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RESEARCH ARTICLE

Approaching a population-level assessment of body size in pinnipeds using drones, an early warning of environmental degradation

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Abstract

Body mass is a fundamental indicator of animal health closely linked to survival and reproductive success. Systematic assessment of body mass for a large proportion of a population can allow early detection of changes likely to impact population growth, facilitating responsive management and a mechanistic understanding of ecological trends. One challenge with integrating body mass assessment into monitoring is sampling enough animals to detect trends and account for individual variation. Harbour seals (*Phoca vitulina*) are philopatric marine mammals responsive to regional environmental changes, resulting in their use as an indicator species. We present a novel method for the non-invasive and semi-automatic assessment of harbour seal body condition, using unoccupied aerial vehicles (UAVs/drones). Morphological parameters are automatically measured in georeferenced images and used to estimate volume, which is then translated to estimated mass. Remote observations of known individuals are utilized to calibrate the method. We achieve a high level of accuracy (mean absolute error of 4.5 kg or 10.5% for all seals and 3.2 kg or 12.7% for pups-of-the-year). We systematically apply the method to wild seals during the Spring pupping season and Autumn over 2 years, achieving a near-population-level assessment for pups on land (82.5% measured). With reference to previous mark-recapture work linking Autumn pup weights to survival, we estimate mean expected probability of over-winter survival (mean = 0.89, standard deviation = 0.08). This work marks a significant step forward for the non-invasive assessment of body condition in pinnipeds and could provide daily estimates of body mass for thousands of individuals. It can act as an early warning for deteriorating environmental conditions and be utilized as an integrative tool for wildlife monitoring. It also enables estimation of yearly variation in demographic rates which can be utilized in parameterizing models of population growth with relevance for conservation and evolutionary biology.

Introduction

In wildlife ecology, there is a need for methods which can detect indicators of population health on a shorter time scale than traditional monitoring of abundance and growth. Changes in the external environment are tracked by changes in mammal life history (Clutton-Brock et al., 1987; Kjellqwist, 1995; Stewart et al., 2005; Ward et al., 2009; Williams et al., 2013). For long-lived K-strategists, such as pinnipeds, the first life history parameters to be affected by a deterioration in environmental conditions are often pup survival and female fecundity, with adult survival being affected last (Clutton-Brock et al., 1987; Hall et al., 2001, 2002; Kjellqwist, 1995; Merrill et al., 2021). As a result, there is a lag between causative environmental changes and their detection as changes in population numbers (Svensson et al., 2011). Body condition, however, fluctuates on a much shorter time scale, enabling signs of population-level stress to be tracked (Kauhala et al., 2017; Pettorelli et al., 2002; Siebert et al., 2022; Silva et al., 2021).

For many species, body mass is a fundamental indicator of internal and external processes (Jakob et al., 1996; Stevenson & Woods, 2006). Body mass is likely to be the result of interacting factors of individual health (e.g. parasite load) and the external environment (e.g. as the result of food availability and quality) (Kauhala et al., 2017; Pettorelli et al., 2002; Ronget et al., 2018). Body mass is also tightly correlated to reproductive success and survival (Bowen et al., 2015; Harding et al., 2005; Merrill et al., 2021; Ronget et al., 2018). The monitoring of body mass in wild animals is therefore valuable for fundamental research, facilitating an understanding of the mechanisms which shape trends in population development. It is also a valuable tool for conservation biology, acting as an indicator of stress which can be used to motivate sustainable management choices, such as changes to harvest quotas (Holmes et al., 2021).

Body condition assessment has been integrated into standardized monitoring systems for wild animals ranging from harbour seals (*Phoca vitulina*) to reindeer (*Rangifer tarandus*) (Albon et al., 2017; HELCOM, 2018). Traditionally, this has required direct interaction with animals, either through the capturing of live individuals (live-capture) or the assessment of dead animals (necropsies). Live-capture inevitably leads to disruption of natural behaviours. Along with high associated costs in terms of time and money, this limits the number of animals which can be assessed. Similarly, the number of necropsies which can be carried out is limited either by the ethical considerations of harvesting or the stochastic nature of opportunistic sampling (Bradshaw et al., 2003; Speakman, 2001).

Increasingly, methods for the remote assessments of body condition have been developed to overcome the limitations of both live-capture and necropsies. Protocols for non-invasively cataloguing animal numbers using remote sensing technologies, such as light aircraft, unoccupied aerial vehicles (UAVs/drones) and satellites are common (Amorosi et al., 2024; Corcoran et al., 2021; Holmes et al., 2007; McMahon et al., 2014; Seganfreddo et al., 2023; Teilmann et al., 2010). These can be automated using machine learning (Infantes et al., 2022; Kellenberger et al., 2018; Seymour et al., 2017). For numerous taxa, methods for estimating mass based on the measurements of key morphological parameters have been established (Baruzzi et al., 2023; Shero et al., 2014). Length and girth, for example, are commonly used to estimate mass in pinnipeds (Castellini & Kooyman, 1990; Usher & Church, 1969; Van Den Hoff et al., 2005). Correlations between photographic observations and body mass have been made for a range of taxa, such as elephant seals (*Mirounga leonina*) and sperm whales (*Physeter macrocephalus*) (Glarou et al., 2023; Haley et al., 1991). For these species, estimates of mass can be made based on photographic observations without the need to disturb the animal (Beltran et al., 2018; Glarou et al., 2023; Haley et al., 1991). Improved access to drones has resulted in their increased use in assessments of body condition. This includes the assessment of indices of morphological characteristics, such as length, width, volume and mass (Allan et al., 2019; Alvarado et al., 2020; Infantes et al., 2022; Krause et al., 2017; Piacenza et al., 2022; Shero et al., 2021). These methods have largely been limited by labour intensive collection and analysis protocols. Overcoming such limitations will allow drone-based body condition estimates to be used as a reproducible non-invasive method of assessing animal health (Stone & Davis, 2023). This can be scaled up to assess a large proportion of a population, particularly for species which gather in seasonal aggregations, such as harbour seals (Härkönen et al., 2002; Lyons et al., 2019). Infantes et al. (2022), for example, presented a method for the semi-automated detection and measurement of length and width for large numbers of harbour seals, although the method was only validated on a single individual.

Harbour seals are a widely distributed opportunistic predator which have a long history of use as an environmental indicator species (Harding et al., 2024; Heide-Jørgensen & Härkönen, 1988; Infantes et al., 2022). As is the case for most mammals, harbour seal maternal body fat reserves are vital for pup growth during lactation (Bowen, Iverson, et al., 2001). Pup mass therefore reflects both their mother's condition and habitat quality (Bowen, Ellis, Iverson, & Boness, 2001; Bowen, Iverson, Boness, & Oftedal, 2001). First-year survival in harbour seals is composed of three important life history stages: the 21-day long lactation period, the first summer months, and overwinter-survival. Autumn body mass is known to be strongly correlated to over-winter survival rates (Bowen et al., 2015; Greig et al., 2019; Harding et al., 2005; Rosen & Renouf, 1997).

In this study, we present a semi-automated method for the non-invasive assessment of harbour seal body mass using drones. Across 2 years, we apply this approach to estimate the mass of harbour seal pups and older seals during the annual breeding aggregation (Spring pupping season, June) and in Autumn (September) in the most important breeding colony in the Skagerrak region of Scandinavia. Based on these measurements, we make estimates of over-winter survival probability. We show that remote sensing can produce consistent and accurate measurements of length, width and mass across years for many individuals. The result is a tool for the assessment of local population health which we recommend be integrated into routine monitoring.

Materials and Methods

Image acquisition

To estimate morphological parameters of seals through remote observation, a consistent method for capturing images with normalized scales of measurement was applied. Images with 80% forward and 80% lateral overlap were collected during automated drone flights at 40 m altitude with the camera in nadir position (pointing directly downwards) and assembled into georeferenced orthomosaics (composite images in which the geometric distortion of individual images has been corrected for, Fig. 1A). Two flight and orthomosaic assembly systems were used. The first followed Infantes et al. (2022), using a DJI Phantom-4Pro v2 drone with orthomosaic assembly carried out in Pix4D (the Phantom system). This drone was equipped with a 1-inch CMOS 20 MP sensor with a f/2.8 lens. Ground sampling distance (GSP) was 1.1 cm/pixel. The second system used a DJI Mavic-II Zoom with orthomosaic assembly carried out in WebODM 1.9.15 (the Mavic system). This drone was equipped with a 1/2.3-inch 12 MP sensor with a f/2.8 lens. GSD was 0.73 cm/pixel. GSDs for both systems were close to the optimal GSD of 0.8 cm/pixel recommended by Stone and Davis (2023) for volume estimation. Orthomosaics generated by both systems are comparable as both Pix4D and WebODM apply camera calibration and correction functionalities (e.g. Focal length, lens distortion and sensor size) to ensure accurate and geometrically correct outputs. A comparison of the two image collection systems and more detail on orthomosaic construction is given in Appendix S1.

For calibration of measurements, a set of orthomosaics containing harbour seals with known morphological parameters (length, girth and mass as described below) was created using the Mavic system. Seals lie in a variety of poses which could potentially impact measurement (Krause et al., 2017). Live seals ($N = 3$) were imaged in a prone pose (stomach towards the ground, Fig. 1B) on a wooden surface during a tagging operation in Færder National Park, Norway (Ramasco et al., 2014). Dead bycaught seals ($N = 8$) were imaged during routine monitoring performed by the Swedish Museum of Natural History (SMNH). Separate images of each individual were taken while placed in prone and lateral (shoulder faced towards the ground, Fig. 1B) poses on an asphalt surface.

The method was tested on six live captive seals in Slottsskogen Zoo, Gothenburg, including one pup of the year ($N = 6$). Individuals were imaged immediately prior to weighing on two occasions, on 2 February 2023 and 4 April 2023, on a concrete surface (Fig. 1C). Each seal was manually identified within images based on unique fur patterns (Langley et al., 2021). Mass was the only morphological parameter which could be determined manually for these individuals.

Orthomosaics of wild harbour seals in the Kosterhavet Archipelago, Sweden, on natural surfaces (primarily rock) were captured during the pupping season (Spring, 8–20 June 2022) and during the Autumn (14–6 September 2022) (Fig. 1D). Mean flight time was 16 min and 6 s. These were combined with the orthomosaics generated by Infantes et al. (2022) (15–17 June 2021 and 15 September 2021). To assess the proportion of pups on land measured during June 2022, the survey method described by Infantes et al. (2022) was used to estimate pup numbers on skerries for which body condition indices were determined.

Image processing

Individual seals in drone orthomosaics were detected using Picterra, an online machine learning (ML) platform which uses a convolutional neural network (CNN) architecture for image segmentation. Detectors were trained to identify seals in orthomosaics, which were later extracted as georeferenced polygons, representing the position and two-dimensional surface area of each individual (Infantes et al., 2022). Due to differences in image background conditions, separate detectors were trained for each surface type (wood, asphalt, concrete and rock). In contrast to the method reported in Infantes et al. (2022), which distinguished between pups and older seals during the training stage to facilitate the counting of pups, a single detector was developed for all seals on each surface. This reduced the length of time spent running detectors and labelling files. Two seals were used for training each of the wood, asphalt and concrete detectors. Overall, 200 seals were used for training the rock detector. Detector accuracy was assessed by calculating F1 scores (a measure of the harmonic mean of precision and recall for the model) as described in Csurka et al. (2013). Polygons less than 0.07 or greater than 0.55 m^2 in area were excluded from analysis as these were unlikely to represent seals. Individual polygons were then overlaid on orthomosaics and removed from the dataset in cases where they were deemed to poorly match the corresponding seal's outline; for example, if a large section of the seal was obscured by water or if the seal had moved causing a 'ghosting' effect (Figure S5).

Morphometric analysis

Each georeferenced polygon, representing the outline of an individual seal, was imported into R (R Core Team, 2017) and projected onto a EPSG:23032 coordination

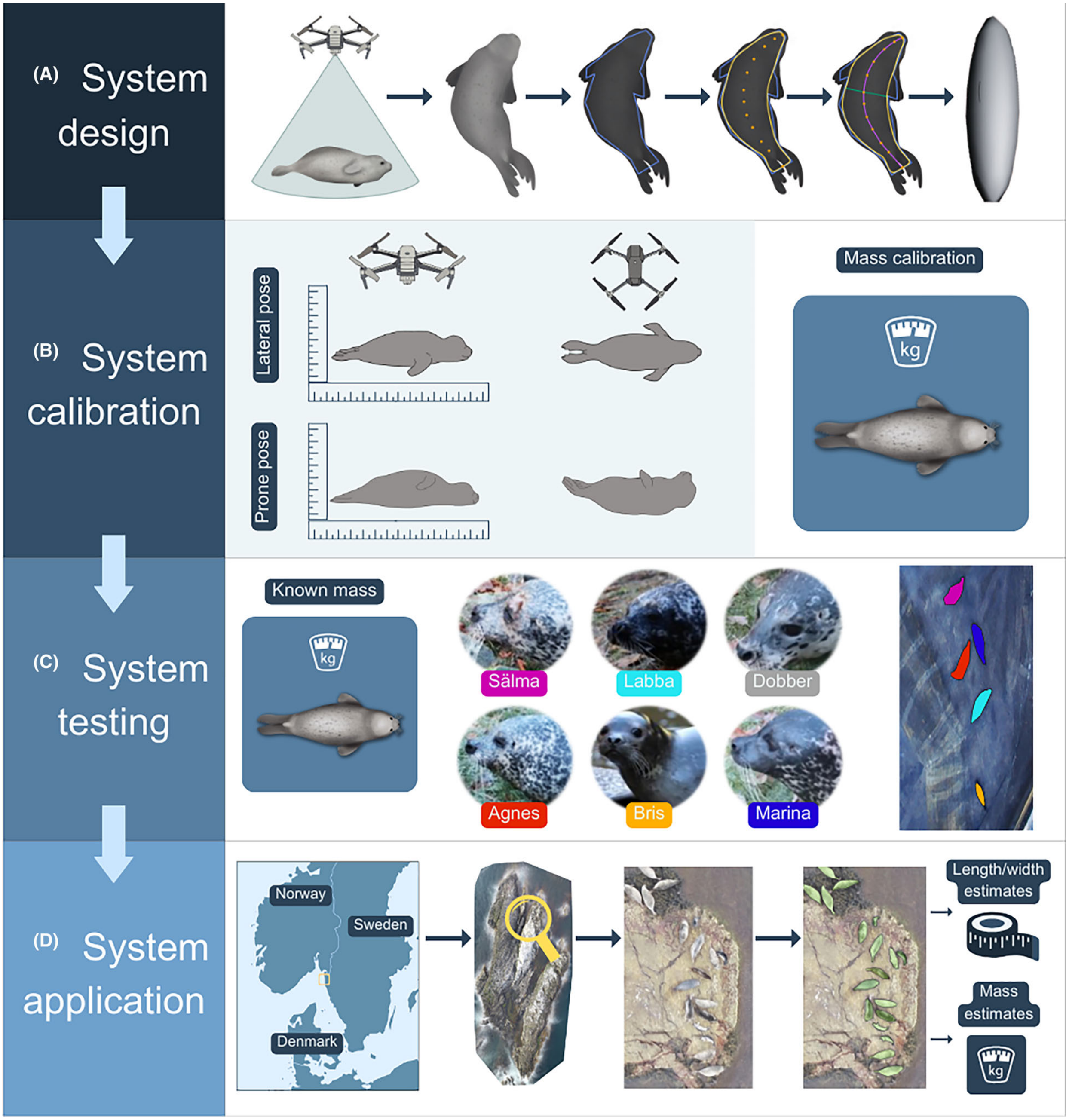

Figure 1. Workflow for drone-based determination of body weight for large groups of pinnipeds. (A) Estimation of harbour seal body length, width and volume using drone imagery. Images were assembled into georeferenced orthomosaics. Within orthomosaics, seals were automatically detected to generate spatial polygons outlining each individual. The curved length and greatest width of each polygon was automatically measured and used to estimate ellipsoid volume. (B) Sampled seals with known morphological parameters (length, girth and mass) were used to maximize accuracy of mass estimation. The impact of pose on estimates was also investigated. (C) The system was tested through drone-based estimation of mass for captive individuals of known mass. (D) The system was applied to estimate morphological parameters for a large number of wild seals in the Kosterhavet Archipelago, Sweden.

system. An adaptation of the automated length and width measurement protocol described by Infantes et al. (2022) was used for drone-based estimation of the following morphological parameters: curved length (L_D, m), width (W_D, m) and ellipsoid volume (V_D, m^3, Fig. 1A). Polygons were smoothed using the *smooth()* command from the *smoothr* package to remove the influence of limbs. The two most distant points of the polygon were found.

Using the *st_split()* command from the *sf* package, the polygon was split into two line segments at these points. Midpoints, equidistant between these line segments, were determined at seven points. A line was drawn between each midpoint and the two most distant points of the smooth polygon with the Euclidean distance between each point recorded as the length of the line. The Euclidean distance between the two terminal points in this line and the original seal outline were added to this length to estimate L_D. The Euclidean distance between the seven midpoints and each line segment was then determined, with the sum of these distances being taken as the width of the individual at each point (Figure S6). The greatest distance was taken as W_D. V_D was calculated according to:

$$V = \frac{4}{3}\pi abc \quad (1)$$

With L_D representing twice the longest axis ($a = L_D/2$) and W_D equal to twice the other two axes ($b = c = W_D/2$, Fig. 1A). A discussion of the selection of this model to represent seal size is given in Appendix S1.

To calibrate drone-based estimates, true mass (M_T, kg), length (L_T, m, measured from the nose to the tip of the tail) and girth (m, measured caudally directly below the forelimbs) were compiled from necropsies performed by Harding et al. (2005 & 2018) and SMNH between the years 2002 and 2021 ($N = 177$, Figure S2) (American Society of Mammalogists, 1967). As width could not be determined during necropsies, true girth was assumed to be the circumference of a circle with the diameter representing true width (W_T, m). An ellipsoid shape was assumed (see Appendix S1), with L_T representing twice the longest axis ($a = L_T/2$) and W_T equal to twice the other two axes ($b = c = W_T/2$).

For individuals with known morphometric measurements, true ellipsoid volume (V_T, m^3) was calculated according to Equation 1. For seals for which both true measurements and drone-based estimates were available ($N = 11$), separate linear regressions were carried out with L_D, W_D or V_D as explanatory variables and L_T, W_T or V_T as response variables. Based on the fit parameters of these regressions, all drone-based estimates were transformed to bring them in line with true measurements (Appendix S2).

To establish the relationship between seal volume and mass, a linear regression with a fixed intercept of zero was carried out with V_T as explanatory variable and M_T as response variable. The fit slope of this regression was used to estimate mass index (M_D, kg) for all drone-based estimates of V_D, along with 99% confidence intervals associated with estimates. Neither age class nor month were found to have a significant impact on this relationship (see Appendix S1 for a detailed discussion).

To compare drone-based estimates of morphological indices to true environmental variation, the mean and standard deviation (SD) in length and mass of female seals older than 4 years of age (a plausible age of first reproduction based on Härkönen & Heide-Jørgensen, 1990 and Silva et al., 2021) were calculated based on historical data compiled from routine monitoring carried out by SMNH and presented in Harding et al. (2005 & 2018).

Estimation of over-winter survival

The over-winter survival probabilities for harbour seal pups present in Kosterhavet Archipelago in September 2022 were estimated. Individuals less than 1 m in length and 34 kg in mass were classified as 'pups' based on analysis of compiled data, with all other individuals being classified as 'older'. Harding et al. (2005) carried out a mark-recapture study on pups-of-the-year in this area. They estimated apparent survival between 1 October and June the following year, with an associated mass, based on frequency of resighting. For pups caught by Harding et al. (2005) between 4 and 30 September from 1984 to 1993, a linear regression was fit with age in days (assuming a birth dated 18 June) as explanatory variable and mass as response variable. The slope of this regression was then used to 'age' drone-based estimates of M_D made for pups in September 2022 to a predicted mass on 1 October 2022. A cubic spline was fit to the mass and survival data presented by Harding et al. (2005). This spline was used to estimate over-winter survival probability based on M_D for wild seals.

Software and analysis

Analysis of polygons was carried out in R (R Core Team, 2017) using packages *sf* (v1.0-9), *smoothr* (v1.0.1), *reshape2* (v1.9.6), *lwgeom* (v0.2-11) and *nlme* (v3.1-162) with visualization using *ggplot2* (v2.0.0). R^2 scores were computed to assess the ability of drone-derived morphological indices (L_D, W_D and M_D) to predict true measurements (L_T, W_T and M_T). Mean Absolute Error (MAE) values for length and mass estimates were calculated separately for all individuals and for pups of known morphological parameters. Separate linear mixed-effects models were fit to test for an influence of i. seal pose (prone vs. lateral, for seals during necropsies) and ii. Month (February vs. April, for captive seals) on M_D estimates. M_D was taken as response variable while M_T and either i. 'pose' or ii. 'month' were taken as main effects. In both cases, interactions between main effects were included and individual was included as a random effect to account from repeated measurements. Subsequent ANOVAs were carried out to test for a significant difference in slope between i. poses or ii. months. Example datasets and instructions for processing can be found in Appendix S2.

All relevant code is available on GitHub: https://github.com/DaireCarroll2023/Seal_Body_Sizes and Zenodo.org https://doi.org/10.5281/zenodo.11066675.

Results

Method calibration and testing

To calibrate body condition indices derived from images of harbour seals, drone images and true body measurements were analysed ($N = 11$, Table 1). To test the system, drone images of captive seals were captured on two visits to Slottsskogen Zoo, Gothenburg, on the 2 February 2023 and 4 April 2023 ($N = 6$, Table 1).

Seals were outlined through the application of separate machine learning detectors for each surface type (wood, asphalt and concrete). On wood and asphalt, 100% of individuals were detected, with F1 scores of 99.46 and 98.93% respectively. On concrete, 100% of individuals were identified during February and 83% during April, with one individual being obscured and removed from analysis (F1 = 97.33%). Images were processed to estimate drone-based morphological indices of curved length (L_D, m), width (W_D, m) and ellipsoid volume (V_D, m^3). Linear regressions were fit using drone-based estimates as explanatory variables and true measurements as predictive variables (Table S1). The fit parameters of these regressions were used to transform all further morphological measurement indices, bringing them in line with true measurements. When comparing drone-based measurements to L_T and W_T, R^2 values of 0.83 and 0.92 respectively were calculated (Fig. 2A, B).

True ellipsoid volume (V_T, m^3) and true mass (M_T, kg) were determined for 177 individuals. A linear regression with a fixed intercept of zero, V_T as explanatory variable and M_T as response variable revealed ellipsoid volume to be significantly correlated with mass (Fig. 2C, slope = 832.81 ± 8.48 kg m^{-3}, $P < 0.001$, RSE = 6.37, DF = 176, $R^2 = 0.98$). Based on this slope, estimates of mass index (M_D, kg) were made for all drone-based ellipsoid volumes. An R^2 value of 0.95 was achieved (Fig. 2D).

The impact of pose on mass index estimation was investigated (Fig. 3A). A linear mixed-effects model resulted in overlapping 95% confidence intervals for estimates of slopes between poses (Table S2). A subsequent ANOVA indicated that there was a significant correlation between M_D and M_T (F-value = 33.27, $P = 0.001$), but no significant difference in either slope (F-value = 0.11, $P = 0.76$) or intercept (F-value = 0.04, $P = 0.85$) between poses (Fig. 3A).

To further test the method, M_D was estimated for six individually identified captive seals of known mass on separate visitations in February and April. A linear mixed-effects model resulted in overlapping 95% confidence intervals for estimates of slopes between months (Table S2). A subsequent ANOVA indicated that, while there was a significant correlation between M_D and M_T (F-value = 841.38, $P = 0.012$), there was no significant difference in either slope (F-value = 0.6, $P = 0.61$) or intercept ($F = 0.68$, $P = 0.5$) between months (Fig. 3B).

Mean absolute error (MAE) for all individuals of known mass was 4.5 kg representing 10.5% of body mass. For those classified as 'pups', MAE was 3.2 kg representing 12.7% of body mass. MAE for all individuals of known length was 0.09 m representing 8% of true length. For 'pups', MAE was 0.1 m, representing 9% of length.

In-field observations

Following testing and calibration of the method, orthomosaics containing wild seals were processed to estimate drone-based morphological indices, including M_D (Fig. 4). Images were collected and processed into georeferenced orthomosaics during the Spring pupping season (8–20 June) and the Autumn (14–16 September). A machine learning detector for seals on rock surfaces was trained and applied to all images resulting in an F1 score of 95.26%. In June 2022, a total of 1980 suitable seal outlines were detected, with 694 of these being classified as pups-of-the-year based on a L_D less than 1 m and a M_D less than 34 kg. The mean percentage of pups for which body condition indices were estimated during June 2022

Table 1. Range of true morphological measurements for seals utilized for the calibration and testing of drone-based estimates of body condition.

Surface	No. individuals	Length range (L_T, m)	Width range (M_T, m)	Ellipsoid volume range (V_T, m^3)	Mass range (M_T, kg)
Asphalt	8	0.97–1.17	0.19–0.25	0.02–0.04	19.2–36.2
Wood	3	1.39–1.47	0.34–0.35	0.09–0.09	73–86
Concrete	6	NA	NA	NA	22.3–109.5

Length and girth are measured as per American Society of Mammalogists (1967). Width and ellipsoid volume are derived from these measurements. Seals on concrete were live individuals measured twice during visits to Slottsskogen Zoo, Gothenburg.

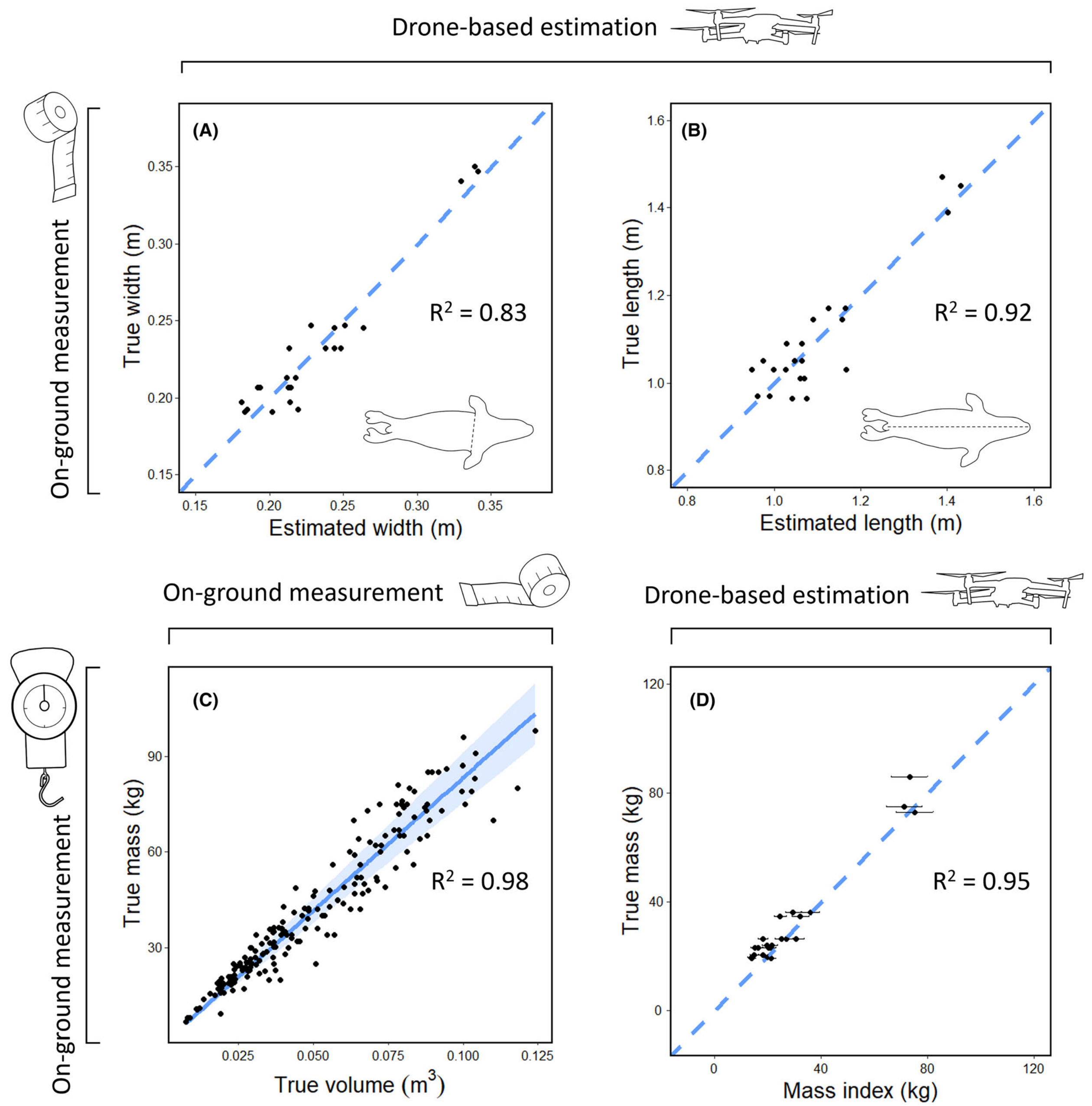

Figure 2. Calibration and estimation of harbour seal morphological parameters using drone-based imaging and on-ground measurement. Drone-based estimates of (A) curved length and (B) maximum width were calibrated by comparison to on-ground (true) measurements of length and width. (C) True masses and ellipsoid volumes (True volume) were compiled from necropsies and fit with a linear regression (solid blue line, shaded region = 99% confidence interval of estimation) with a fixed intercept of zero. (D) The fit slope of this regression was used to estimate mass index for all drone-based estimations of ellipsoid volume along with 99% confidence intervals (horizontal error bars). Blue-dashed lines in (A, B, D) have a slope of 1 and intercept of (0, 0) representing a perfect prediction of true measurements by estimates.

was 82.5% with an SD of 0.05% based on comparison to video surveys of the same skerries. In September of the same year, 185 suitable seal outlines were detected with 26 of these being classified as pups-of-the-year.

The seal outlines defined by (Infantes et al., 2022) in 2021 were combined with 2022 survey data. This provided 613 seal outlines for June 2021, of which 232 were classified as pups, and 125 outlines for September 2021 of

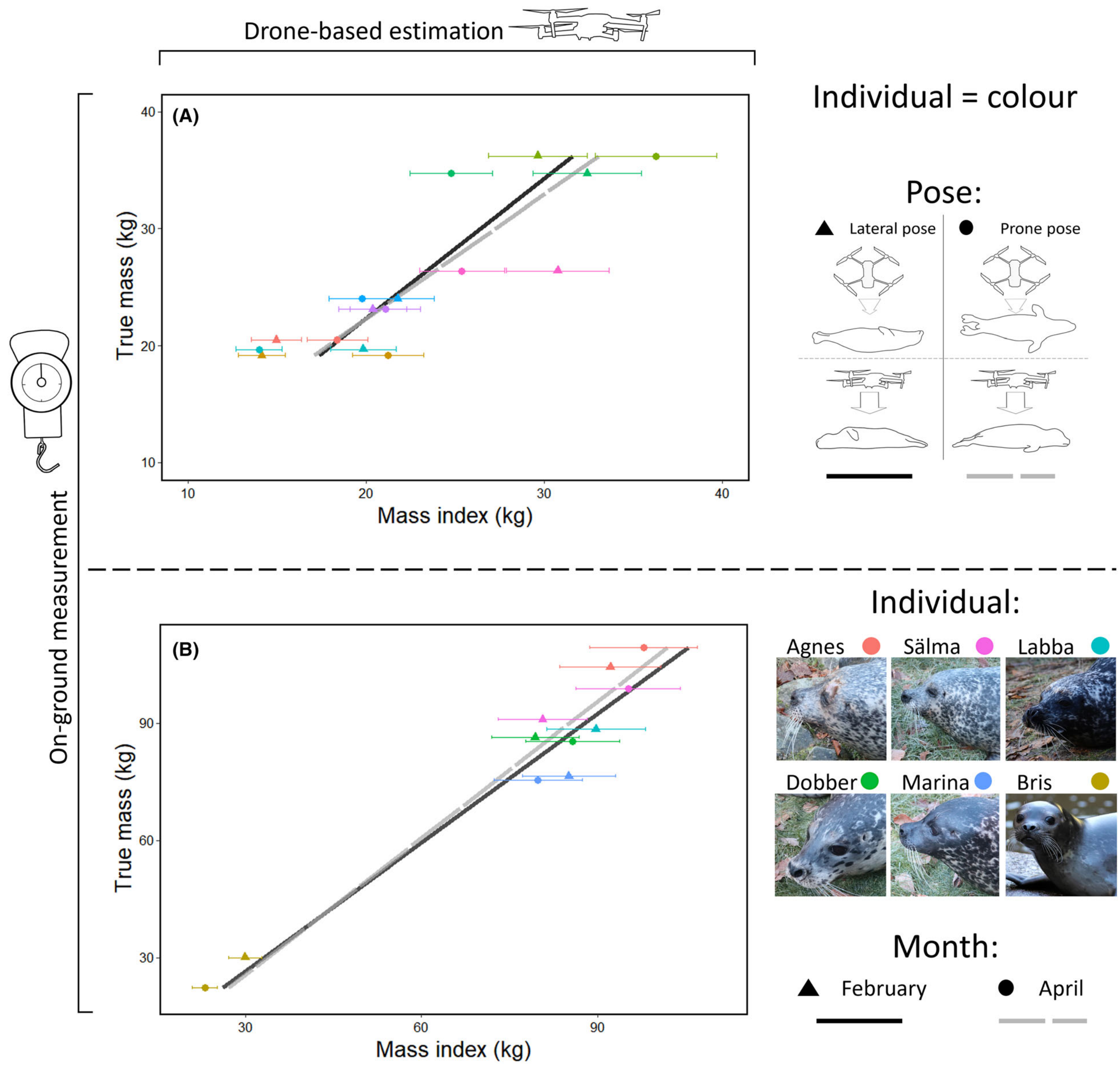

Figure 3. The effect of pose on mass index estimation and drone-based validation of harbour seal morphological parameters. (A) A strong correlation was evident between mass index and true mass. Pose (indicated by point type and line colour) had little effect on mass index estimation. (B) The method was tested by repeated drone-based estimation of mass index for six captive harbour seals immediately prior to weighing. Seals were measured on two different months (indicated by point type and line colour). In (A, B), individuals are represented by different coloured points.

which only three were classified as pups. Mean M_D and SDs for June closely aligned for both years (Table 2, Fig. 4), with means differing more noticeably in September. Based on historical data compiled from routine monitoring carried out by SMNH and presented in Harding et al. (2005 & 2018), the mean and SD in length ($N = 137$, mean = 1.43 m, SD = 0.1 m) and mass ($N = 71$, mean = 55.7 kg, SD = 14.66 kg) were calculated for female seals older than 4 years of age.

Daily increase in mass for pups in September was estimated to be 0.25 kg day^{-1} with a standard error (SE) of 0.05 based on the data presented in Harding et al. (2005) ($t(58) = 4.637$, residual standard error (RSE) = 3.48, $P < 0.001$, Fig. 5A). M_D estimates for individuals classified as pups in September 2022 were increased based on this value to give a predicted M_D on the 1 October 2022. Over-winter survival probability for each of these individuals was then estimated. There was a range of pup

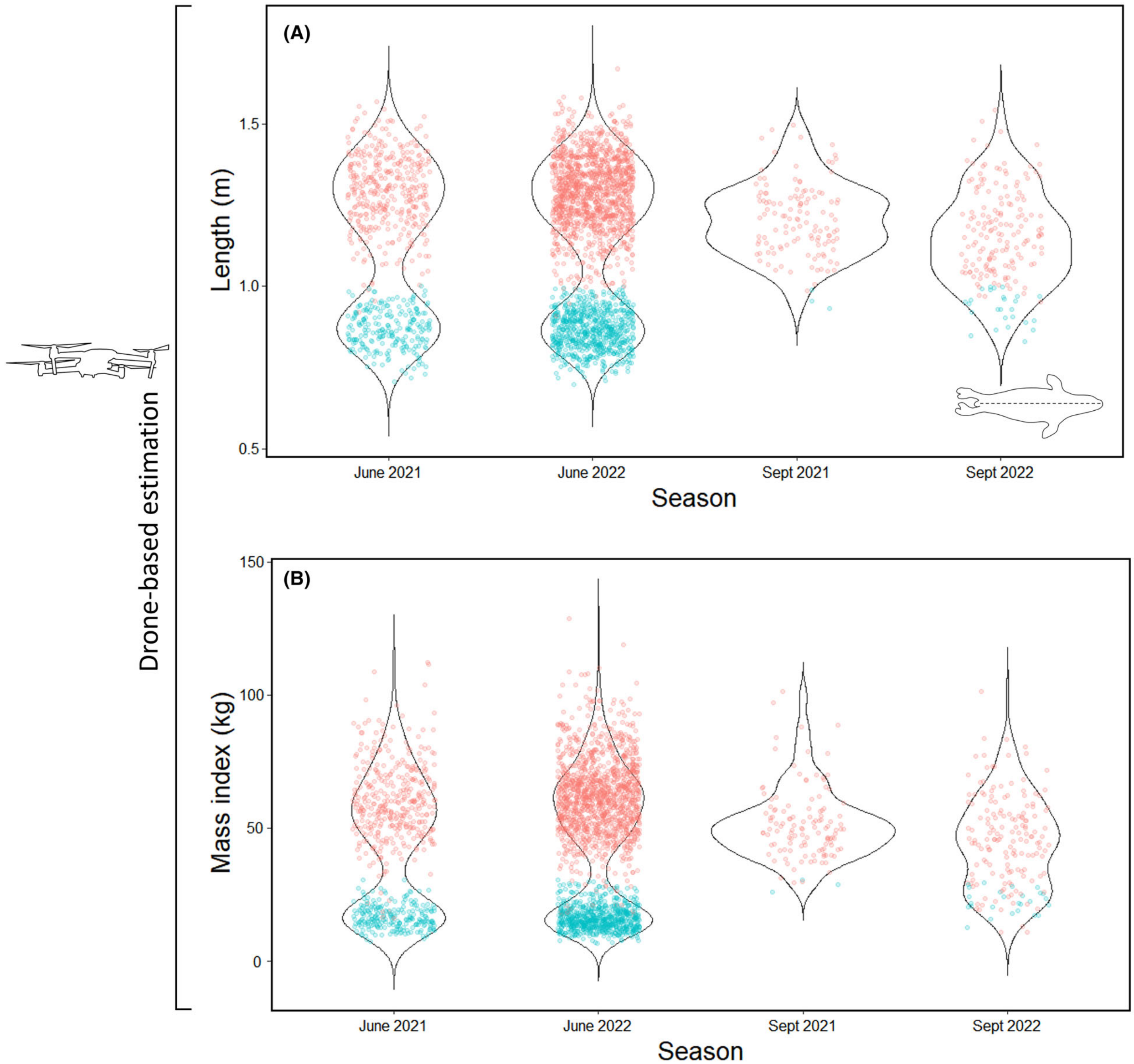

Figure 4. Drone-based estimates of morphological parameters across 2 years during the Spring and Autumn periods. Drone-based estimates of (A) curved length and (B) mass index were made using a total of 2903 individual wild seal images taken during the Spring and Autumn periods of 2021 and 2022 in the Kosterhavet Archipelago. Each point represents a single observation. Violin plots represent the distribution of the data. Blue points represent individuals classified as 'pups', while pink points represent individuals classified as 'older'.

survival values from 0.97 (33.44 kg) to 0.63 (16.86 kg) with a mean of 0.89 and SD of 0.08 (Fig. 5B).

Discussion

We have presented a novel method for the semi-automatic quantification of body condition indices for harbour seals based on remote observations. The F1 score of 95.26% achieved for the detection of wild seals was similar to Infantes et al. (2022) (96.65%). High R^2 values indicated a good prediction of drones-based measurements of length ($R^2 = 0.83$), width ($R^2 = 0.92$) and mass ($R^2 = 0.95$) compared to manual measurements. This method can be applied to a large proportion of the population (a mean of 82.5% of pups on surveyed skerries in 2022).

Other methods for remote estimation of pinniped body mass have been developed, using two-dimensional images (e.g. Alvarado et al. (2020) for elephant seals), and three-dimensional point clouds (e.g. Shero et al. (2021) for grey

Table 2. Mean drone-based morphological indices for wild seals in the Kosterhavet Archipelago during Spring (June) and Autumn (September) of 2021 (Infantes et al., 2022) and 2022 (this study).

Year	Month	Group	Curved length (m)	Greatest width (m)	Mass index (kg)
2021	June	Pups	Mean = 0.87 SD = 0.06	Mean = 0.21 SD = 0.02	Mean = 16.87 SD = 4.45
		Older	Mean = 1.29 SD = 0.11	Mean = 0.31 SD = 0.03	Mean = 60.27 SD = 14.77
	September	Pups	Mean = 0.95 SD = 0.03	Mean = 0.26 SD = 0.01	Mean = 28.69 SD = 2.32
		Older	Mean = 1.21 SD = 0.11	Mean = 0.31 SD = 0.03	Mean = 47.1 SD = 16.23
2022	June	Pups	Mean = 0.86 SD = 0.06	Mean = 0.21 SD = 0.02	Mean = 16.36 SD = 4.49
		Older	Mean = 1.29 SD = 0.11	Mean = 0.32 SD = 0.03	Mean = 61.97 SD = 14.52
	September	Pups	Mean = 0.93 SD = 0.05	Mean = 0.23 SD = 0.02	Mean = 22.69 SD = 4.31
		Older	Mean = 1.18 SD = 0.12	Mean = 0.29 SD = 0.04	Mean = 52.26 SD = 13.24

Seals less than 1 m in length and 34 kg in mass are assigned to the 'pups' group, all other seals are classified as 'older'. SD, standard deviation.

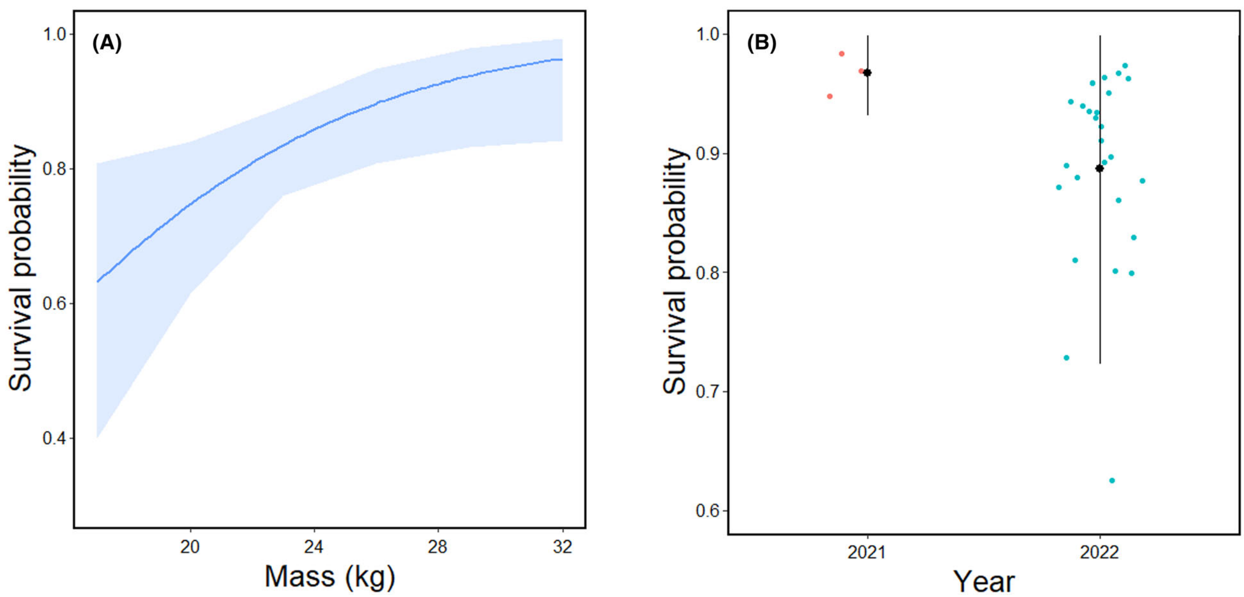

Figure 5. Estimation of pup survival probabilities based on mass index. (A) Mean over-winter survival probabilities for pups-of-the-year with associated mass on the 1 October 2022 were taken from Harding et al. (2005) and fit with a cubic spline (blue line). Shaded regions represent 95% confidence intervals. (B) This spline was used to estimate survival probabilities for seals classified as 'pups' during September 2022 based on mass index values increased by 0.25 kg day^{-1} to represent predicted mass on the 1 October 2022.

seals, *Halichoerus grypus*). These methods have generally involved a high degree of additional labour beyond image collection, resulting in lower sample sizes than were acquired using the semi-automated method. Alvarado et al. (2020) and Shero et al. (2021) made 22 and 673 mass estimates respectively, while we acquired 2903 measurements across 2 years.

Our mean absolute error values (MAE) for all individuals (4.5 kg or 10.5% of body mass) and seals classified as 'pups' (3.2 kg or 12.7% of body mass) are comparable to those achieved through more labour intensive, and potentially disruptive methods, such as the volumetric estimation presented by Shero et al. (2021) (3.8 kg or 2.1% of body mass for adult females and 4.1 kg or 9.8% of body mass for pups). These required lower altitude flights (down to 15 m) which may be disruptive to harbour seals (Pérez Tadeo et al., 2023; Shero et al., 2021). It should be noted that the small size of harbour seals, and in particular harbour seal pups, relative to other pinnipeds increases error as a percentage of body mass, meaning our methods may prove even more successful for assessing the body condition of larger species.

The accuracy of image collection might be improved through acquisition of a greater number of images at lower altitude, at the cost of increasing survey time, reducing the number of animals imaged and increasing the risk of disturbance. The method we have presented is particularly suitable for use in systematic surveys to track temporal trends in body mass or for comparative analysis between regions due to the large sample sizes that can be collected. The use of inexpensive drones is also an advantage, for example, the Mavic-II zoom costs approximately 1200 USD at time of publication.

Drone-based mass estimates should be considered indices rather than true measurements. They lack the standardization of measurements which can be achieved during necropsies (American Society of Mammalogists, 1967). However, they have the advantage of being nondisruptive and capturing data for many more individuals than traditional labour-intensive methods. We designed surveys to capture a large proportion of pups born to the Kosterhavet breeding colony (Amorosi et al., 2024; Infantes et al., 2022). The result is a reliable measure of mass for a known age class which is approaching a population-level survey. As we collected data from multiple days, the same individual may be represented more than once. Issues of resampling can be overcome by considering daily trends and changes in mean body condition indices, or by comparing only a single day, such as the day on which the maximum number of pups is observed. If integrated into routine systematic monitoring, the 2-year data set we have presented could form the beginning of a timeseries tracking trends in overall pup mass. This could be used to investigate how pup condition is impacted by environmental changes. As measurements are associated with dates and positions, fine scale analysis of spatial and temporal trends in body mass could also be investigated (Hoekendijk et al., 2023). This promises to be particularly useful when combined with non-invasive individual identification techniques using natural pelage pattern markings (Langley et al., 2021), which may be possible using drones (Pomeroy et al., 2015, this study). Such a study would enable the interaction of body condition with parameters such as survival and habitat quality to be more fully explored.

As body condition indices were estimated for older seals, trends in the mass of, for example, lactating seals could also be tracked (Shero et al., 2021). For older seals, classic indices of body condition, for example ratio index (mass/length, Jakob et al., 1996), could be estimated. Drone-based estimates of mean lengths for older seals were lower than those calculated for mature seals based on the data presented in Harding et al. (2018) by 0.14 m, while mean masses were between 6.27 kg higher and 8.1 kg lower. All values were within realistic ranges for harbour seals. Differences in length may be a result of the collection method; however, they could also reflect true variability in the population; for example, if immature individuals were present in the breeding colony. The measurements presented for older seals can be considered an index for use in comparative analysis. It is likely that the older seals present during June represent the females with the best body condition, as only these individuals complete pregnancy. As a result, males, subadult seals and year skipping mature females are likely absent from our data (Härkönen et al., 1999). Surveying of the population during other times of the year, such as the annual moult, may therefore provide more representative indicators of population health.

We have presented estimated over-winter survival probabilities for pups-of-the-year observed in September 2022. A number of assumptions were made to make these estimates. In particular, the assumption was made that growth remained constant between surveys and 1 October 2022. The accuracy of these estimates should therefore be tested in future work by tracking average growth, which could be achieved using the survey methods developed in this study. It is also important to consider the low number of pups-of-the-year observed in the Autumn relative to the number born in June, indicating a bias in sampling towards individuals remaining in or returning to the survey area. While these estimates should therefore be interpreted as an incomplete sample, they are still valuable for the assessment of the probable survival of pups in the survey area which could be expanded upon in future work.

The mean estimated pup survival of 0.89 falls within the range of 0.63 and 0.96 presented by Harding et al. (2005) for the same area. The low number of pups-of-the-year present in the survey area during September 2021 prohibited a meaningful estimation of mean over-winter survival. The different structure of the population for the 2 years could indicate higher levels of emigration or mortality in 2021, possibly resulting from different environmental conditions. These estimates can be integrated into population models to inform parameterization of first-year survival rates or be used to explain apparent stochasticity in population growth rates (Plard et al., 2019; Sæther, 1997).

Body masses could also be integrated into individual-based energetics modelling (e.g. dynamic energy budget modelling) (Silva et al., 2020). This could enable the development of more predictively and mechanistically accurate models for use in population viability analysis, informing management decisions (Carroll et al., 2024; Silva et al., 2021). The ability to routinely monitor body mass within and among populations of pinniped species also has the potential to enable the study of drivers of evolution in body size between and among species (Churchill et al., 2015).

We assumed seals to have a simplistic ellipsoid shape with the longest axis represented by curved length and the other two axes represented by width. We found a strong correlation between these metrics, with little evidence that the relationship is influenced by collection month, pose or age class. For historical data, used to develop the model for estimating mass based on volume, only length and girth were available, necessitating this assumption. Although such assumptions have been used for pinniped mass estimation in the past (Castellini & Kooyman, 1990; Usher & Church, 1969; Van Den Hoff et al., 2005), they could be avoided in future by collecting drone images of more individuals with known morphological parameters. The inclusion of more morphological measurements in mass estimation, or direct estimation of volume, could improve the methods ability to cope with changes in pose, or even seasonal variations in body composition (Shero et al., 2021; Stone & Davis, 2023). The method presented also has the potential to be applied to other pinnipeds, many of which haul out on more homogenous substrates such as sand and ice which may facilitate automatic detection (Shero et al., 2021).

Several marine mammal populations are currently recovering from historical overhunting. At the same time, they are challenged by the collapse of important prey fish populations as the result of overfishing and eutrophication (Frank et al., 2005). It is likely that the coming decade will see large annual variations and declines in marine mammal populations, as the result of constrained energy budgets (Silva et al., 2020). Average body condition and survival of young-of-the-year will be one of the first indicators to fluctuate as food limitation takes effect. Changes in body condition can act as an early warning proceeding population decline (Clements et al., 2017). The method presented here can help identify the mechanisms behind population trends. It can be used to guide management strategies, such as extended protective periods and trawling free zones to improve prey abundance in important breeding areas, reducing stress during lactation and improving first-year survival.

Conclusions

The remote sensing method presented is a tool for accurately and reproducibly monitoring body condition for many wild pinnipeds using non-invasive methods. We have shown its potential for tracking changes in body mass at the individual and population level. The method has the potential to improve our understanding of fundamental processes in population dynamics and the selective forces acting on the evolution of body sizes. As body mass is an indicator of environmental condition, the method can be used to detect ecosystem changes affecting pinnipeds before they become apparent through analysis of longer-term trends in population growth. We have also estimated over-winter survival probabilities for pups-of-the-year using drone-based mass estimates, demonstrating the value of the method as a tool for informing population models. We recommend that remote assessments of body condition be integrated into ongoing monitoring of seal populations to act as a rapid indicator of population health and help explain broad scale trends in population growth.

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Author contributions

DC, EI and KCH conceived the ideas and designed methodology; DC, EI, EVP and KCH collected the data; DC analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Data availability statement

All data and code used in this study are publicly available All relevant code is available on GitHub: https://github.com/DaireCarroll2023/Seal_Body_Sizes and Zenodo.org https://doi.org/10.5281/zenodo.11066675.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Comparison of flight and orthomosaic assembly systems.

Figure S2. To calibrate drone-based estimates, length (measured from the nose to the tip of the tail), and girth (measured caudally directly below the forelimbs) were compiled from necropsies.

Figure S3. Comparison of models for the estimation of mass based on morphometric measurements.

Figure S4. No interaction of age class or collection month were found on the correlation between ellipsoid (true) volume and mass.

Figure S5. Example of polygons, representing seal outlines, which were removed from further analysis during manual evaluation.

Figure S6. Illustration of the automated measurement of curved length for a seal in the prone and lateral position.

Table S1. Outcomes of linear regression fitting using drone-based estimates of 75 morphological measurement indices as explanatory variables and true measurements as 76 predictive variables.

Table S2. Output of linear mixed-effects models.

Appendix S2.

