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LASER-METRICS OF FREE-RANGING KILLER WHALES

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Data on morphometrics are central to understanding key features of both population and behavioral ecology, including phenotypic differences between species (Perryman and Lynn 1993, Meijaard and Groves 2004) and populations (Perryman and Lynn 1994), life history traits such as patterns of individual growth (Read *et al.* 1993, Lee and Moss 1995), and morphological differences related to mating systems (Boonstra *et al.* 1993, Tolley *et al.* 1995, Plavcan and van Schaik 1998). In the marine environment, it has proved difficult to obtain measurements from free-ranging cetaceans. Capture operations can yield precise data on morphometrics (*e.g.*, Read *et al.* 1993), but such disruptive procedures are generally not feasible and are restricted to smaller species. On a more remote level, photogrammetric approaches have been successfully applied to estimate body size from aerial platforms (*e.g.*, Perryman and Lynn 1993) and from underwater images (Klimley and Brown 1983, Spitz *et al.* 2000), but stereophotogrammetric methods require a camera configuration that is somewhat cumbersome (Klimley and Brown 1983, Brager *et al.* 1999, Brager and Chong 1999), and can be difficult to implement from small-boat research platforms alongside routine data collection.

We describe a simple approach for obtaining morphometric measurements based on photographing two laser dots that have been projected onto the body of a whale using two small laser-pointers. These laser-pointers are mounted in a parallel orientation to maintain a fixed and known separation distance, and the dots therefore provide a scale of known dimension on the image of the whale that can be used to calibrate morphometric measurements. The lightweight laser setup can be conveniently mounted on a camera lens, allowing this approach to be implemented by a single photographer in conjunction with photo-identification studies. We demonstrate the utility of this approach by estimating the dorsal fin height of free-ranging killer whales (*Orcinus orca*).

Our measuring setup is based on two small commercially available green-beam laser pointers 10 cm in length and 2 cm in diameter (model# BTG10; www.z-bolt.com[1]). These lasers are relatively inexpensive, retailing at $70 US in 2005. Green lasers are preferable to red lasers because they have beam wavelengths of 532 nm, which is the wavelength most easily detected by the human eye, thus making the laser dots more easily visible. The laser pointer that we chose had a glass lens to focus the beam more sharply, in addition to having a range of more than 100 m in daylight. The laser pointers' constant on/off switch was also convenient for activating the laser for multiple photographic attempts in quick succession. The power output of the laser module is 4.5–5 mw, and is designated as a Class IIIa laser ($<$5 mw), which complies with the safety regulations for lasers administered by the U.S. Food and Drug Administration (http://www.fda.gov; FDA/CDRH Accession # 0010873–09). There is no realistic risk to the health and safety of the whales or researchers posed by brief exposure to Class IIIa lasers. These lasers are judged to present a health hazard only with prolonged exposure ($>$10 s) to the retina. The lasers were projected at the dorsal fins of killer whales, away from the researchers, and far from the whales' eyes that were typically submerged beneath the water's surface. To prevent any accidental exposure to the whales' eyes, we avoided the use of the lasers when whales were engaged in aerial behavior when their eyes may have been above the water, and also in the presence of young calves that typically surface with their heads raised out of the water. Even if accidental exposure did occur, the speed of the surfacing whales ensured that it would have certainly been of a momentary rather than prolonged nature. We did not observe any noticeable reactions from the whales when the lasers were being projected, indicating that their eyes were likely not exposed for even momentary durations.

To set the two lasers in a parallel orientation we commissioned a professional machine shop to drill two cylindrical holes, with their centers 10 cm apart, at a parallel angle through a rectangular plastic mounting block. The holes were 2 cm in diameter to seat the laser-pointers securely. The mounting block was attached to an aluminum L-bracket using an adjustable bolt, so that the vertical orientation of the two lasers could be adjusted. A hole in the bottom of the L-bracket accommodated a camera mounting screw with a three-prong clamping collar, enabling attachment to a standard tripod mount hole. This mount was also relatively inexpensive, with production costing approximately US $100 for both parts and labor. The large camera mounting screw was hand tightened to attach the laser apparatus firmly to the tripod-mounting plate on a Nikon 80–200-m zoom lens (Nikon Inc., Melville, NY). The tripod mount on the lens can be rotated through 360°, allowing the lasers to be conveniently positioned above the camera lens (Fig. 1). With the lasers securely positioned within the mount, we confirmed that the fixed 10-cm separation between the laser dots was maintained at distances up to 100 m, verifying that the laser pointers were correctly mounted in a parallel fashion.

[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Figure 1. Two laser-pointers mounted in parallel within a lightweight plastic housing attached to the adjustable tripod-mount of a Nikon 80–200-mm zoom lens.

As an example of the utility of this setup, we measured the heights of killer whale dorsal fins during routine photographic identification surveys of whales in Puget Sound, Washington State. The photographed whales were members of the "southern resident" population that has been monitored through photo-identification techniques since the early 1970s (Bigg 1982). Consequently, each member of this population can be photographically identified and coupled with known life-history data, including both sex and age (Bigg *et al.* 1987, Olesiuk *et al.* 1990). Killer whale dorsal fins are a prominent secondary sexual characteristic. The fins of subadult males "sprout" and begin to exceed the height of adult female dorsal fins as they approach physical maturity (Olesiuk *et al.* 1990). As such, dorsal fin height provides a useful measure of both sexual dimorphism and sexual maturity.

To measure dorsal fin height of free-ranging whales, we acquired photographs of projected laser dots concurrent with routine photo-identification studies on a single day in December 2004 during an encounter consisting of known individuals of both J and K pods. Our camera configuration enabled us to project laser dots onto killer whale dorsal fins while taking identification photographs of the fin and adjacent saddle patch area for individual recognition purposes (Fig. 2; Ford *et al.* 2000). Photographs were taken from a small boat at distances of between 15m and 50 m from the whales. We used a Nikon D70 digital SLR camera equipped with an 80–200-mm zoom lens mounted with the laser pointer apparatus to obtain 357 identification photographs during the encounter, documenting all 42 individual whales present on this day. A total of 177 (50%) of these images displayed visible laser dots, comprising photographs of 31 different individuals (66% of the whales present). However, to

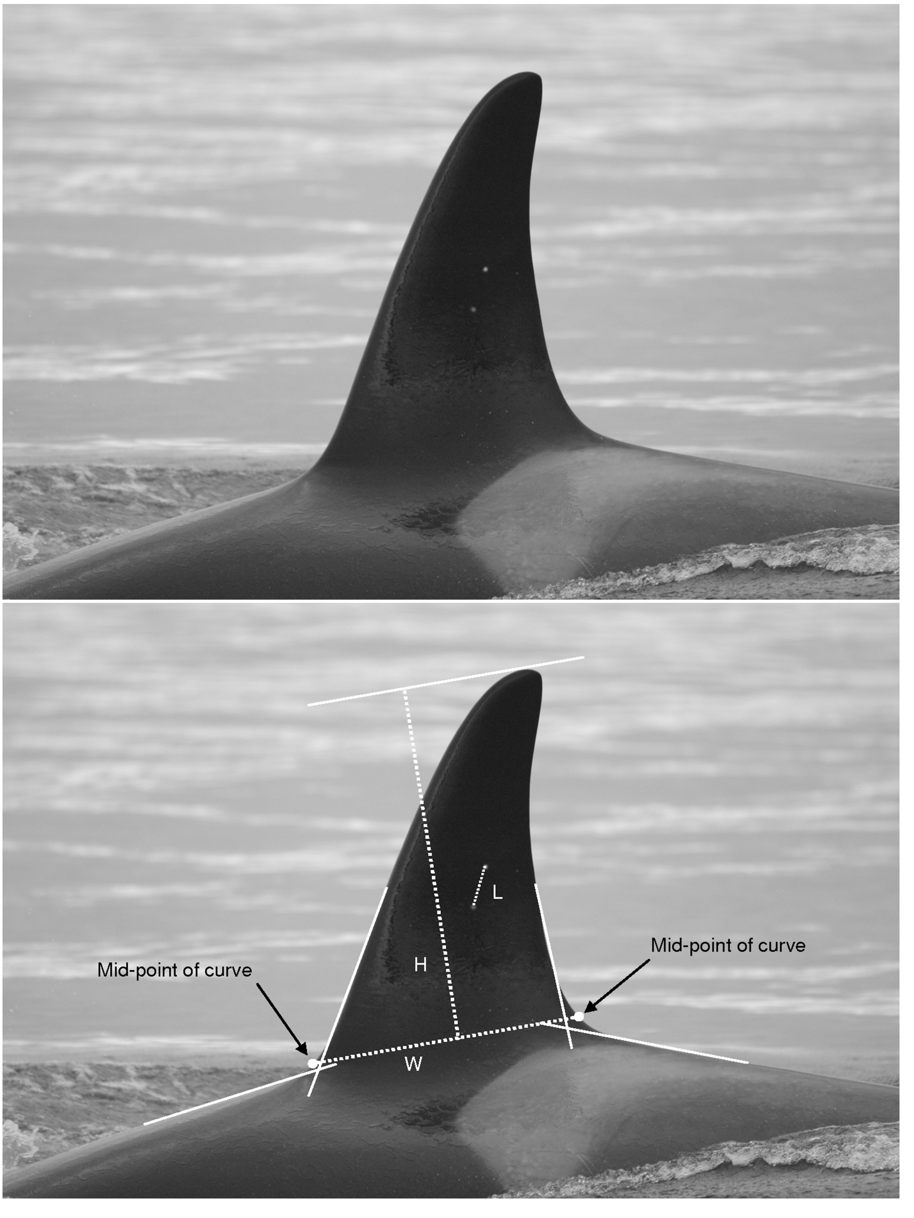

Figure 2. The two fixed-distance laser dots (top) projected onto the dorsal fin of a sub-adult male killer whale (J30); and the metrics measured from the photograph (bottom). Fin width (W) was measured between the anterior and posterior insertions of the dorsal fin (white circles), defined (following Olesiuk *et al*. 1990) to be the mid-point of the curve between intersecting reference lines that follow the main axes of the dorsal fin and adjacent back (solid white lines). The fin height was then measured from a line (H) drawn perpendicular to the width line W and extending to a line perpendicular to the maximum height of the dorsal (the broken lines). These measurements were calibrated for actual size based on the measured dimensions between the laser dots (L) of known 10-cm separation.

increase the robustness of our measurements, this sample was reduced to 120 images, documenting 27 whales (64% of whales present), after a quality-grading process. All photographs that did not contain the entire dorsal fin in focus, where the body axis of the whale was not oriented perpendicular to the camera lens, or where both laser dots were not clearly focused on the animal were deemed "low-quality" and were removed from the data set.

It is likely that the main factor limiting the number of useful measurements in our case was the difficulty of precisely projecting two lasers onto the dorsal fin, rather than the visibility of the projected laser dots. Of 153 images where the whales' fins were displayed in good focus and orientation, 24 images displayed just a single laser dot, with the second laser "missing" the whale, but only 9 images did not display the lasers as well defined dots when both lasers were projected onto the whale. It is likely that the vast majority of the 180 images without any visible lasers represented complete "misses," rather than problems with detecting the laser dots. Slight changes in the orientation of the parallel lasers at the camera translated to large variations in location of the projected dots, particularly at distances typically greater than 15 m, and many photographs simply did not document the whale in the center of the frame where the lasers were oriented. The chances of such "misses" are clearly greater when the dorsal fin occupies a smaller proportion of the frame as a result of increasing distance to the whale, and our photographs indicate that the images without laser dots were generally of lower quality where the image of the whale was smaller and off-center in the frame.

To further demonstrate the application of this method we examined high-quality photographs for six individual whales for which we obtained a sample of repeat identification photographs that clearly captured the projected laser dots. These six whales were the only individuals that were photographically documented with more than five repeat measurements, and therefore their selection for this example analysis was an objective choice, determined by sampling variability, that was intended to demonstrate the variability in measurements obtained using this approach. These six whales comprised a physically mature adult female (K16), four subadult males (J30, J27, J26, and K21) at various stages of physical development, and an adult male (J1) that has been physically mature since photo-identification monitoring of this population began in the 1970s (Ford *et al.* 2000).

Dorsal fin height was measured directly from the digital images using software tools. In an attempt to limit subjectivity in defining where the dorsal fin rises from the back of the whale, we used *ACDSee Photo Canvas* (ACD Systems International Inc., Saanichton, BC, Canada) to draw a series of reference lines on the image (Fig. 2), following the approach of Olesiuk *et al.* (1990). We also used *ACDSee v6* to adjust image contrast and color tones to highlight the laser dots where necessary. The software package *Image Tool* (http://ddsdx.uthscsa.edu/dig/itdesc.html) was used to measure the width of the dorsal fin at the base and the maximum height of the fin above this base, with measurements recorded in pixels. Pixels were then converted to actual size measurements using the conversion factor derived from the pixel measurement of the known 10-cm separation distance between the two laser dots (Fig. 2).

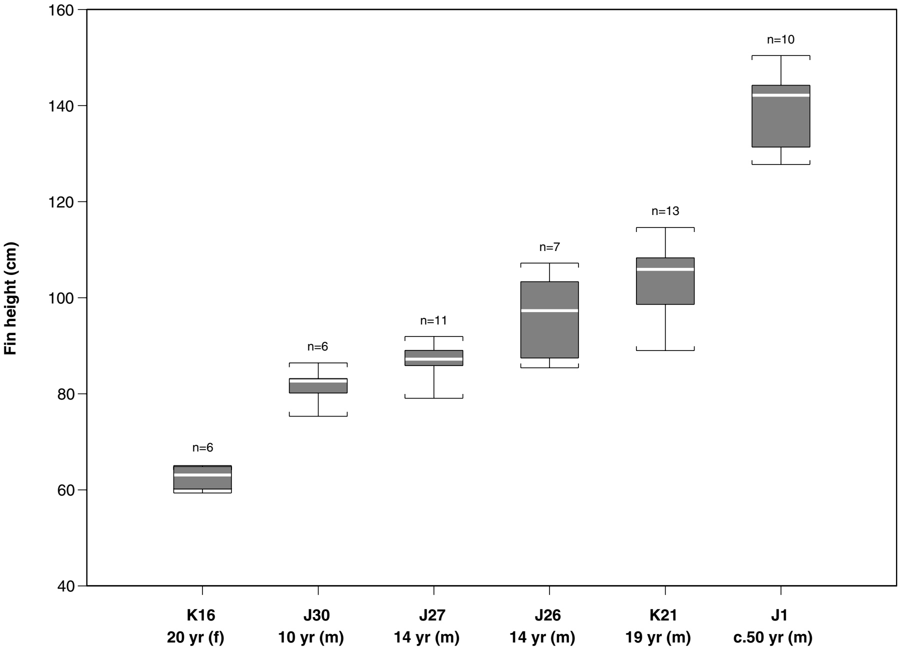

Figure 3. Box plot of the variability in measurements of dorsal fin height for six different individuals for which more than five measurements were obtained. The bars represent the full range of measurements, shaded boxes represent the inter-quartile range of the central 75% of the measured values, and the median of these whales is represented by the white line within the box. Age and sex (m or f) are displayed below each individual's identification number on the *x*-axis (data from Ford *et al*. 2000).

Variability in dorsal fin height estimates was greater between whales than within the set of measurements for a given individual (Fig. 3). The estimated fin height was smallest for the adult female (median height K16 = 63 cm), and generally increased with increasing age of the subadult males whose fins were "sprouting." As expected, dorsal fin height was greatest for the adult male (median height J1 = 142 cm). These estimates of fin height for both the adult male and the adult female were consistent with previous morphometric measurements obtained from adult captive killer whales (Clark and Odell 1999). Variability within individuals generally increased as the estimated fin size increased, which is to be expected given potential extrapolation error. Measurements for the adult female varied by only 6 cm (9% of median) compared to 23 cm (16% of median) for the adult male. However, this variability was inflated by a small number of "outlier" measurements, and in general, the measurements were consistently repeatable. This is evidenced by the relatively tight clustering of measurements within the interquartile ranges (central 75% of measured values).

Apparent variability in dorsal fin size estimation is likely due to two main sources of error. *Parallax error* may occur when a photographer is looking down on the whales. When this occurs, the plane of the lasers is not parallel to the water's surface, and therefore the laser projection is not absolutely perpendicular to the whale's fin. This will result in estimates of fin height being negatively biased because the fin will appear smaller relative to the 10-cm reference provided by the laser dots. The magnitude of this error will vary depending on the distance between the whale and the photographer, and the height of the photographer above the whale, with the greatest error at close distances and greatest height difference. However, this error was minimized by taking photographs over distances typically greater than 15 m from a small-boat platform where the photographer's feet were at water level. Parallax error along the vertical axis can also occur because whales often surface with their fins not being perfectly upright, and therefore the plane of the lasers will not be perpendicular to the fin. The degree of error will increase the greater the fin is from a perpendicular axis, regardless of whether it is leaning toward or away from the photographer. Similarly, horizontal-axis error may occur if the whale's body orientation is not parallel to the camera's focal plane. This will not be a concern for dorsal fin height, but it may be relevant for other characters of interest. Although such errors are often unavoidable, we suggest that they can be minimized through careful selection of photographs to be measured, considering the apparent angle of the whale relative to the focal plane of the image.

Definition error may result from subjective determination of the placement of the anterior and posterior insertions of the dorsal fin. We attempted to minimize subjectivity by adopting the procedure of drawing reference lines along the main axes of the back and dorsal fin and using the intersection of these lines to define the fin's insertion (*e.g.*, Olesiuk *et al.* 1990). However, the angle of the back is dependent upon the surfacing behavior of the individual, adding inherent variability to definitions of where the fin insertions occur and resultant fin measurements. It is unlikely that such error can be completely eliminated from this procedure, and instead we advocate the approach of taking repeat measurements of the same individuals to quantify the variability and incorporate it directly into hypothesis testing.

In this example, the key age/sex effects appear to be greater than the individual variation. There was no overlap in the height measurements between the adult female and any of the subadult "sprouter" males, and similarly no overlap between the sprouters and the adult male (Fig. 3). This is consistent with the earlier findings of Olesiuk *et al.* (1990) that subadult males over 10 yr old can be readily distinguished from adult females based on dorsal fin morphometrics. These authors also judged the mean age of physical maturity to be 21 yr of age, and this is consistent with the separation in estimated fin size between our sprouter males (oldest 19 yr) and the adult male who has been physically mature since the early 1970s and therefore could be greater than 50 yr old (Ford *et al.* 2000). Although there was considerable overlap between the fin-height measurements among the sprouters, larger measurements were typically obtained for the older whales. However there was some evidence of individual variation in growth rates, particularly from the two sprouter males of the same age (J27 and J26). This variation would be interesting to explore with a larger sample size of individuals, and with regular monitoring through laser-metrics.

The utility of our laser setup is not restricted to only measuring dorsal fin size. The tripod mount on the lens can be rotated through 90° to position the lasers in a horizontal pattern that may be more suitable for projecting onto the flat surface of whale flukes. Similarly, if the lasers are projected onto a part of the body that can also be used for individual recognition, then once the body part has been measured, subsequent photographs without laser dots can also be used to measure other body parts if the individually recognizable measured body part is also in the frame. For example, additional images from the killer whales we encountered could be used to measure blowhole to dorsal fin distances, with the aim of estimating total body length using known allometric relationships (Heimlich-Boran 1986, Clark and Odell 1999).

The advent of high-quality digital photography has greatly facilitated the laser-metric approach. Large numbers of high quality images can now be obtained without the prohibitive consumption of film. This permits a "brute force" approach of taking a large number of photographic images in the hope that some will be of sufficiently high quality and will display usable laser dots. This is particularly useful if photographs are already required for photo-identification purposes. In our example, we obtained usable laser measurements for 27 out of the 42 individuals that were present, even though the primary purpose of the field effort was the photographic documentation of individual presence, demonstrating how this tool could be used routinely alongside photo-identification studies to assess individual morphology and to monitor the growth of individuals over time.

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