel. Pilot whales were generally observed within 10 km from shore, and were approached slowly alongside the group, in accordance with the DFO whale-watch guidelines.

Two parallel laser pointers (Z-bolt Duet Emerald D5G) were secured 23.5 cm apart on an aluminum frame, which could be attached to any camera via the tripod mount (Fig 1a). A Canon 50D digital camera with a 300mm f/4L lens (Canon Inc., Tokyo, Japan) was used to photograph the whales. Laser pointers projected dots onto the blowhole to dorsal fin area of whales as they surfaced. Green lasers (power output: 4.0-5.0 mW) were preferentially used over red lasers, due to their greater visibility in daylight conditions and their long range (>100 m). In addition, the lasers used were designated as Class IIIa by the U.S. Food and Drug Administration, meaning brief exposure to whales and researchers is presumed not to cause any significant health consequences (Durban and Parsons 2006). As a precautionary measure, lasers were powered off when the whales displayed behaviours, such as "spy-hopping", which are among the

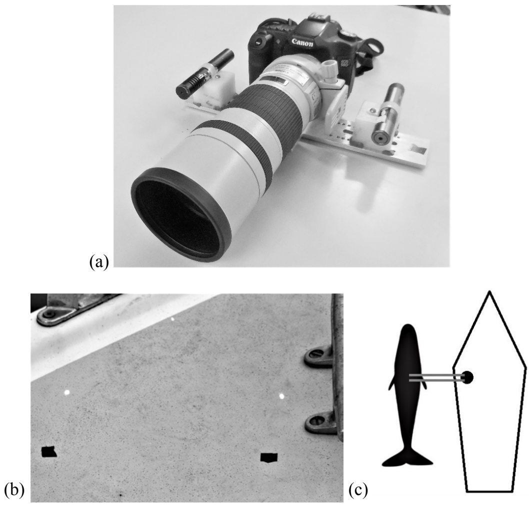

Fig 1 **Laser photogrammetry system used to obtain field measurements: (a) Laser photogrammetry setup, where two laser pointers are held in parallel by an aluminum frame; (b) Photograph of laser projections onto reference points taped 23.5 cm apart on vessel; (c) Perpendicular positioning of photographer relative to photographed whale.**

rare events when the whales have their eyes above water, and potentially exposed to the lasers.

Laser measurement precision is most commonly challenged by non-parallel alignment of lasers, horizontal axis error and parallax error (Durban and Parsons 2006, Bergeron 2007, Deakos 2010). Non-parallel alignment could result from physical interference with the mount during rough sea conditions. To ensure that lasers remained parallel throughout encounters, laser pointers were aligned at the start and end of each encounter at varying distances of 50 cm, 250 cm, 500 cm, 1000 cm, and 1250 cm. A photograph was taken of the laser projections onto fixed scale reference points (23.5 cm apart) (Fig 1b). To further minimize misalignment during trips, checks back to these fixed scales were conducted every ten minutes. Horizontal axis error occurs when the lasers are not perpendicular to the target, such that the target appears smaller than is actually indicated by the reference lasers, resulting in negatively-biased estimates (Durban and Parsons 2006). To minimize horizontal axis error, photographs were taken as perpendicular to whales as possible (Fig 1c). Finally, parallax error occurs when the plane of the lasers is not parallel to the water at which the whales are surfacing. As such, whales directly below our vessel that required the photographer to look down at the animal, were not photographed.

Photographic effort began when the boat entered within a ~80 m range from the whales, marking the start of an encounter. Dorsal fins were photographed to identify individuals (Auger-Méthé and Whitehead 2007), and whales with distinctly-notched fins were preferentially photographed for ease of recognition in analysis, and availability of previously-collected life history data, such as sex. When possible, a sequence of photographs during the surfacing period were taken in an attempt to capture the maximum length, or blowhole to dorsal fin region of an individual. “Logging” whales, or those that were seen resting at the surface, were preferentially photographed for ease of obtaining length measurements. An individual consistently surfacing at the front of the cluster (individuals within one body length of each other), was categorized as a group leader.

Photographic analysis

To ensure consistent and precise length estimates, we selected photographs that were in focus, contained both laser points on the whale, captured the entire dorsal fin, and for which the angle between the whale and camera axis was about 90°. From these images, a catalogue of recognizable individuals was compiled based on nicks and notches in the dorsal fin, saddle patch pattern, tooth rakings, and any other identifying natural scars (Auger-Méthé and Whitehead 2007). When multiple photographs of an individual were taken during the same encounter, the photograph that captured the whale’s body in its most elongated form was chosen for analysis (Rowe and Dawson 2008; Webster *et al*. 2010). To determine whether lasers remained parallel during encounters, photographs taken of the fixed scales were measured using *ImageJ* software. To provide the most consistent estimates as possible, only cases where the distance between laser projections at the start and end of the encounter did not differ by more than 5% were used in our analysis.

To assess the precision of the laser measurement system, we compared the differences between measured dorsal base lengths (DBL) of the same individual across separate encounters (ΔDBL), and generated a coefficient of variation (CV). DBL was defined as the axis running from the anterior to the posterior insertions of the dorsal fin

(Fig 2a). The approximate distance of the whale from the photographer was compared with the ΔDBL in order to determine whether the photographer's proximity to the whale had a significant effect on the precision of the laser measurements. Approximate distance to photographed whales was calculated using the following formula:

$$\text{Distance} = \frac{(\text{focal lens length} \times \text{DBL} \times \text{width of camera frame in pixels})}{(\text{image width in pixels} \times \text{sensor width of camera})}$$

We wanted to verify whether we could estimate the total body length of pilot whales based on features of the dorsal fin or other morphometric measurements. Because Bloch *et al*. (1993) found that DBL was a better predictor of total body length than fin height in pilot whales, the DBL of each individual in our study was measured using *ImageJ*.

To determine whether partial body lengths would be appropriate for estimating the total length of pilot whales, photographs of a surfacing sequence were overlaid using GIMP software (GNU Image Manipulation Program; Fig 2b). The resulting image represented a larger section of the pilot whale body, generally including the blowhole to anterior insertion of the dorsal fin (BAID). To verify whether the DBL or BAID were correlated with total body length, we used morphometric data of locally-stranded pilot whales in Nova Scotia, collected by the Marine Animal Response Society (MARS). MARS has been operating a stranding record database for Nova Scotia since 1990, and as part of their protocol they measure, with a measuring tape, 15 body sections of deceased whales. These body sections include DBL, total length, tip of the upper jaw to the tip of the dorsal fin, and tip of the upper jaw to the blowhole. The records provided by MARS had measurements for 17 pilot whales, to which we applied simple regressions to understand the relationships of total length with DBL and BAID. If closely correlated, the estimated parameters from the regression could be used to predict the total length of the pilot whale based on laser measurements of DBL and BAID. MARS's stranding measurements of DBL and BAID were also used to verify whether our laser-estimated lengths from whales photographed at sea were representative of realistic measures.

(a)

(b)

Fig 2 Morphometric measurements showing (a) DBL as measured on all 194 individuals, and (b) BAID as measured on the 12 sequenced individuals, in which a straight line angled at 90 degrees from the blowhole was used to measure BAID across merged photographs in *ImageJ* (measures indicated by white line).

All photographed individuals were compared to a catalogue of whales that had been sexed previously, using DNA extracted from skin biopsies (Augusto *et al*. 2013). The DBL of known sex individuals were compared to assess whether the DBL could be used to differentiate male pilot whales from females. Similarly, the DBL of the leading whale in an encounter, was compared to those from the remaining individuals in the cluster. All photographic analyses were performed by J. Wong to minimize variability between observers.

RESULTS

Precision of laser photogrammetry structure

A total of 1179 photographs of 194 identifiable individuals displayed projected laser dots, where whales were also in-focus and orientated perpendicular to the camera. All individuals were photographed multiple times within each encounter (2 to 15 photographs per individual). Thirty-three individuals were photographed during multiple encounters (2 to 3 encounters), producing a mean Coefficient of Variation (CV) of 5.09%, and a median CV of 3.59% for the variability of DBL between photographs.

Comparisons of the DBL difference between first and second encounters of the same individual (ΔDBL), and the distance between the whale and the photographer, indicated lasers produced more consistent measures when photographs were taken in close proximity to the whale (Fig 3). When the distance between the whale and the photographer was relatively small (11 – 22 m; defined by a DBL that comprised >45% of the frame), the ΔDBL was minimal (mean = 3.31 cm, median = 1.82 cm; <15 cm different, or a 4.9% mean size difference between encounters) (Fig 3). Conversely, in cases where the photographer was farther away (23 – 120 m; DBL comprised <45% of the frame) from the photographed whale, the ΔDBL was greater (up to 45 cm between encounters or an 8.9% mean size difference, mean = 10.83 cm, median = 6.96 cm) (Fig 3).

Although in some cases the measurements were imprecise, our laser system produced relatively consistent measures of DBL for the same individual across encounters. The ΔDBL was less than or equal to 5 cm different in 58% of all measured cases (Fig 3). In comparison, individuals that were photographed closer to the vessel (<22 m), had a ΔDBL less than or equal to 5 cm in 82% of cases (Fig 3). A <5cm ΔDBL was equivalent to a 2.1% mean size difference between DBL measures.

Estimating the total body length

A simple regression between the DBL and the total body length of 17 locally stranded pilot whales revealed a weak, yet significant, correlation between the two measures, as represented by a low r value of 0.610 (p = 0.009; Fig 4a). However, comparison between the BAID (Fig 2b) to the total length of the pilot whales, indicated a much stronger significant correlation (r = 0.805, p < 0.001; Fig 4b). Thus, BAID was used to estimate the total length of the free-swimming whales in this study.

Surfacing sequences for 12 individuals were digitally overlaid to construct a larger section of the pilot whale body. Only 12 individuals

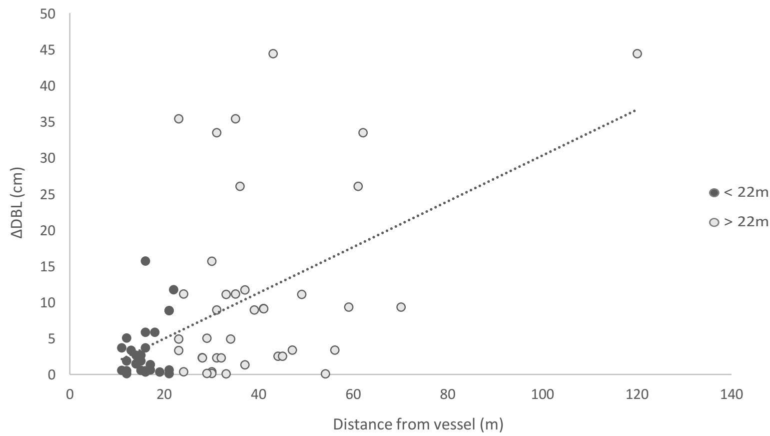

Fig 3 ΔDBL for 33 individuals, where photographs taken within close proximity of whales (< 22m) are shown in relation to photographs taken at all ranges.

were used as these represented the only sequences where all visible sections of the individual were photographed. Estimation of the total length from the BAID from these individuals produced a range of lengths from 335–837 cm, with a mean body length of 568 cm (Fig 5). An independent two-sample t-test was conducted to compare total length of whales that were stranded, and those that were estimated using our sequenced photographs. There was a significant difference in the mean lengths for stranded (368 cm, SD = 120 cm) and photographed (568 cm, SD = 165 cm) individuals ($t_{14} = 3.78$, $p < 0.001$), suggesting that lengths estimated using the lasers were greater than those recorded from strandings.

Using DBL to differentiate sex

Eight individuals were matched to a catalogue of 87 previously-biopsied individuals, identifying three males and five females. The mean male DBL was 133 cm (range: 79 to 198 cm), while the mean female DBL was 92 cm (range: 62 to 134 cm; Fig 6). The DBL of male whales was more varied, while those for females were closer to the mean length. Although the largest DBL was exhibited by a male, the DBL of males and females did not differ significantly from one another ($t_3 = 1.08$, $p = 0.36$).

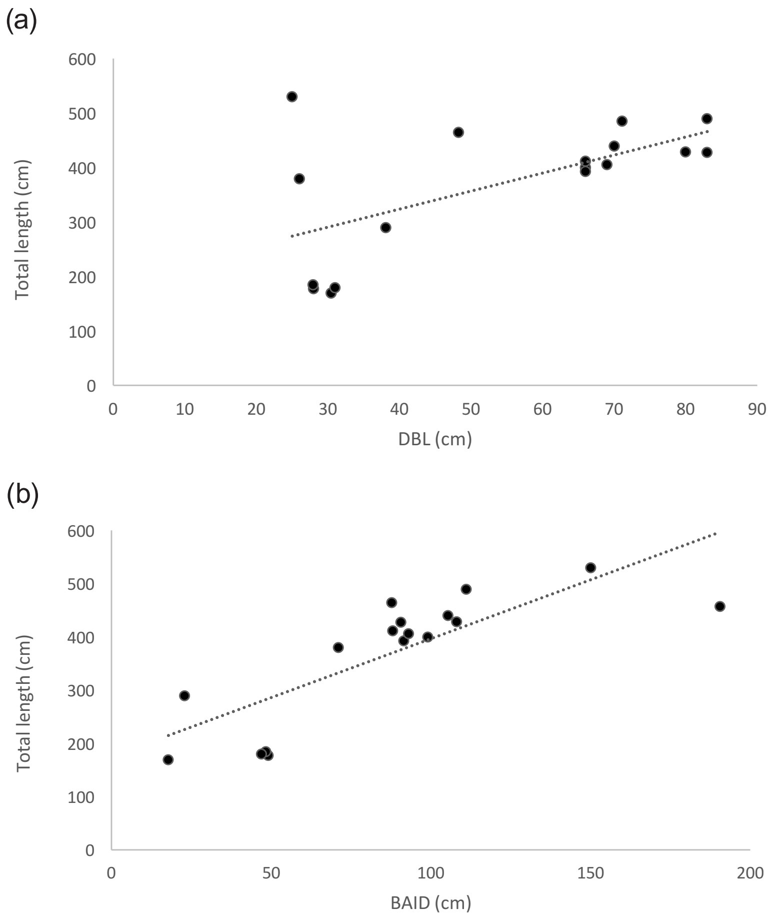

Fig 4 **Linear regression indicating the relationship between: (a) DBL and the total length, and (b) BAID and the total length, for 17 locally-stranded pilot whales.**

Using DBL to differentiate leaders

Four leaders were identified in four encounters and their DBL measurements were compared to those of the remaining individuals that surfaced within the same cluster. Leaders were either the largest (50% of cases; cluster size = 5-6 individuals), in which case their DBL was at least 30 cm larger than the largest non-leader, or the third-largest whales (remaining 50% of cases; cluster size = 5-8 individuals) within their cluster (Fig 7).

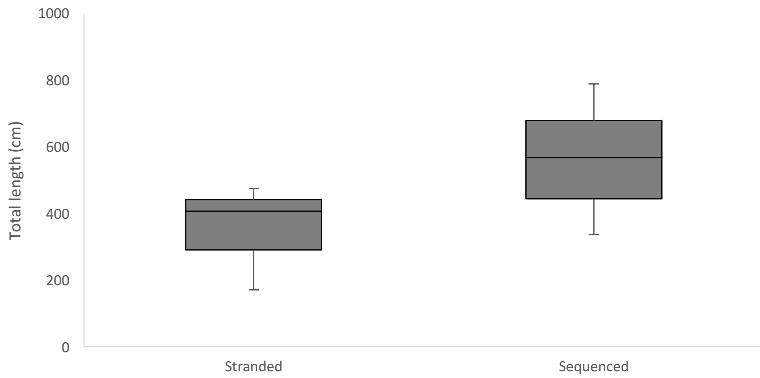

Fig 5 **Estimated total length of 12 photographed individuals based on measuring BAID, in relation to the measured total length of 17 locally-stranded individuals.**

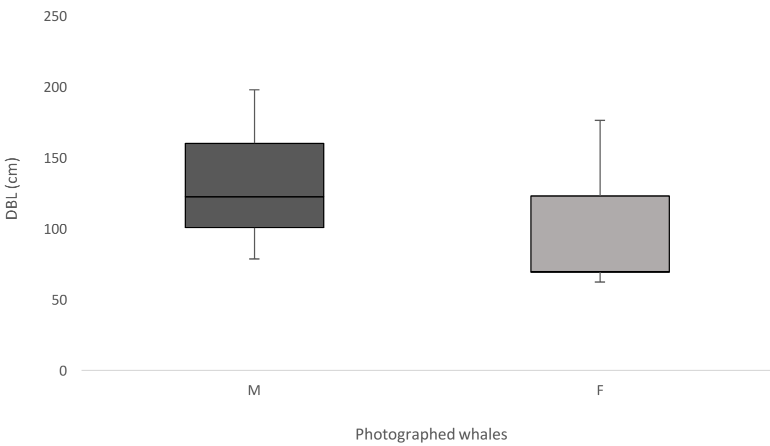

Fig 6 **DBL of photographed males (M) and females (F).**

DISCUSSION

Laser photogrammetry was used to obtain morphometric measurements of free-ranging pilot whales. Taking such measurements may have otherwise been impossible. Not only was this technique easily operable by a single researcher, but the materials involved in setting up the laser system were easily available and inexpensive.

As cetaceans are photographed in motion while their bodies are flexed, even repeated measurements of the same individual under

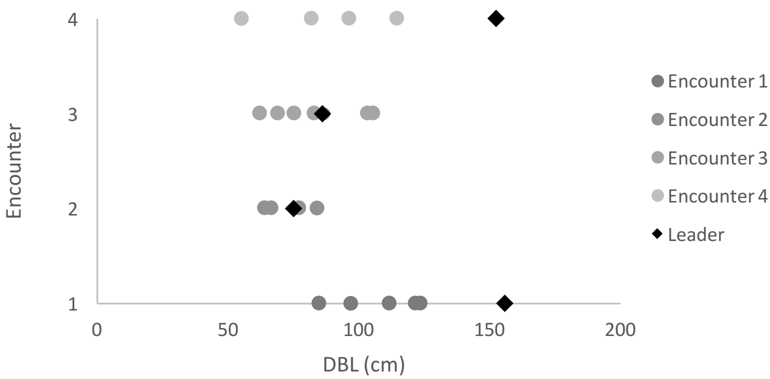

Fig 7 **DBL of four leaders in relation to other individuals in the same encounter, where each point represents one individual in the observed cluster.**

perfect conditions will not generate identical measurements (Webster *et al*. 2010). Therefore, measurement precision was assessed using ΔDBL, which quantifies the difference in measurements of DBL for the same individual. Multiple measurements from different encounters were available for 33 individuals, resulting in a mean CV of 5.09% and a median CV of 3.59% for DBL. These values are comparable to other photogrammetric techniques used to measure cetaceans. Laser photogrammetric measurement of DBL in Hector's dolphins resulted in a mean CV of 3.71% (Webster *et al*. 2010), while sperm whale fluke measurements resulted in a median CV of 1.3% (Jaquet 2006). Median CV's ranging from 1.29% to 4.56% were obtained from morphometrics of right whales, measured through aerial photogrammetry (Best and Rüther 1992). Stereo-photogrammetry on sperm whales produced a mean CV of 4.38% (Dawson *et al*. 1995), and underwater videogrammetry on humpback whale lengths yielded a mean CV of 3.08% (Spitz *et al*. 2000). The rounded angle of the anterior and posterior insertions of the dorsal fin challenge the establishment of DBL 'start' and 'end' points. Despite this, our laser structure had similar precision to that of laser photogrammetric measurements of flukes with clear points of measure. Therefore, the laser structure used in this study is considered to be reasonably precise, and even suitable for measuring difficult body sections.

The majority of individuals had a relatively small ΔDBL of less than 5 cm or 2.1% mean difference in DBL between encounters. All large ΔDBL values (median = 6.96 cm) were associated with whales photographed at a greater distance from the vessel (23 – 120 m) suggesting that an increase in distance had a negative effect on measurement precision. When laser photogrammetry was used to obtain dorsal fin height of orcas, slight changes to the parallel orientation of the lasers resulted in large variations in the location of the projected laser points, with increased variation when the whale was photographed beyond a 15 m range (Durban and Parsons 2006). Similarly, our laser structure may not have been properly aligned for long ranges of up to 120 m. Despite best efforts to align lasers in parallel, minor shifts in laser orientation may have caused laser projections to slightly converge or diverge with increasing distance from the whale. As a result, measurements of DBL were less precise. In the future, mounts should be constructed to prevent laser movement, and/or studies may be limited to situations when whales are within close range.

Based on the stranding data, BAID was shown to be a better predictor of total length in pilot whales than DBL, as indicated by a high r value of 0.805. Comparison of laser-estimated body lengths (based on BAID) to length measurements collected from locally-stranded pilot whales, indicated that laser-estimated lengths were significantly larger. Despite this difference, photographed whales produced length estimates (mean length: 568 cm, maximum length: 837 cm) that were similar to the mean and maximum lengths expected for free-ranging whales (mean length, male: 565 cm, mean length, female: 340 cm, maximum length: 617 cm, Sergeant 1962; maximum length: 760 cm, NOAA Fisheries 2014). There may be several potential reasons why length estimated with the lasers were greater than those of the stranded whales. First, there is likely a bias towards measuring larger whales at sea because larger individuals are more easily observed and photographed. Second, measurement via the laser method may have overestimated length; slight changes in laser alignment (i.e. physical disturbance) may have shifted laser projections out of parallel orientation, resulting in an imprecise scale. Third, stranded whales, with the exception of mass strandings and old age mortality, are typically smaller than the general population. Individuals that are young, weak or unhealthy, are more likely to beach as a result of environmental factors (Duignan *et al*. 1995, Ogle 2017, Yunus *et al*. 2017), thus morphometric measurements gathered on stranded individuals may be more representative of the smaller individuals in that population. Of the 17 stranded whales for which we had data, 65% were female, and 24% were juveniles. Adult females (340 cm) and juveniles (<200 cm) are smaller than adult males (565 cm, Sergeant 1962), which potentially suggests a bias towards smaller whales in our sample of stranded whales (mean total length: 368 cm). Fourth, the curvature of the whale's body upon surfacing could influence the measurement of the BAID, which in turn would affect the total length estimate. Furthermore, length measurements collected from strandings may not account for the curvature of the whale's body when swimming. Measurements of beached pilot whales before and after the body was straightened produced differences of up to 8 cm (Sergeant 1962). In this case, deviations between total lengths derived from free-swimming whales and those directly measured from beached whales, should be considered in future applications of this technique.

As one of the few studies that compared laser-estimated measures to locally-stranded cetaceans, potential problems and biases associated with extrapolating body length from body parts were recognized. While most of our laser-estimated lengths fell within the range of known lengths for pilot whales, this may not always be the case in laser-photogrammetry studies. Studies that estimate body length without validation using existing measurement data risk overlooking potentially stronger biases, thereby decreasing the validity of length estimates obtained this way.

In delphinids, sexual dimorphism can be expressed physically through differences in overall body size, or in traits such as dorsal fin shape and pigmentation patterns (Murphy and Rogan 2006). In bottlenose dolphins, dorsal fins of males were taller and wider at the base (larger DBL) than those of females (Rowe and Dawson 2008). Augusto *et al*. (2013) studied the sexual dimorphism of pilot whales and found no significant differences between male and female dorsal fin shape, saddle patch density, or number of mark points (nicks and notches in trailing edge of dorsal fin; Ottensmeyer and Whitehead 2003, Auger-Méthé and Whitehead 2007). However, our analysis of the DBL showed that, while laser photogrammetry cannot be used reliably to distinguish sexes, DBL may allow for the identification of large adult males. Although mean DBL's estimated using the laser system are not necessarily indicative of an individual's sex, a DBL greater than 150 cm likely suggests that the whale is male (Fig 6).

Our small sample of individuals for which we had sex information (n = 8) likely impacted our results, and future use of laser photogrammetry alongside genetic sampling may shed more light on sexual dimorphism in pilot whales.

Leaders within a cluster were not typically bigger or smaller than their counterparts, suggesting DBL may not be indicative of leadership in pilot whales. Pilot whales coexist in an extended matriline, where mothers, offspring, and recent ancestors maintain long-term associations (Amos *et al*. 1993, Ottensmeyer and Whitehead 2003, Alves *et al*. 2013, Augusto *et al*. 2017). Furthermore, pilot whales have been shown to undergo menopause – a rare post-reproductive phase experienced by only a few mammals – suggesting older females have an important social role, beyond reproduction (Marsh and Kasuya 1991, Johnstone and Cant 2010). Given this, it is not unlikely that the leader may be an older, experienced female (Brent *et al*. 2015), which might be smaller in size than the large subadult males in her cluster. Such social dynamics could explain why two of our observed leaders were not the largest in their encounter. However, the two other leaders both had a DBL > 150 cm, and were thus likely males. Adult males have been shown to stay with their mothers and remain within their natal groups long after maturity (Amos *et al*. 1993). Despite the fact that pilot whales appear to follow a "key whale" (the first individual in the group) during mass stranding events (Oremus *et al*. 2013), a set leader may not exist during regular travel. Even in killer whales, leadership by females was not absolute, despite suggested group leadership by post-reproductive females during foraging (Brent *et al*. 2015). Ultimately, the small number of identified leaders in our study (n = 4) likely impeded the significance of our results and this case study was only used to exemplify how laser photogrammetry can be used in cetacean research.

Distinguishing sex and group leaders are just two examples of the application of laser photogrammetry. Future applications of laser photogrammetry could involve differentiation between the DBL of long-finned and short-finned pilot whales (*Globicephala macrorhynchus*) where distribution overlaps in warmer waters. Short-finned and long-finned pilot whales are known to exhibit differences in flipper length, skull shape, and number of teeth (Olson 2008), but these features are unlikely to be observable above water. Thus, identifying a visible difference in dorsal fin size may improve pilot whale species identification in the field.

Several limitations challenge the application of laser photogrammetry for studying cetaceans. For example, to determine whether laser-estimated measurements are realistic requires comparison to pre-existing measurement data. As a result, this method may be limited to species that mass strand, are hunted, or those with significant bycatch (Webster *et al*. 2010). In addition, as individual identification is required to gauge laser precision, laser photogrammetry has been limited to species that surface frequently, have prominent dorsal fins, and are identifiable by natural markings (e.g. pilot whales, Auger-Méthé and Whitehead 2007, Alves *et al*. 2013; killer whales, Baird and Stacey 1988, Würsig and Jefferson 1990; bottlenose dolphins, Wells and Scott 1990; Hector's dolphins, Slooten and Dawson 1988).

We identified several potential sources of error associated with the design of our laser system. The laser pointers we used projected a laser beam that was not collimated, meaning that the axis of the laser beam may not have been parallel to the outer casing surrounding the laser. Thus, high quality laser pointers that allow for beam adjustment should be used in future studies. Furthermore, the nylon blocks used to secure the laser pointers were originally constructed to be adjustable to allow for laser alignment. However, the slightest movement of these blocks greatly altered the parallel alignment of the lasers and impeded the precision of our measurements. Future mounts should permanently hold lasers in parallel once aligned, such that physical disturbance to the structure during fieldwork does not bias the measurements.

Despite these limitations, the precision and repeatability of laser photogrammetry in obtaining morphometrics of free-ranging animals, makes it a valuable tool in cetacean research. Laser dots project a scale in every photograph, allowing measurement of any visible body proportion. Once the dorsal fin size is known for recognizable individuals, the DBL itself could be used as a reference in future photogrammetry studies to approximate the relative size of other body proportions, or other natural markings, in adults. Not only does laser photogrammetry enable simultaneous collection of photo-identification and morphometric data, but inferences about population demographics, such as growth rate, can also be made directly for individuals observed at sea, avoiding the need to rely on potentially-biased stranding or catch data (Rowe and Dawson 2008, Webster *et al*. 2010).

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