Techniques for determining Elasmobranch body size: a review for evaluation and enhancing current methodologies. (#100369)

First revision

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- Clear, unambiguous, professional English language used throughout.
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- Article content is within the Aims and Scope of the journal.
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- Methods described with sufficient detail & information to replicate.
- Is the Survey Methodology consistent with a comprehensive, unbiased coverage of the subject? If not, what is missing?
- Are sources adequately cited? Quoted or paraphrased as appropriate?
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VALIDITY OF THE FINDINGS

- **Impact and novelty is not assessed.** Meaningful replication encouraged where rationale & benefit to literature is clearly stated.
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Comment on strengths (as well as weaknesses) of the manuscript	*I commend the authors for their extensive data set, compiled over many years of detailed fieldwork. In addition, the manuscript is clearly written in professional, unambiguous language. If there is a weakness, it is in the statistical analysis (as I have noted above) which should be improved upon before Acceptance.*

Techniques for determining Elasmobranch body size: a review for evaluation and enhancing current methodologies.

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There is global awareness that several species within the *Elasmobranchii* subclass have life history characteristics that make them susceptible to overexploitation. The study of these animals both *in-situ* and *ex-situ* is critical, as it contributes to increasing knowledge of these specimens and aids in their conservation. Particularly, growth rate, age, and size at maturity are key parameters for defining management and conservation strategies in elasmobranchs. Biometric data collection allows these parameters to be determined and considered in the evaluation of population demography. Over the last decades, several methodologies for measuring elasmobranch size have evolved, progressing from traditional capture-based methods to sophisticated, non-intrusive techniques. The present review aims to understand and analyze all the existing non-invasive techniques that currently allow the collection of zoometric data in elasmobranchs and, later, to highlight the advantages and limitations of each technique, with comments on their application to field work. To this end, 49 articles were selected, representing seven measurement techniques: photogrammetry using distance to the individual, bar photogrammetry, laser photogrammetry, stereo-DOV, stereo-BRUV, stereo-ROV, and aerial photogrammetry. Globally, the last four techniques are excellent alternatives to methods that imply animal capture or death, as they are practical, simple to use, minimally invasive, and highly accurate. Technique's requirements related to equipment and cost, limitations, and distinctive features are here presented and summarized to guide researchers on what's available and how to select the best fit for their studies.

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ABSTRACT

There is global awareness that several species within the *Elasmobranchii* subclass have life history characteristics that make them susceptible to overexploitation. The study of these animals both *in-situ* and *ex-situ* is critical, as it contributes to increasing knowledge of these specimens and aids in their conservation. Particularly, growth rate, age, and size at maturity are key parameters for defining management and conservation strategies in elasmobranchs. Biometric data collection allows these parameters to be determined and considered in the evaluation of population demography. Over the last decades, several methodologies for measuring elasmobranch size have evolved, progressing from traditional capture-based methods to sophisticated, non-intrusive techniques. The present review aims to understand and analyze all the existing non-invasive techniques that currently allow the collection of zoometric data in elasmobranchs and, later, to highlight the advantages and limitations of each technique, with comments on their application to field work. To this end, 49 articles were selected, representing seven measurement techniques: photogrammetry using distance to the individual, bar photogrammetry, laser photogrammetry, stereo-DOV, stereo-BRUV, stereo-ROV, and aerial photogrammetry. Globally, the last four techniques are excellent alternatives to methods that imply animal capture or death, as they are practical, simple to use, minimally invasive, and highly accurate. Technique's requirements related to equipment and cost, limitations, and distinctive features are here presented and summarized to guide researchers on what's available and how to select the best fit for their studies.

Keywords: *Elasmobranchii*; Biometry; Stereo-video; Photogrammetry; Non-invasive techniques.

Introduction

The cartilaginous fishes, Chondrichthyans, comprises sharks, rays, and chimaeras. Compared to bony fishes, the class Chondrichthyes is relatively small, with 1294 (and rising) valid known living species, and the group of rays covers more than half of this number (Cailliet et al., 2005; Serena et al.; 2020, Ebert et al., 2021, Jorgensen et al., 2022, Fricke et al., 2024). Concerning body shape, chimaeras and most sharks have fusiform bodies, while rays and some sharks have flattened bodies. The subclass *Elasmobranchii* (sharks and batoids) comprise the most common living Chondrichthyans (Ebert et al., 2021) and the number of known species raises each year (Fricke et al., 2024). Most elasmobranchs are marine and may be present at various depths. Although most species have a relatively restricted distribution, it is possible to find species from coastal areas to > 2000m in depth across the globe and, occupying a wide range of habitats (Cailliet et al., 2005; Ebert et al., 2021). It is widely reported that Elasmobranchs' life history traits (such as slow-growth with late maturity, high longevity, low fertility, low productivity, and long gestation) makes them extremely vulnerable to overexploitation and to recover from population decreases (Dulvy et al., 2014, 2021; Ebert et al., 2021). Accurate biometric data collection is therefore key to fill the gaps on this specimen's biology and crucial to apply on fishing regulations and effective conservation actions to prevent their extinction (Dulvy et al., 2014, Jorgensen et al., 2022).

The study and identification of specimen characteristics are defined as biometrics. Biometric measurements cover a large set of features such as height, weight, fingerprints, and facial recognition (Jain & Pankanti, 2006). Some of these measurements can also be performed in animals, where different characteristics are used for their identification, such as physiological, morphological, behavioral and biochemical. The shape and structure of marine organisms vary, therefore morphological measurements may vary according to different groups (Dineshbabu et al., 2014; Kumar et al., 2017). Zoometry is the area of animal biometry that focuses on specifically collecting and analysing the dimensions of an animal's body. Currently, this is a widely used and growing research area with a significant demand for non-invasive techniques, which are the major focus of this study, without major disadvantages or known associated problems (Bugge et al., 2011; Petso et al., 2022).

In elasmobranchs, when one intends to evaluate the demography of a population to define management and conservation strategies, the most important parameters are the growth rate, age and size at maturity, fecundity, and reproduction. Ideally these data should be collected in individuals in their natural habitat however, this is not always feasible. Therefore, studying these individuals' *ex-situ* is the next best option, acknowledging that the growth patterns differ from those collected in the natural habitat (Jañez et al., 2018; Nielsen et al., 2020; Jorgensen et al., 2022). Some examples of studies conducted in artificial conditions include life cycles, ecology, behavior, reproduction, disease, and conservation. These projects, in addition to helping institutions improve their husbandry practices, also complement *in-situ* conservation programs (i.e., in the natural habitat), thus contributing to species conservation (Conde et al., 2019; Da Silva et al., 2019; Kögler et al., 2020; Boggio-Pascua et al., 2022; IUCN SSC, 2023).

Capturing elasmobranchs is a complex and demanding process, which involves the use of specialized professionals and equipment, and it can be hazardous for handlers since these animals are usually wild specimens whose behavior is unpredictable and many of them are large and with powerful jaws, and poisonous spikes. Due to all these factors, different methodologies for measuring elasmobranchs, both *in-situ* and *ex-situ* were explored over time to reduce the previously mentioned risks (Klimley & Brown, 1983; Dunbrack, 2006; Delacy et al., 2017; Raoult et al., 2019).

The present review is an innovative study that aims to assess the non-invasive techniques available for measuring elasmobranchs, and analyze each method's requirements, associated errors, and distinctive features (positive and negative) to provide guidance on the most advantageous and reliable ones to use, according to the research purposes.

Survey methodology

This review was based on a literature search using Google Scholar and ISI Web of Knowledge databases. The following expressions/keywords, were searched for: “simple field method length measurement”, “size measurement of elasmobranch”, “measuring elasmobranch”, “size measurement of sharks”, “size estimates in elasmobranch”, “measuring skates body size”, “length measurement skates”, “remote measurement elasmobranch”, “stereo systems to measure elasmobranch length”, “stereo systems to remote measurement of sharks”, “stereo-video to assess body size in elasmobranch”, “stereo systems to remote measurement elasmobranch”, “baited remote systems in sharks”, “BRUV length Batoidea”, “BRUV for measuring sharks”, “ROV for measuring elasmobranchs”; “using diver operated stereo-video system to measure”, “using diver operated stereo-video system to measure sharks”, “stereo-DOV for remote measurement of elasmobranch”, “aerial photogrammetry for measuring elasmobranchs“, “the use of drones for elasmobranch measurements“, “remote techniques for measuring sharks and rays “, “parallel lasers remote measurements in elasmobranch”,

“determination of size "laser photogrammetry"”, “using lasers to measure elasmobranch”, “laser photogrammetry in elasmobranch”, “laser photogrammetry in sharks”, “measurement with parallel lasers in sharks”, “measuring sharks using bar photography”, “measuring sharks body size with bar”. Additionally, an analysis of the bibliography of the collected articles was undertaken to increase the number of relevant articles to include in this revision.
Bibliographic research was restricted to peer-reviewed articles that referred to body measurement methods and techniques specifically applicable to *Elasmobranchii*. Papers on other species, measurement techniques by “eye”, capture and/ or death of individuals, works focused on population counts, species abundance, behavioral studies and articles that rely exclusively on the photo-identification of individuals were excluded. Microsoft Office Excel Software was used to organise the data during the bibliographic collection. The seven photogrammetry techniques analyzed are presented and briefly described in Table 1 and for each one, a summary of its requirements and distinctive features (positive and negative) are presented in Table 2. The selected articles' information was organised in a table where the technique, title, authors, publication date, species under study, search engine, keywords and link to the article were included. This information was subsequently compiled to present the technique used in each study, the authors and publication date, main goals, reported error when present, the main outcomes, and limitations of each study, mentioned by its authors (Table 3).

Conclusions

This review is the first to identify the more representative, non-invasive techniques that have been used so far, for measuring elasmobranchs.

The 49 articles selected for further analysis (from the 68 initially found) allowed the identification of seven techniques reported to measure *Elasmobranchii*: photogrammetry using distance to the individual; bar photogrammetry; laser photogrammetry; diver operated stereo-video system (stereo-DOV), stereo baited remote underwater video system (stereo-BRUV), stereo-video remoted operated vehicle (stereo-ROV) and aerial photogrammetry using Unmanned Aerial Vehicles (UAVs, commonly mentioned as drones). A brief description of each technique is available in Table 1. Still, it was possible to verify that from these, only five techniques are currently being used. Photogrammetry using distance to the individual and bar photogrammetry, although being the first steps towards developed photogrammetry methodologies are obsolete and limited, not presently being chosen. The studies integrated in the present review were published between 1983 and 2023 and considered 42 shark and 7 ray species. This finding corroborates previous studies indicating that population trend assessments are heterogeneously distributed. Sharks, particularly Lamniformes and Carcharhiniformes, are much more extensively assessed compared to batoids and less charismatic species (Dulvy et al., 2014; Flowers et al., 2020; Jorgensen et al., 2022). The complete list of papers analyzed can be found in the review references section. Table 2 presents the main requirements and distinctive features of each technique, and Table 3 summarizes the information retrieved from the 49 analyzed articles.

Inspection of Table 3 revealed that *Rhincodon typus* (Smith, 1828) was the more frequently studied species (12 studies). For the rays, *Mobula alfredi* (Krefft, 1868) was the most cited, in three articles. From all studies considered, only two were carried out in controlled conditions (Govender et al., 1991; Delacy et al., 2017). Regarding the used techniques, one article referred to photogrammetry using the distance to the individual, one used bar photogrammetry, 17 applied laser photogrammetry, eight the stereo-DOV, 17 the stereo-BRUV, two the stereo-ROV and three used aerial photogrammetry (Table 3). Further inspection of this table in a cost/ benefit approach allows the identification of two techniques (photogrammetry using distance to the individual and bar photogrammetry) that are more limited and obsolete although implying lower application cost, while the other five (laser photogrammetry, stereo-DOV, stereo-BRUV, stereo-ROV, and aerial photogrammetry) are more accurate, allowing for larger and broader sampling but also requiring a considerable cost in terms of equipment and time to process the images.

Although not 100% accurate, the methodologies listed represent excellent alternatives to other methods, such as visual censuses (e.g. Moreno et al., 2021) or those involving the capture or killing of individuals (e.g. Merly et al., 2019). Thus, they hold great potential for application both *in situ* and *ex situ*. It is noteworthy that these approaches can be used for various purposes such as studies of population's abundance or structure (Barley et al., 2017, Tuya et al., 2021), photoidentification (Bansemer & Bennett, 2009; O'Connell & Leurs, 2016), growth patterns (e.g., Perry et al., 2018), reproductive ecology (e.g., Deakos, 2012), and morphometric traits (Carrier et al., 2019; Rastoin-Laplane et al., 2020). They can even be applied to other marine species, e.g., blue whales (Durban, 2016), pilot whales (Wong, J. B., & Auger-Méthé, M. (2018), bottlenose dolphins (Aswegen, 2019) and various teleost fish (Schramm et al., 2020). The versatility of these methodologies is so extensive that they have also been applied in *ex situ* environments, mostly in aquaculture facilities and targeting teleost fish (Harvey et al., 2003; Costa et al., 2009). The main objective of this review is to describe the least invasive methods used to measure elasmobranchs, highlighting their advantages, requirements, limitations, and applications.

The limitations of laser photogrammetry, such as the requirement for individuals to be perpendicular to the device, at the same level as the observer, and without body flexion, make sampling complex and time-consuming to obtain high-quality images for measurement. Overcoming these challenges implies investing in expensive equipment to ensure the lasers' distance and parallel alignment, as well as advanced software to process the images. This investment reduces the primary advantage of this technique, which is its low cost. Lasers have also been used ex-situ with fair results (error ≈5%) (Rogers et al. 2017) although published studies are scarce. New technologies provide a three-dimensional and more realistic approach thus, laser photogrammetry will probably be replaced with more advanced methods (Pulido Mantas et al., 2023). No article using this technique was found published in the last five years, corroborating this evidence.

Based on the articles and techniques described, and considering their advantages and disadvantages, it is evident that stereo-DOVs have a vast field of application in the wild when the sampling area is within a diver's reach and the diver's presence has minimal impact on the target species. The pioneering use of Stereo-DOV was reported in 1983 by Klimley and Brown, and this technique is now widely applied. It also has great potential for use in environments such as aquariums, where many of the issues described (see Table 2) become less relevant: good visibility of the individuals, large aquariums to accommodate the diver's presence, desensitization of animals to their environment reducing flight risk, and the availability of technical and financial resources.

Stereo-BRUVS solve the depth limitations and might present bias results related to the use of bait and additional lights. This technique is suitable to wild environments but has low potential for use in controlled conditions. A similar situation applies to stereo-ROVs, where the accurate measurements require a higher investment in equipment and training. These robust devices are mostly designed to sample at greater depths and according to literature, for different survey purposes than biometrics, like fish assemblages' visual assessments (Sward et al., 2019) or industry inspections and opportunistic sightings (Todd, 2020). Considering a reasonably small and affordable apparatus, the complex logistics and the limitations of stereo-ROVs should not make this technique preferable to a stereo-BRUV or to a stereo-DOV sampling method (Schramm et al., 2020). Aerial surveys using drones, sample large areas, require considerable altitude space and analyze animals close to the surface. This recent technique is being used *in situ*, to assess species that best fit these requirements (mostly marine mammals), but has mainly been applied to studies of abundance, distribution, behavior, and shark-human interactions (Butcher et al., 2021; Whitehead et al., 2022).

The initial costs associated with video techniques are often considered high compared with more traditional biometric data collection methods and may probably be the cause of their scarce application in some research fields. However, several authors mentioned that the costs may be off-set by a reduction in field time, staff needed, observer bias, and providing a permanent visual record that allows archived images to be revisited and contrasted directly against time series data for the detection of spatial and temporal variability of a vast range of species (e.g., Bennett et al., 2016, Langlois et el., 2020). Moreover, reduced costs of cameras and monitoring procedures made the use of video techniques more accessible to researchers over the past decades (Bennett et al., 2016; Delacy et al., 2017; Pulido Mantas et al., 2023). Non-invasive techniques for biometric data collection are of extreme importance for elasmobranch studies as explored in the present review. They represent accurate, accessible, and versatile methodologies that contribute effectively to elasmobranchs' management and conservation.

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Table 1(on next page)

Name and brief description of non-invasive photogrammetry techniques analysed for the measurement of elasmobranchs.

Table 1 - Name and a brief description of each non-invasive photogrammetry technique analysed for the measurement of elasmobranchs.

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Technique	Brief description
Photogrammetry using distance to the individual	It involves estimating the size and shape of elasmobranchs by measuring the distance from the camera to the individual. It requires precise distance measurement tools to ensure accurate scaling of the images.
Bar photogrammetry	This technique uses a calibrated bar of known length placed in the camera's field of view, serving as a reference scale for measuring the size of the elasmobranchs captured in the images.
Laser photogrammetry	Utilizes parallel and calibrated laser pointers projected onto the elasmobranchs, forming a scale of known distance on the animal's body. The spacing between the laser points provides a reference for accurate size measurements.
Stereo-DOV	Involves divers using calibrated stereo camera systems to record video of elasmobranchs. The two cameras capture images from slightly different angles, allowing for three-dimensional measurements of the animals.
Stereo-BRUV	This method employs stereo camera systems mounted on baited frames. The bait attracts elasmobranchs into the field of view, enabling the capture of stereoscopic images for size and behaviour analysis.
Stereo-ROV	Uses stereo cameras mounted on remotely operated vehicles to capture three-dimensional images of elasmobranchs in their natural habitat, providing accurate measurements and detailed observations without diver intervention.
Aerial photogrammetry (UAV)	Involves unmanned aerial vehicles (drones) equipped with cameras to capture images of surface-swimming elasmobranchs surveying large areas from above.

Table 2(on next page)

Summary of the 49 articles analyzed. Publication details, applied techniques, main outcomes and limitations of each study, and associated error.

Table 3 - Summary of the 49 articles analyzed. Publication details: authors, year of publication and applied technique ([1] Photogrammetry using distance to the individual, [2] Bar photogrammetry, [3] Laser photogrammetry, [4] Stereo-DOV, [5] Stereo-BRUV, [6] Stereo-ROV, [7] Aerial photogrammetry); species studied; goals; main outcomes and limitations, and associated error (when mentioned). Errors are presented as follows: coefficient of variation (CV), standard deviation (SD), average error (AE), standard error (SE), mean absolute error (MAE), mean error (ME), and maximum error (MXE). Main limitations of each study are also presented.

Table 3 - Summary of the 49 articles analyzed. Publication details: authors, year of publication and applied technique ([1] Photogrammetry using distance to the individual, [2] Bar photogrammetry, [3] Laser photogrammetry, [4] Stereo-DOV, [5] Stereo-BRUV, [6] Stereo-ROV, [7] Aerial photogrammetry); species studied; goals; main outcomes and limitations, and associated error (when mentioned). Errors are presented as follows: coefficient of variation (CV), standard deviation (SD), average error (AE), standard error (SE), mean absolute error (MAE), mean error (ME), and maximum error (MXE). Main limitations of each study are also presented.

Publication	Species studied	Goals	Main outcomes and associated error	Main limitations of the study
Lacey et al. (2010)[1]	*Cetorhinus maximus* (Gunnerus, 1765)	To study the relationship between body length and swimming speeds in basking sharks.	Large sample collection without capture.	Individuals sampled must be at the surface.
Govender et al. (1991)[2]	*Carcharias taurus* (Rafinesque, 1810)	To evaluate the growth of *C. taurus* in controlled conditions.	Robust for size estimation. Error 5%.	Light refraction through different media introduced error.
Araujo et al. (2014)[3]	*Rhincodon typus* (Smith, 1828)	To describe the presence of Whale Sharks in Oslob, analysing population structure and residence patterns.	Effective and efficient technique.	Only perpendicular photographs were used; weather and camera vision limited full photographs and length estimates for females.
Bansemer & Bennett (2009)[3]	*Carcharias taurus* (Rafinesque, 1810)	To Investigate pregnant females' aggregation of *C. taurus* in Wolf Rock evaluating their reproductive periodicity and behavior.	Detailed monitoring of adult females' reproductive cycle. Error 5%.	Individuals needed to be perpendicular and without body flexion for laser measurements; poor weather shortened tracking sessions.
Barker & Williamson (2010)[3]	*Carcharias taurus* (Rafinesque, 1810)	To determine abundance and movement of *C. taurus*, evaluating methods with contributions from the community.	First web-based data request method for retrospective analysis. Added individuals to the data base. Lasers proved to be accurate. Error 3%.	Laser measurements began in the second year; community participation was inconsistent; image distortion increased error.

Deakos (2010)[3]	*Mobula alfredi* (Krefft, 1868)	To analyse the accuracy and effectiveness of laser photogrammetry in a resident population of *M. alfredi* in Hawaii.	Effective for *M. alfredi* measurement, with the conversion of disc length to disc width by applying a ratio function. AE 0.38% and CV 0.54%.	Difficulty incorporating target species into camera view; individuals had to be fully stretched; reactions to divers and less accurate disc width measurements occurred.
Deakos (2012)[3]	*Mobula alfredi* (Krefft, 1868)	To study the reproductive cycle of *M. alfredi* and the role of body length in their reproductive ecology.	Evaluated multiple factors of *M. alfredi's* reproductive ecology.	Individuals had to be fully stretched to avoid underestimating length.
Devine et al. (2018)[3]	*Somniosus microcephalus (Bloch & Schneider, 1801)*	To estimate the abundance of the Greenland Shark in the Canadian Arctic Archipelago.	Local and regional abundance of *S. microcephalus* demonstrated.	Only individuals in full field of vision with aligned lasers were measured.
Guttridge et al. (2017)[3]	*Sphyrna mokarran* (Rüppell, 1837)	To investigate the residence of *S. mokarran* and its movements and connectivity between the US and the Bahamas.	Philopatric behavior of *S. mokarran* demonstrated.	Only perpendicular images were selected for measurement.
Hearn et al. (2016)[3]	*Rhincodon typus* (Smith, 1828)	To report the marking and movements of large *R. typus* females on Darwin Island.	Tagged large *R. typus* females.	Some tagging devices were unsuccessful.
Jeffreys et al. (2013)[3]	*Rhincodon typus* (Smith, 1828)	To build an accurate laser photogrammetry system to measure *R. typus* during the mating season.	The device demonstrated ease of calibration, robustness, and reliability, with reduced costs, and safely provided accurate measurements in water. CV2.44%	Photographs had to be taken at the same level and perpendicular; factors like body movement contributed to error.
Leurs et al. (2015)[3]	*Carcharodon carcharias* (Linnaeus, 1758)	To evaluate size of *C. carcharias,* while comparing visual measurements with laser photogrammetry.	The non-invasive technique effectively evaluated species size and growth, showing	Larger deviation from actual length with increasing reference angle; measurements required visible calibrated lasers, and minimal

			superiority over visual estimates, and enhancing photo-identification using dorsal fins. Error 1.3%.	body curvature.
O'Connell & Leurs (2016)[3]	*Sphyrna mokarran* (Rüppell, 1837)	To determine whether notch coding was a good identification method. To combine laser photogrammetry and photo-identification for sizing.	Laser photogrammetry was effective for *S. mokarran* measurements, aiding future studies on growth rates and site fidelity.	Only perpendicular photographs with visible lasers and no body curvature were selected; site fidelity analysis was not possible.
Perry et al. (2018)[3]	*Rhincodon typus* (Smith, 1828)	To evaluate the accuracy of three measurement methods. To determine size and growth patterns among whale sharks in the Maldives.	Laser and tape measure techniques had lower errors and were more accurate than visual estimates. CV 2.03%.	Study conducted over 10 years; photographs had to be perpendicular to individuals.
Rezzolla el al. (2014)[3]	*Sphyrna lewini* (Griffith & Smith, 1834), *Carcharhinus amblyrhynchos* (Bleeker, 1856)	To present the first observations of the behavior, and size composition of shark groups on the reefs of Sudan.	Low-cost, continuous, non-invasive equipment effectively monitored species' ecology, producing substantial data in challenging environments over a brief study period.	Laser measurements were limited to seven individuals due to selective sampling.
Rogers et al. (2017)[3]	*Scyliorhinus canicula* (Linnaeus, 1758)	To combine different techniques to identify morphometric indices that predict *S. canicula's* maturity stages and sex.	This study was the first to use allometry changes to detect shark maturity, with laser measurements proving accurate. SE 5.2% and CV 1.8%.	Increasing distance from individuals increased measurement error; limited results for estimating male maturity stages of *S. canicula*.
Rohner et al. (2011)[3]	*Rhincodon typus* (Smith, 1828)	To demonstrate the accuracy of laser photogrammetry in	Laser photogrammetry was economical and accurate for measuring *R.*	Photographs required sharks to be fully stretched and lasers visible and aligned; limited to low

		measuring *R. typus.*	*typus* in natural habitats, surpassing visual methods.	turbidity conditions.
Rohner et al. (2015)[3]	*Rhincodon typus* (Smith, 1828)	Describe the size ranges and sex ratios of sharks at these sites. Assess maturity length. To test whether photogrammetry can detect estimated growth rates over a 1–3 year period.	The technique enhanced size estimation accuracy for whale sharks compared to visual methods. AE 3.2cm and CV 0.17%.	Lasers had to be parallel and visible; photographs taken at the same level and perpendicular; technique not effective for short-term growth rate analysis.
Rowat et al. (2011)[3]	*Rhincodon typus* (Smith, 1828)	Compare the membership periods of the Djibouti aggregation between size classes.	Laser photogrammetry provided more accurate length assessments than visual or tape measurements by divers.	Disparities in sampling periods between sites; lower research actions in initial years.
Delacy et al. (2017)[4]	*Carcharhinus longimanus* (Poey, 1861)	To test the effectiveness of a stereo system in a controlled environment and in the field, comparing with other studies.	Simple equipment and software yielded accurate measurements, with 2D calibration proving as effective as 3D calibration. MAE 0.34% (calibration), 0.33% controlled tests, and 1.6% between techiniques.	Controlled environment tests showed increased error with a higher bar angle to the camera.
Goetze et al. (2018)[4]	*Aetobatus ocellatus* (Kuhl, 1823), *Carcharhinus amblyrhynchos* (Bleeker, 1856), *C. melanopterus* (Quoy & Gaimard, 1824), *Negaprion acutidens* (Rüppell, 1837), *Taeniura lessoni* (Last, White & Naylor, 2016), *Triaenodon obesus* (Rüppell, 1837) and *Urogymnus granulatus*	To assess reef shark abundance and biomass in the Solomon Islands. To provide information on shark and ray abundance, and assess key drivers of abundance/biomass.	This study first quantified shark and ray abundance, biomass, and diversity in the Solomon Islands. Over 100 sharks were measured.	Some species were removed due to low sampling; lower relative abundance levels compared to other Pacific areas but higher observation rate per hour.

	(Macleay, 1883).			
Klimley (1987)[4]	*Sphyrna lewini* (Griffith & Smith, 1834)	Describe some traces of life history, differences in diet, segregation and growth between sexes, in *S. lewini*.	First study to describe sex segregation in *S. lewini*. Females mature at a larger size and grow more rapidly than males.	Na
Klimley & Brown (1983)[4]	*Sphyrna lewini* (Griffith & Smith, 1834)	To describe a stereo system technique to study group positioning in *S. lewini. To* explain how the method was modified to provide accurate measurements and the three-dimensional position of an active individual.	The portable measurement method with two cameras was effective for *S. lewini* size and position determination. MXE 5%.	Only parallel individuals were measured; weather conditions often hindered accuracy.
May et al. (2019)[4]	*Carcharodon carcharias* (Linnaeus, 1758)	To obtain the exact length of *C. carcharias*. To determine the observer's ability to visually estimate total length, and to assess how length, observer experience, and gender affected estimates.	Visual estimates by experienced observers were validated for *C. carcharias* studies. SE 0.63 m	Stereo photographs for measurements were minimally addressed.
Meekan et al. (2020)[4]	*Rhincodon typus* (Smith, 1828)	To assess the growth of the Whale Shark population on the Ningaloo Coast. Using data from previous studies to identify previously measured individuals. To	Studies on sex-specific life history patterns provided insights into species' ecology. Different average asymptotic total length between males and	Sampling error potential with slow-growing sharks; fast growers less likely to be sighted.

		examine specific patterns of size and growth.	females.	
Salinas-de-León et al. (2016)[4]	Miscellaneous (not all species observed and measured were specified, nor whether they were analyzed by the DOV or by visual census).	Establish comprehensive abundance estimates for sharks and predatory fish assemblages on Darwin and Wolf Islands. It was also intended to use this information to make recommendations for this species protection.	The first quantitative fish survey using stereo-video improved length estimate accuracy and highlighted the ecological value of Darwin and Wolf Islands.	Biomass results from visual censuses and DOV showed relevant average differences.
Sequeira et al. (2016)[4]	*Rhincodon typus* (Smith, 1828)	Compare length estimates derived through stereo measurement techniques and visual estimates, to obtain estimates of the whale shark population that has reached sexual maturity.	The stereo system accurately estimated *R. typus* length.	Visual estimates had high error; stereo device was large and heavy.
Acuña-Marrero et al. (2017)[5]	*Galeocerdo cuvier* (Peron & Lesueur, 1822)	Investigate the spatial ecology of Tiger Sharks by focusing on residence patterns in relation to Green Turtle nesting beaches. BRUVs, satellite telemetry and acoustics were used.	First study on tiger sharks' movement and habitat uses in the Galapagos, revealed large sharks fidelity to sea turtles nesting areas	Some satellite and acoustic tracks failed; BRUV sampling was limited and focused on frequently sighted locations.

Asher et al. (2017)[5]	* *Carcharhinus galapagensis* (Snodgrass & Heller, 1905) and *Triaenodon obesus* (Rüppell, 1837)	Compare the relative abundances and length-based distributions of the main species contributing to predator assemblages. Investigate mesophotic habitats that remain inaccessible to visual censuses.	BRUV offered benefits over diver surveys for assessing predator populations at greater depths.	Obstructed footage was excluded; BRUV had limitations in vertical habitats.
Asher et al. (2019)[5]	* *Carcharhinus galapagensis* (Snodgrass & Heller, 1905) and *Triaenodon obesus* (Rüppell, 1837)	Quantify the subregional level differences in predator abundance rates at ≤30m depth. To incorporate and compare methods covering different depths. To evaluate the size distribution of predators using four techniques.	This large-scale predator comparison using BRUVs and RUVs showed benefits over diver-based methods, especially beyond 30m depth.	Towed diver counts were negatively biased due to boat noise and movement; bait type influenced results.
Dunbrack (2006)[5]	*Hexanchus griseus* (Bonnaterre, 1788)	To describe the performance of a stereo-video in line measurement system, designed to obtain length frequency data for a population of *H. griseus*.	The technique was relatively insensitive to camera alignment changes, providing accurate length measurements for demersal species. AE 1.6%.	Na
Dunbrack & Zielinski (2005)[5]	*Hexanchus griseus* (Bonnaterre, 1788)	To collect quantitative behavioral and population data of *H. griseus* using a non-invasive system. A stereo-video technique was used to analyze the body length-frequency relation.	The minimally invasive, remote technique provided significant data on *H. griseus'* populations. AE 2%, MXE 4.9%.	Vertical device placement sometimes obscured individuals: measurements limited to visible individuals.

Goetze & Fullwood (2013)[5]	*Carcharhinus albimarginatus* (Rüppell, 1837), *C. amblyrhynchos* (Bleeker, 1856), *C. melanopterus* (Quoy & Gaimard, 1824), *Stegostoma fasciatum* (Hermann, 1783) and *Triaenodon obesus* (Rüppell, 1837).	To assess the relative abundance and biomass of reef sharks, inside and outside the Namena Marine Reserve, using BRUV systems.	The study demonstrated the positive impact of a Marine Reserve on reef shark biomass, showing BRUVs' suitability for sampling.	Camera obstructions and failures prevented some measurements.
Harasti et al. (2016)[5]	*Carcharodon carcharias* (Linnaeus, 1758)	To assess the size and presence of great whites through the use of BRUVs.	BRUVs effectively monitored *C. carcharias'* juvenile abundance and size over 24 months. SE 1.19 cm.	The measurements' accuracy was unclear due to the absence of pre-measured tagged sharks. BRUVs' low position affected measurements by cutting off the top of the caudal fin in the video.
Harasti et al. (2019)[5]	*Carcharodon carcharias* (Linnaeus, 1758)	To use BRUVs for reliably testing juvenile Great Whites' growth and size frequency.	BRUVs demonstrated success in monitoring *C. carcharias* juveniles, showcasing practicality for long-term assessments. SE 0.4 cm.	Population abundance estimation was not possible due to data lack; reobserved individuals appeared smaller in second measurements.
Letessier et al. (2013)[5]	Not all measured species are specified.	To develop a technique that produces relevant data for the implementation and monitoring of pelagic species in large marine protected areas (MPAs).	The system offered a low-cost, efficient tool for fast, non-extractive monitoring of pelagic fish and shark populations. Mean CV 6.1%.	Some species were only identified to the family level; short BRUV deployment times hindered measurements.
Lewis et al. (2023)[5]	*Notorynchus cepedianus* (Peron, 1807)	To obtain data on the size and sex structure of broadnose sevengill sharks, present in southern New Zealand, using low cost equipment for the development of a BRUV system.	The system had a small error and produced accurate, repeatable measurements. ME 0.63%, MXE 1.13%, and CV 0.3%.	Small sample size: total length estimated from pre-dorsal length, leading to biases.

Pimentel et al. (2019)[5]	*Carcharhinus falciformis* (Müller & Henle, 1839), *C. galapagensis* (Snodgrass & Heller, 1905), *C. perezi* (Poey, 1876), *Galeocerdo Cuvier* (Péron & Lesueur, 1822) , *Ginglymostoma cirratum* (Bonnaterre, 1788) and *Sphyrna lewini* (Griffith & Smith, 1834).	To present records of sharks obtained from surveys using remote underwater video systems (BRUVs) in the Brazilian oceanic islands of Trindade and in the São Pedro and São Paulo archipelago (ASPSP).	BRUV was a useful complement to other non-invasive methods.	Na
Pinte et al. (2020)[5]	*Centrophorus harrissoni* (McCulloch, 1915), *C. squamosus* (Bonnaterre, 1788), *Centroscymnus owstonii* (Garman, 1906), *Dalatias licha* (Bonnaterre, 1788), *Deania calcea* (Lowe, 1839), *Etmopterus granulosus* (Günther, 1880), *E. molleri* (Whitley, 1939) and *Proscymnodon plukenti* (Waite, 1910).	To assess the occurrence and relative abundance of sharks at depths from 300 to 1200m in New Zealand using BRUVs. These deployments made it possible to measure ecological characteristics such as size, swimming speed and tail-beat frequency of eight species of deep-sea sharks.	First *in-situ* study of deep-sea species' swimming speeds. 253 speed and 135 size measurements from 28 species. Error 0.91 cm.	Individuals were sometimes not fully visible in the camera.
Ryan et al. (2015)[5]	*Carcharhinus albimarginatus* (Rüppell, 1837), *C. amblyrhynchos* (Bleeker, 1856), *C. brevipinna* (Müller & Henle, 1839), *C. plumbeus* (Nard, 1827), *C. obscurus* (Lesueur, 1818), *Furgaleus macki* (Whitley, 1943), *Galeocerdo cuvier* (Peron & Lesueur, 1822), *Hemitriakis falcata* (Compagno & Stevens, 1993), *Heterodontus*	To measure cruising speed in different shark species using BRUVs. To generate a predictive model of cruising speed as a function of body size, body shape, habitat, trophic level, temperature, and taxonomic order.	The study amassed a large dataset on species' cruising speeds and sizes, proving BRUV useful for speed measurements.	Only 100% visible individuals were analysed; model may overestimate cruise speeds.

	portusjacksoni (Meyer, 1793), *Mustelus a ntarcticus (*Gunther, 1870), *Nebrius ferrugineus* (Lesson, 1831), *Negaprion acutidens* (Rüppell, 1837), *Parascyllium variolatum* (Duméril, 1853), *Sphyrna lewini* (Griffith & Smith, 1834) and *Triaendon obesus* (Rüppell, 1837).			
Santana-Garcon et al. (2014a)[5]	* *Carcharhinus limbatus* (Müller & Henle, 1839), *C. plumbeus* (Nard, 1827), *Carcharhinus spp.*, *Galeocerdo cuvier*(Peron & Lesueur, 1822), *Rhizoprionodon acutus* (Rüppell, 1837), *Sphyrna lewini* (Griffith & Smith, 1834) and *S. mokarran* (Rüppell, 1837).	Compare catch composition, relative abundance and length distribution of fish sampled by pelagic BRUVs and conventional scientific longlines.	Pelagic BRUVs provided a non-lethal alternative for shark sampling, with estimates comparable to longline methods.	Individuals had to lie upright for measurement, differences in coverage area and bait amount between techniques.
Santana-Garcon et al. (2014b)[5]	* *Carcharhinus limbatus* (Müller & Henle, 1839), *C. plumbeus* (Nard, 1827), *Carcharhinus spp., and Galeocerdo cuvier* (Peron & Lesueur, 1822).	To study protected species in the Houtman Abrolhos Islands. To evaluate pelagic BRUVs as a monitoring technique for land closure. Contribute to the debate on the use of these spatial areas for conservation and management of highly mobile fish species.	The robust, non-destructive method allowed standardized studies of fish assemblages, providing permanent species records and behavioral observations.	Measurements limited to individuals within 8m and over 45° orientation: species identification challenges.

Tickler et al. (2017)[5]	*Carcharhinus albimarginatus* (Rüppell, 1837), *C. amblyrhynchos* (Bleeker, 1856), *C. melanopterus* (Quoy & Gaimard, 1824), *Galeocerdo cuvier* (Peron & Lesueur, 1822), *Nebrius ferrugineus* (Lesson, 1831), *Sphyrna lewini* (Griffith & Smith, 1834), *S. mokarran* (Rüppell, 1837) and *Triaenodon obesus* (Rüppell, 1837).	Use of BRUVs to model relationships between measurements of shark assemblages with a combination of environmental variables, measurements of abundance, biomass and diversity of reef fish.	Grey shark lengths differed significantly between locations and shark abundance is related with planktivore biomass.	Visibility and camera range issues caused measurement errors; some footage discarded.
Yon et al. (2020)[5]	* *Carcharhinus melanopterus* (Quoy & Gaimard, 1824), *Chiloscyllium punctatum* (Müller & Henle, 1838), *Hemitriakis falcata* (Compagno & Stevens, 1993), *Nebrius ferrugineus* (Lesson, 1831), *Negaprion acutidens* (Rüppell, 1837) and *Triaenodon obesus* (Rüppell, 1837).	To assess whether elasmobranch abundance, size, and assemblage vary between samplings inside and outside marine protected areas (MPAs). To identify habitat and substrate variables, and to assess the status of elasmobranch populations in the marine park of Cobourg in relation to similar habitats.	Abundance data suggested potential refuges for reef-associated shark and ray species.	BRUV footage was often obstructed or restricted, limiting sampling.
Vögler et al. (2022)[6]	*Hexanchus griseus* (Bonnaterre, 1788)	First *in situ* documented record for *H. griseus* in Rapa Nui (the largest protected MPA in Latin America).	ROVs with HD cameras and laser pointers documented and estimated rare shark specimens' lengths at 320m depth.	Opportunistic sighting of a rare shark species provided; no disadvantages mentioned.

McLean et al. (2019)[6]	*Rhincodon typus (Smith, 1828), Mobula birostris* (Walbaum, 1792), *Taeniurops meyeni* (Müller & Henle, 1841), *Carcharhinus amblyrhynchos* (Bleeker, 1856) and *Triaenodon obesus* (Rüppell, 1837)	To use a high-resolution stereo-video system mounted on an industrial ROV. To assess fish and marine growth habitats associated with an oil platform in Western Australia. To investigate stereo-ROVs' viability for robust scientific information collection. To assess fish growth changes from the surface to 130m depth.	The study allowed industry-specific tasks and scientific data collection, including accurate fish identification and habitat analysis using stereo-ROV transects.	Sampling protocol limitations included low camera light capabilities and stereo camera package disruptions.
Oleksyn et al. (2020)[7]	*Bathytoshia brevicaudata* (Hutton, 1875)	To investigate the influence of body size, tide, and time of day on the movement of *Bathytoshia brevicaudata*. Drone technology was used to gain morphological measurements of the rays and to track the speed and sinuosity of their swim trajectories.	UAVs offered a low-cost, non-invasive method to collect high-resolution marine animal data, with long tracking capabilities across tidal stages. Accuracy of measurements between 1 and 5 cm.	UAVs had short battery life, weather dependency, and screen glare issues; rays needed to be close to the surface. Challenges with the on-board altitude system's accuracy.
Setyawan et al. (2022)[7]	*Mobula alfredi* (Krefft, 1868)	To develop a novel method to measure the body size of surface feeding *M. alfredi*. To employ aerial photogrammetry techniques including na object of known length as a reference scale to measure three morphometric dimensions.	The study demonstrated an accurate, affordable method to measure surface-feeding *M. alfredi*, with minimal animal impact and strong linear correlation in dimensions. SD < 2.2 cm.	Useful only for surface-feeding manta rays; measurements couldn't be attributed to tracked individuals over time.

Whitehead et al. (2022)[7]	*Rhincodon typus (Smith, 1828)*	To use a small UAV to obtain aerial images of whale sharks for photogrammetry analysis, with the aim of determining the effectiveness of this method for obtaining accurate morphometric measurements.	The first UAV study measuring whale sharks from aerial imagery, providing a viable method for obtaining biological information and tracking live individuals over time. Error 0.35%.	Water turbidity and cloud cover affected aerial visibility, method unsuitable for vertical feeding sharks.

Table 3 (on next page)

Equipment requirements and distinctive features of each non-invasive photogrammetry technique.

Equipment requirements and distinctive features (positive and negative) of each non-invasive photogrammetry technique.

1 Table 2 - Equipment requirements and distinctive features (positive and negative) of each non-invasive photogrammetry technique.

Technique	Equipment requirements	Distinctive positive features	Distinctive negative features
Photogrammetry using distance to the individual	Minimal equipment is needed for its application (e.g., camera, known reference length object) so the associated cost is low.	Very simple technique with minimal requirements ideal for species that approach the surface and when only.	Limited to individuals near the surface. Only partial visibility of an individual may restrict measurements and body bending affects measurement accuracy.
Bar photogrammetry	Few equipment is needed (e.g. camera, reference bar, mounting system) for its application, so the associated cost is reduced.	Simple technique with few requirements ideal for species that can be encouraged to approach and stay parallel to the bar	Requires individuals to be parallel and close to the bar. Increased error due to passage through various media.
Laser photogrammetry	Laser pointers or rangefinders to project laser lines onto the specimens are required. These lasers should be parallel and calibrated for accurate measurements. Software for processing images and calculate measurements is needed.	Low associated cost. Low impact on individuals. Various free measurement software available. Low error percentage if precautions are followed.	Need for parallel lasers and immobile equipment to minimize error. Strict requirements for image collection (perpendicular, 2D approach). Susceptibility to environmental conditions affecting laser visibility.
Stereo-DOV	Specific hardware and software are available with considerable cost; low cost options are also available; diver required.	Selective sampling due to diver manoeuvrability allows for targeting specific species populations.	Depth limitation due to diver's capabilities.
Stereo-BRUV	Specific hardware and software available with considerable cost; low cost options are also available; it usually requires BRUV deployment and collection from a boat.	Remote sampling capability, enabling sampling in very deep locations without the need for divers.	The presence of bait can be disruptive and bias the results.

Stereo-ROV	Specific hardware and software available with considerable cost; reduced cost options available with significant limitations; it requires higher manoeuvring skills and equipment maintenance costs.	Versatility for multiple studies including size structure, behaviour, and 3D modelling; works at great depths; advanced industry ROVs can be used in combined scientific campaigns and opportunistic images recorded could be of great scientific value.	Requires specific deployment and operation protocols that have limitations to sampling. Sound and lights used have a deterrent effect on fish.
Aerial photogrammetry (UAV)	Specific hardware and software available with considerable cost; low cost options are also available (short battery life); it usually requires a known length object as a scale or sophisticated altitude sensors.	Minimal impact on measured animals; suitable for simple, accurate, and affordable measurements with small, commercially available drones.	It only allows measurements close to the surface, with calm water conditions and good surface visibility.

2