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A blacktip's black tip: The reliability of using dorsal-fin patterns for photo identification of blacktip reef sharks (*Carcharhinus melanopterus*)

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Abstract

Photo identification (photo ID) has increasingly become a valuable technique serving not only to identify individual animals but also to monitor populations, track migration patterns and assess wildlife health, among others uses. Various species of sharks are amenable to photo ID, among which the blacktip reef shark (*Carcharhinus melanopterus*) is a particularly suitable subject. Their distinctive pigmentation and dorsal-fin patterns serve as potential key identifying features. This study focuses on the variation in dorsal-fin patterns among individual neonatal and juvenile *C. melanopterus* around Moorea, French Polynesia. We employed a Gower distance matrix to assess dissimilarities in dorsal-fin patterns and conducted an elliptical Fourier analysis (EFA) to characterize shape variations. The results from the EFA were further summarized using principal component analyses. Additionally, we explored the potential symmetry between the left and right sides of the dorsal fin. To assess the long-term reliability of using pigmentation patterns for photo ID, dorsal-fin patterns of recaptured individuals were compared using regressions of log-transformed dorsal-fin measurements over log-transformed pre-caudal lengths. Recaptures occurred over varying time frames, ranging from as short as 2 weeks to as long as 9 months. The diverse range allowed us to evaluate the temporal stability of dorsal-fin patterns across different intervals. The analyses revealed that each individual shark's dorsal-fin pattern is unique, but the left and right sides are asymmetrical. Regarding the analysis of recaptured individuals, the ontogenetic changes in dorsal-fin size were not significant enough to alter the dorsal-fin patterns, thus ensuring their temporal stability. The application of photo ID techniques, as demonstrated in this study, underscores its indispensable role in conservation strategies, promoting a deeper understanding of elasmobranch species.

KEYWORDS
elasmobranch, elliptical Fourier analysis, French Polynesia, individual recognition, ontogeny

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1 | INTRODUCTION

In conservation ecology, recurring questions related to population size, survival rates, migration patterns and the effects of environmental variables are commonly approached using capture-mark-recapture techniques (Lettink & Armstrong, 2003). Such techniques involve capturing the animals for initial marking (e.g., tagging) and subsequent recaptures (Pradel, 1996). Tagging is widely used in elasmobranch (i.e., sharks, skates and rays) studies that use such capture-mark-recapture techniques (Kohler & Turner, 2001). However, it requires repeated capture and handling of sharks, which may lead to changes in behaviour, injury, physiological stress or mortality (Putman, 1995). The stress caused by capture can trigger abortions in pregnant sharks in some instances (Adams et al., 2018), underscoring the potential risk to reproduction. Additionally, repeatedly capturing and handling large, mobile marine animals is resource-intensive, requiring specific gear, skilled personnel and substantial financial resources, which can be impractical in remote or difficult-to-access areas.

In conjunction with capture-mark-recapture studies, a non-invasive technique may be photo identification (hereafter, photo ID) (Gore et al., 2016; Marshall & Pierce, 2012). Photo ID allows for the identification of individual sharks without physical capture, offering a scalable, non-invasive alternative for long-term population monitoring. It reduces stress, injury and the logistical demands associated with capture-mark-recapture techniques. This technique is used to track individual animals based on distinct physical features, such as natural pigmentation, markings or scars, and can be used as an alternative to capture-mark-recapture techniques. Photo ID offers a non-invasive and cost-effective tool for monitoring individuals over time and can provide critical data on population size, survival rates and movement patterns.

However, this method is not universally applicable. Photo ID is most feasible in areas where water visibility is consistently good and individuals are accessible to snorkelers and divers. In regions with turbid waters or where sharks are difficult to approach without capture, the benefits of non-invasiveness may be negated. Furthermore, photo ID is particularly effective at aggregation sites, where individuals are reliably encountered across years. In areas lacking such aggregations, obtaining sufficient and repeated sightings of the same individuals may pose a challenge.

This method can fill significant gaps in current research by enabling long-term monitoring without the need for repeated capture and handling, which can be stressful and harmful to the sharks. By facilitating the identification of individual sharks based on their unique fin patterns, photo ID can improve our understanding of population dynamics, aid in the assessment of conservation efforts and ultimately contribute to the development of more effective management plans for vulnerable species. Although primarily employed for marine mammals (Bertulli et al., 2016; Langley et al., 2022; Marshall & Pierce, 2012; Urian et al., 2015), photo ID has also been applied to rays (Armstrong et al., 2019) and a variety of shark species, including the small-spotted catshark (*Scyliorhinus canicula* L. 1758; Navarro et al., 2018), whale shark (*Rhincodon typus* Smith 1828; McKinney et al., 2017), sharptooth lemon shark (*Negaprion acutidens* Rüppell 1837; Buray et al., 2009), epaulette sharks (*Hemiscyllium ocellatum* Bonnaterre 1788; Lonati et al., 2024), white shark (*Carcharodon carcharias* L. 1758; Gubili et al., 2009) and Atlantic nurse shark (*Ginglymostoma cirratum* Bonnaterre 1788; Kohler et al., 2023). As such, this method allows for the identification of previously identified individuals, therefore facilitating mid- and long-term research on known populations (Gubili et al., 2009). Photo ID was first used on sharks in the 1970s (Myrberg & Gruber, 1974), and since then, it has been employed on various elasmobranch species to replace capture-mark-recapture approaches for estimating features of population demographics (Andrzejaczek et al., 2016; Gore et al., 2016; McKinney et al., 2017) and geographic distribution patterns (Araujo et al., 2017; Armstrong et al., 2019; Marshall & Pierce, 2012; Rowat et al., 2007). Collecting photographic data is relatively simple and can involve the general public, especially divers who already own photography equipment. The opportunity to participate in shark research by providing data in the form of photographs may encourage divers to become citizen scientists (Davies et al., 2012; Marshall & Pierce, 2012; Vianna et al., 2014).

The blacktip reef shark (*Carcharhinus melanopterus* Quoy & Gaimard 1824), characterized by its distinctive black-tipped fins, serves as an ideal model for expanding the application of photo ID in elasmobranch research. This medium-sized shark species is commonly found in reef, mangrove and shallow inshore waters throughout the Indo-Pacific region (Bonfil & Abdallah, 2004; Stevens, 1984; Thompson & Springer, 1965). However, despite its widespread presence in the Indo-Pacific, populations have declined significantly due to overfishing and habitat degradation (Graham et al., 2010; MacNeil et al., 2020; Simpfendorfer et al., 2023). Consequently, this CITES-listed species is now classified as ‘vulnerable’ on the International Union for Conservation of Nature (IUCN) Red List (Simpfendorfer et al., 2020). The body and fin pigmentation variations in *C. melanopterus* have been previously used for identifying individuals (Mourier et al., 2012). However, fin shape can change throughout ontogeny (e.g., Fu et al., 2016; but see Irschick & Hammerschlag, 2015), and neonatal *C. melanopterus* show pronounced allometric growth (Weideli et al., 2019). These allometric changes in fin size may result in variations in the pattern on the dorsal fin. The skin pigmentation of some species has also been demonstrated to change over time and can respond to various factors, including melanism, induced by ontogenetic, physiological or environmental changes. For instance, evidence of ontogenetic pigmentation changes on Indo-Pacific leopard sharks (*Stegostoma tigrinum* Forster 1781) has been documented (Dahl et al., 2019; Lonati et al., 2024). *C. melanopterus* is one of the key species found in French Polynesia, where its populations have been under protection since 2006 (Séguigne et al., 2023). The establishment of a complete shark sanctuary throughout the entire French Polynesia Exclusive Economic Zone in 2012 (Séguigne et al., 2023; Ward-Paige, 2017) offers protection from fishing pressure and provides a unique opportunity for research. Importantly, the good visibility of lagoon and reef waters, combined with frequent human–shark interactions, makes French Polynesia particularly suitable for applying photo ID approaches. The popularity of water-based tourism in French Polynesia, such as recreational scuba diving and snorkelling (Clua, 2018), coupled with the rise of elasmobranch tourism, offers a fertile ground for employing citizen science in photo ID research. The Polynesian Shark Observatory (ORP) network has demonstrated the effectiveness of involving citizen scientists, recording over 13,000 observations of sharks and rays, including rare specimens (Séguigne et al., 2023). Moreover, a long-term study yielded preliminary insights into the population structure and distribution of manta rays (*Mobula alfredi* Krefft 1868; *Mobula birostris* Walbaum 1792) using data collected by citizen scientists (Carpentier et al., 2019). Specifically for *C. melanopterus*, involving the general public in photo ID research could yield extensive, cost-effective data collection, thus improving our ability to monitor this species and its behaviour and potentially providing a model for broader elasmobranch conservation efforts.

The primary objective of this study was to determine whether the dorsal fin of *C. melanopterus* can serve as a reliable photo ID feature while minimizing potential biases in the field such as assuming symmetry between fin sides or expecting pattern changes as individuals grow. By assessing the stability and symmetry of these fin patterns, this study aims to establish a reliable method for photo ID in *C. melanopterus*. It is hypothesized that the blacktip pattern is unique to every individual in the population, is asymmetrical between left and right sides and does not change over time. This study was done using a photo ID catalogue comprising 928 individuals and builds on the previous findings where individuals were successfully identified using photographs that were taken 10 years apart (Mourier et al., 2012). As such, it sets a precedent for similar approaches in other elasmobranch species and offers a valuable tool for ecological and conservation research.

2 | MATERIALS AND METHODS

2.1 | Ethics

The research protocols and data collection were approved by the James Cook University Animal Ethics Committee (A2089, A2394 and A2769) and the Ministère de la Promotion des Langues, de la Culture, de la Communication, et de l'Environnement of French Polynesia (Arrêté N°9524, N°5129 and N°11,491). This project was a collaboration between Centre de Recherches Insulaires et Observatoire de l'Environnement (CRIOBE) and the Physioshark Project, which allowed for data collection over seven parturition seasons (from late September to the end of February, 2016–2023) as part of the long-term fisheries-independent surveys carried out around Moorea, French Polynesia.

2.2 | Sampling location and data collection

Ten sites around the island of Moorea have been selected over the years as potential parturition areas (Bouyoucos et al., 2022) and for their abundance of newborn and juvenile *C. melanopterus*. The parturition period of *C. melanopterus* in this region occurs from September to January (Debaere et al., 2023), with newborns typically measuring between 330 mm for the smallest recorded (Bonham, 1960) and 666 mm for the largest recorded (Chin et al., 2013) in total length. For the purpose of this study, sharks that have an open umbilicus are referred to as newborns, whereas those with a fully healed umbilicus (i.e., completely closed skin) are referred to as juveniles (Debaere et al., 2023). As part of the long-term, fisheries-independent surveys (2013–present) in collaboration with CRIOBE and the Physioshark Project, each site was visited and sampled twice per month for at least 3 h at dusk (i.e., 1700–2000 h) between October and February, therefore resulting in each site being sampled 10 times per season.

Newborn and juvenile *C. melanopterus* were caught using gillnets (50 × 1.5 m, 5 cm mesh-size) set perpendicular to shore (Bouyoucos et al., 2022; Chin et al., 2015; Mourier & Planes, 2013). All sharks caught were tagged with coloured T-bars (Hallprint) or passive integrated transponder (PIT) tags (Biomark) to facilitate identification in case of recapture. Their morphometrics were recorded (i.e., total length in cm and mass in kg), and then each individual was photographed at a straight angle to minimize distortion of the fin and alongside a ruler for scale. The photographs were organized by sex, and each shark was assigned an ID starting with 'CM' for '*C. melanopterus*' followed by the five last digits of their respective T-bar and/or PIT tags. The entire catalogue comprised 928 unique individuals.

2.3 | Image processing

The distinguishing feature used to identify individual *C. melanopterus* is the 'dorsal-fin patch', which refers to the black pattern found on the dorsal fin (Figure 1). Although the full photographic catalogue contained 928 individuals, it was not feasible to include all the individuals in the analyses due to time, computational constraints and, most importantly, image quality. Many photographs taken before 2020 were excluded due to insufficient resolution, motion blur or the absence of key features such as a visible ruler for scaling or a flat, undistorted dorsal fin. Therefore, a systematic filtering process was implemented to retain only high-quality photographs where the dorsal fin was clearly visible, properly aligned and accompanied by a scale. This ensured the reliability and the consistency of the shape-based measurements. Rather than selecting individuals based on particular patterns or desired outcomes, we applied consistent quality-control criteria to all images and then randomly selected representative individuals from the remaining pool to ensure diversity in size, sex and fin pattern. Different sample sizes were used depending on the requirements of each specific analysis. For example, a sample of 18 individuals was used to examine dorsal-fin pattern variation and asymmetry. This sample size reflected the number of individuals for which both left and right sides (for asymmetry) or at least one high-quality image (for shape variation) were available after applying the aforementioned criteria. For the asymmetry analysis, three individuals were excluded due to the absence of right-side photographs, reducing the sample to 15.

For assessing changes over time, we focused on a subset of 13 individuals from the 64 sharks that were recaptured. The sample size was limited by the need for multiple high-quality photographs of the same individual across capture events, with consistent orientation, lighting and scale. Many recaptured sharks were excluded because their earlier or later images did not meet quality standards, particularly in terms of quality, visibility of the dorsal-fin patch or availability of scale. The final 13 individuals provided a robust dataset for assessing longitudinal changes without compromising analytical reliability. To ensure a consistent scale, the photographs were adjusted using the measurement tool in ImageJ (version 1.52). The marker pen tool and filling option in Paint 3D (version 6.23) were employed to digitally extract greyscale silhouettes of the dorsal-fin patch.

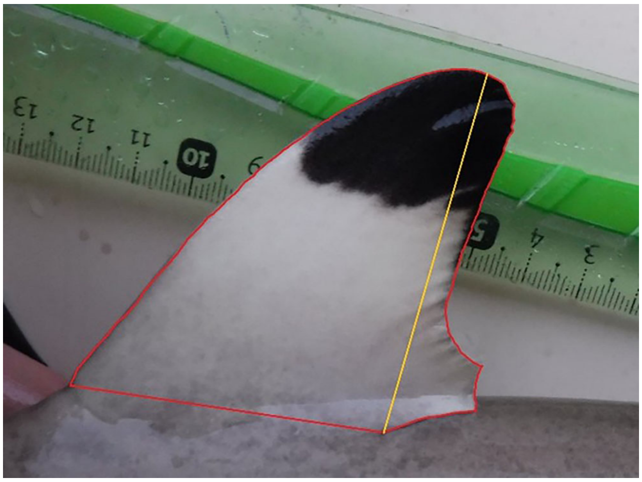


FIGURE 1 A dorsal fin (CM99336) used for area and length measurements. The dorsal-fin area was measured inside the red selection. The yellow line was used to measure the dorsal-fin length.

As a result of the filtering process, only photographs taken between 2020 and 2023 were retained, as they consistently met the quality standards. Images dating back to 2016 were excluded primarily due to lower resolution, blur or missing elements such as scale, which could compromise the analysis.

2.4 | Shape variation

A summary of the sample characteristics is presented in Table 1, detailing the sex, age, size, capture date and location of the individuals (see Bouyoucos et al., 2024 for a map of sampled locations). Each selected shark had only one left-side high-quality photograph included in the analysis to maintain consistency and reduce potential biases.

The choice to employ a Gower distance analysis as the initial step was driven by the need to accurately quantify the dissimilarities between individual sharks based on the pigmentation patterns of their dorsal fins. The Gower distance metric (Gower, 1971) is particularly well suited for analysing multidimensional datasets, such as the array of images depicting shark dorsal-fin patterns. Unlike traditional distance measures, the Gower distance can handle various types of data, including categorical, ordinal and numerical variables, making it versatile for the heterogenous dataset of this study. Moreover, the resulting values of the Gower distance range from 0 to 1, with values closer to 0 indicating higher resemblance and those closer to 1 indicating

TABLE 1 Samples used to measure shape variation in dorsal-fin patterns.

ID	Sex	Age	Size (PCL) in cm	Capture date	Location
CM00043	Female	Neonate	42.8	04/01/2023	Pihaena
CM00045	Female	Neonate	41.2	11/01/2023	Apaura
CM31903	Male	Neonate	42.4	26/10/2021	Tiki
CM31956	Male	Neonate	40.6	09/11/2020	Vaiare
CM31984	Male	Neonate	40	14/10/2020	Tiki
CM32146	Female	Neonate	41.4	04/10/2021	Paorea
CM32385	Female	Neonate	42.4	09/11/2020	Vaiare
CM45205	Male	Juvenile	46.4	23/01/2020	Paorea
CM99275	Male	NA	42.4	20/01/2022	Papetoai
CM99323	Male	Neonate	43.4	22/11/2021	Haapiti
CM99344	Male	Neonate	39	03/01/2022	Haapiti
CM99346	Female	Juvenile	44.4	10/11/2021	Maharepa
CM99638	Male	Juvenile	45	22/12/2022	Maharepa
CM99642	Female	Juvenile	60.4	08/12/2022	Maharepa
CM99643	Female	Neonate	38.8	23/12/2022	Haapiti
CM99646	Male	Neonate	40.8	23/12/2022	Haapiti
CM99722	Female	Neonate	38.2	22/11/2022	Haapiti
CM99983	Male	Juvenile	38.8	10/02/2023	Paorea

Abbreviation: PCL, pre-caudal length.

greater dissimilarity, providing a comprehensive understanding of the similarity relationships within the dataset (Bello et al., 2021).

Python 3.11 and relevant libraries, such as *numpy*, *pandas*, *matplotlib* and *pyplot*, were used to compute the Gower distance matrix from the imported shark dorsal-fin silhouettes. This initial step allowed for accurately quantifying the shape variations present in the black dorsal-fin patches of individual sharks. An elliptical Fourier analysis (EFA) was applied directly to the silhouettes of the dorsal-fin images to capture the shape variation in the black dorsal-fin patches (as per Fu et al., 2016). Ultimately, conducting a principal component analysis (PCA) on the EFA results simplified and visually represented the intricate data in a reduced dimensional format, thereby preserving crucial information for the analyses.

2.5 | Asymmetry

To assess asymmetry, the same analytical method used for shape variation was applied: EFA and PCA. Left and right dorsal-fin patches were superimposed for each individual. From the initial sample of 18 sharks selected for shape variation, only 15 could be included in the asymmetry analysis due to missing right-side photographs for three individuals (CM99323, CM99344 and CM9346). These exclusions were based solely on image availability and quality, following the same strict quality-control criteria as described above and not on any visual inspection or expected outcome of the asymmetry.

2.6 | Changes over time

To observe changes in dorsal-fin patterns over time, a subset of 13 sharks was selected from the 64 individuals that had been recaptured. Although 64 recaptured individuals were available, the vast majority could not be included due to at least one of the necessary images failing to meet quality standards. These criteria included the presence of blur, distortion, inconsistent angles, lack of visible scale or poor lighting. Only sharks with at least two left-side, high-quality and properly scaled photographs – taken at different capture events – were included in the final analysis. This subset was chosen to ensure that any observed changes in fin morphology or pigmentation were genuine and not artefacts of poor imaging. In addition, two of these sharks were captured and photographed a third time, resulting in a total of 28 photographs. The time elapsed between the captures varied among individuals, ranging from 2 weeks to 9 months. A summary of the sample characteristics is presented in Table 2, detailing the sex, age, size, capture date and location of the individuals.

Using ImageJ, the photographs were scaled, and measurements were obtained for the dorsal-fin area, the dorsal-fin length and the blacktip area. The dorsal-fin length was measured as the distance from the tip of the fin to the insertion of the dorsal fin. For the dorsal-fin area, all parts above an imaginary straight line at the base of the dorsal fin were considered (Figure 1). The scaling metric used was the pre-caudal length (PCL; see Irschick & Hammerschlag, 2015). The measurements were done by the same person.

Using Rstudio 4.3.1 (packages used: *statmod*, *lme4*, *ggplot2*, *MuMIn*) (RStudio Team, 2020), all variables were log transformed, and then dorsal-fin length and dorsal-fin area were regressed against PCL values using linear regression. Additionally, dorsal-fin length was regressed against dorsal-fin area. All these results are presented using scatter plots (Supplementary Information S1). Based on the idea that fin length and fin area both grow proportionally to the PCL, the blacktip area was also regressed against the dorsal-fin area.

3 | RESULTS

3.1 | Shape variation

The PCA from the EFA resulted in four harmonics, four coefficients (A, B, C and D) and therefore 16 variables for each of the principal

TABLE 2 Samples used to measure changes over time in dorsal-fin patterns (*N* = neonate; J = juvenile; PCL = pre-caudal length in cm).

ID	Sex	Age_1	Age_2	Age_3	PCL_1	PCL_2	PCL_3	$Date_1$	$Date_2$	$Date_3$	Location
CM31885	F	N	N	NA	45	45.8	NA	05/10/2021	26/10/2021	NA	Tiki
CM99331	M	N	N	NA	40.8	43.6	NA	26/11/2021	07/01/2022	NA	Vaiare
CM99336	M	N	J	NA	43.8	44.6	NA	16/11/2021	14/12/2021	NA	Paorea
CM99337	M	J	J	NA	41	43.6	NA	16/11/2021	30/11/2021	NA	Paorea
CM99338	F	N	J	NA	41	44.2	NA	25/11/2021	06/01/2022	NA	Papetoai
CM99367	F	N	NA	NA	41.2	46.8	NA	30/11/2021	20/02/2022	NA	Paorea
CM99437	F	N	J	J	43	43.6	43.8	14/12/2021	11/01/2022	08/02/2022	Paorea
CM99454	M	N	J	J	42.6	42.8	44	30/11/2021	28/12/2021	25/01/2022	Paorea
CM99475	M	NA	NA	NA	44.4	45.4	NA	08/02/2022	22/02/2022	NA	Paorea
CM99623	M	N	J	NA	41	41	NA	16/12/2022	10/01/2023	NA	Vaiare
CM99659	F	N	J	NA	39.6	40	NA	28/11/2022	16/12/2022	NA	Vaiare
CM99678	F	N	J	NA	42.6	43.6	NA	23/12/2022	25/01/2023	NA	Haapiti
CM99788	M	N	N	J	39.4	39.6	44.2	02/11/2022	15/11/2022	15/02/2023	Vaiare

TABLE 3 Principal component analysis (PCA) result of four harmonics from elliptical Fourier analysis (EFA) that described the shape of the black tip among a sample of sharks.

	PC1	PC2	PC3	PC4
% of variation explained	94.85	1.95	1.23	0.96
A1	14.397	−0.375	0.152	−0.124
A2	−0.760	1.199	0.128	−0.274
A3	0.046	0.117	0.065	−0.128
A4	−1.518	0.019	0.015	−0.208
B1	3.128	0.365	−0.009	1.113
B2	−1.977	−0.344	0.987	−0.136
B3	−2.337	−1.172	−0.374	0.022
B4	−1.527	0.013	0.011	−0.208
C1	0.906	0.581	0.200	−0.427
C2	−3.439	−0.720	0.802	0.353
C3	−1.476	−0.577	−0.842	0.341
C4	−1.525	0.015	0.011	−0.208
D1	0.438	−0.333	−0.378	−0.352
D2	−2.038	0.735	0.020	0.681
D3	−0.792	0.457	−0.799	−0.189
D4	−1.524	0.021	0.012	−0.212

components (Table 3). Because the harmonics resulting from the EFA are difficult to understand or to compare to concrete morphological measurements, the results were represented on a scatter plot projecting the dorsal-fin patches on principal component 1 (PC1) (*x*-axis) and principal component 2 (PC2) (*y*-axis) (Figure 2; as per Fu et al., 2016). Each point on the scatter plot represents the multidimensional information of a photograph, with the silhouettes of the dorsal-fin patches included alongside their corresponding points. The first two principal components explain most of the information: PC1 explains 94.85%, and PC2 explains 1.95%, accounting for a total of 96.8% of the total shape variation.

The first principal component appears to represent the width of the dorsal-fin patch. Individuals with high PC1 values have wider or more elongated patches, whereas individuals with lower PC1 values tend to have tighter patches. PC2 shows less variation, with most individuals below 0.50. However, individuals with higher PC2 values tend to have taller patches (i.e., so potentially taller dorsal fins), whereas, individuals with lower PC2 values tend to have shorter patches (i.e., potentially shorter dorsal fins).

The Gower distance coefficients describe the analogy between a variety of shapes for the dorsal-fin patches (Figure 3). In summary, the individuals with higher values have very different dorsal-fin patches, whereas, those with values closer to zero have more similar patches.

3.2 | Asymmetry

Similar to the shape variation analysis, the PCA from the EFA resulted in four harmonics, four coefficients (A, B, C and D) and therefore 16 variables for each of the principal components (Table 4). To facilitate visual analysis of left and right images of the same shark, each individual is assigned a shape and colour on a scatter plot showing the projection of left- and right-sided photographs of 15 different individuals on PC1 versus PC2 obtained from the EFA (Figure 4a). The asymmetry between both the left and right silhouettes of the dorsal-fin patches from the 15 sharks considered in this analysis is easily visible (Figure 4b).

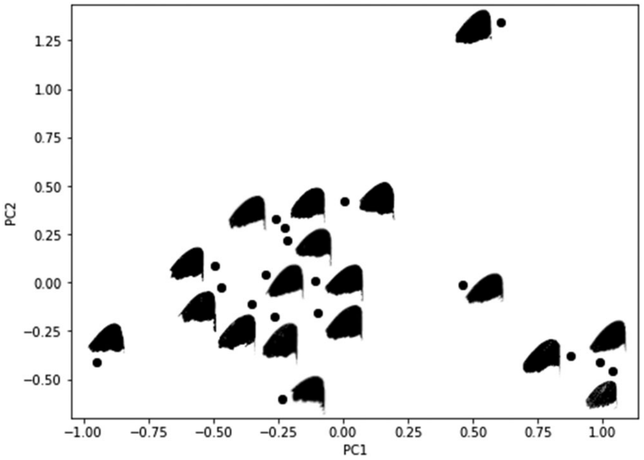


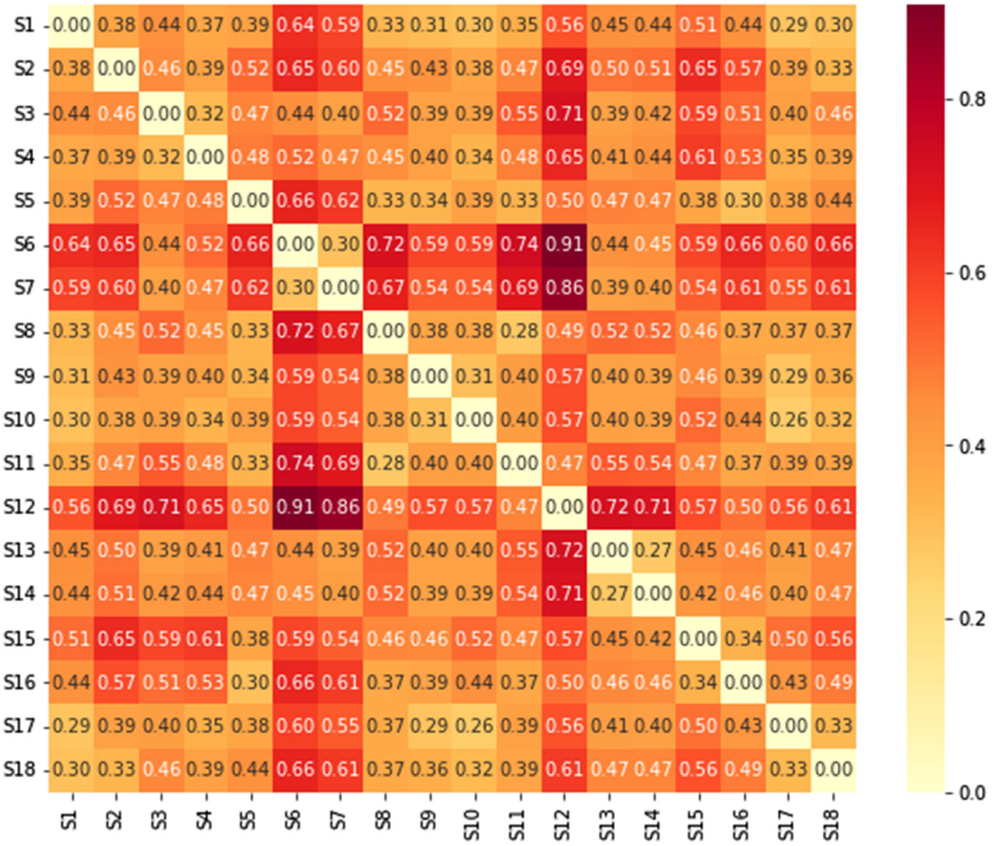
FIGURE 2 Projection of the left-side dorsal-fin patches on PC1 (*x*-axis) and PC2 (*y*-axis) from the principal component analysis (PCA) based on the elliptical Fourier analysis (EFA). The silhouettes of dorsal-fin patches are included on the scatter plot to demonstrate the variety in shapes among the sharks sampled.

3.3 | Changes over time

When conducting the temporal analysis, dorsal-fin length and dorsal-fin area both showed a positive relationship with PCL, as well as with each other (Data S1). The log-transformed blacktip area was regressed against the log-transformed dorsal-fin area (Figure 5). With a value of 1.04 ($r^2 = 0.906$), the slope describes a positive relationship that is almost isometric. As an example, Figure 6 compares dorsal-fin patterns separated by intervals of, respectively, 9 months, 41 days and 3 months.

4 | DISCUSSION

The purpose of this study was to demonstrate that photo ID can be used to identify *C. melanopterus* individuals using unique physical features, which could lead to the creation of a photo ID catalogue for this species. Despite a relatively small sample size of 18 individuals used in this analysis, drawn from a comprehensive catalogue containing 928 individuals, this study successfully demonstrated individual differences in dorsal-fin patterns, revealing shape variations. These findings contribute to the growing body of research supporting photo ID as a viable, non-invasive alternative to tagging methods for monitoring shark populations. This approach facilitates the study of population



	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18
S1	0.00	0.38	0.44	0.37	0.39	0.64	0.59	0.33	0.31	0.30	0.35	0.56	0.45	0.44	0.51	0.44	0.29	0.30
S2	0.38	0.00	0.46	0.39	0.52	0.65	0.60	0.45	0.43	0.38	0.47	0.69	0.50	0.51	0.65	0.57	0.39	0.33
S3	0.44	0.46	0.00	0.32	0.47	0.44	0.40	0.52	0.39	0.39	0.55	0.71	0.39	0.42	0.59	0.51	0.40	0.46
S4	0.37	0.39	0.32	0.00	0.48	0.52	0.47	0.45	0.40	0.34	0.48	0.65	0.41	0.44	0.61	0.53	0.35	0.39
S5	0.39	0.52	0.47	0.48	0.00	0.66	0.62	0.33	0.34	0.39	0.33	0.50	0.47	0.47	0.38	0.30	0.38	0.44
S6	0.64	0.65	0.44	0.52	0.66	0.00	0.30	0.72	0.59	0.59	0.74	0.91	0.44	0.45	0.59	0.66	0.60	0.66
S7	0.59	0.60	0.40	0.47	0.62	0.30	0.00	0.67	0.54	0.54	0.69	0.86	0.39	0.40	0.54	0.61	0.55	0.61
S8	0.33	0.45	0.52	0.45	0.33	0.72	0.67	0.00	0.38	0.38	0.28	0.49	0.52	0.52	0.46	0.37	0.37	0.37
S9	0.31	0.43	0.39	0.40	0.34	0.59	0.54	0.38	0.00	0.31	0.40	0.57	0.40	0.39	0.46	0.39	0.29	0.36
S10	0.30	0.38	0.39	0.34	0.39	0.59	0.54	0.38	0.31	0.00	0.40	0.57	0.40	0.39	0.52	0.44	0.26	0.32
S11	0.35	0.47	0.55	0.48	0.33	0.74	0.69	0.28	0.40	0.40	0.00	0.47	0.55	0.54	0.47	0.37	0.39	0.39
S12	0.56	0.69	0.71	0.65	0.50	0.91	0.86	0.49	0.57	0.57	0.47	0.00	0.72	0.71	0.57	0.50	0.56	0.61
S13	0.45	0.50	0.39	0.41	0.47	0.44	0.39	0.52	0.40	0.40	0.55	0.72	0.00	0.27	0.45	0.46	0.41	0.47
S14	0.44	0.51	0.42	0.44	0.47	0.45	0.40	0.52	0.39	0.39	0.54	0.71	0.27	0.00	0.42	0.46	0.40	0.47
S15	0.51	0.65	0.59	0.61	0.38	0.59	0.54	0.46	0.46	0.52	0.47	0.57	0.45	0.42	0.00	0.34	0.50	0.56
S16	0.44	0.57	0.51	0.53	0.30	0.66	0.61	0.37	0.39	0.44	0.37	0.50	0.46	0.46	0.34	0.00	0.43	0.49
S17	0.29	0.39	0.40	0.35	0.38	0.60	0.55	0.37	0.29	0.26	0.39	0.56	0.41	0.40	0.50	0.43	0.00	0.33
S18	0.30	0.33	0.46	0.39	0.44	0.66	0.61	0.37	0.36	0.32	0.39	0.61	0.47	0.47	0.56	0.49	0.33	0.00

FIGURE 3 Results from the Gower distances matrix on a sample of 18 dorsal-fin patches.

TABLE 4 Principal component analysis (PCA) results of four harmonics from the elliptical Fourier analysis (EFA) describing the shape of left- and right sides of the dorsal-fin patches from a sample of sharks.

	PC1	PC2	PC3	PC4
% variation explained	93.83	2.48	1.44	0.92
A1	18.492	−0.614	−0.182	−0.148
A2	−1.247	1.832	−0.036	−0.461
A3	0.043	0.272	0.033	−0.178
A4	−2.135	0.182	0.090	−0.330
B1	4.215	1.153	−0.276	1.130
B2	−2.622	−0.634	−1.206	−0.230
B3	−2.893	−1.435	0.577	0.012
B4	−2.151	0.180	0.093	−0.331
C1	0.838	0.523	−0.469	−0.616
C2	−4.283	−1.161	−1.262	0.492
C3	−1.598	−0.736	0.857	0.706
C4	−2.144	0.180	0.097	−0.330
D1	0.448	−0.858	0.566	−0.458
D2	−2.289	0.679	−0.245	0.840
D3	−0.530	0.253	1.268	0.242
D4	−2.146	0.185	0.095	−0.337

structure and dynamics without the need for physical recapture or scanner-based identification for previously tagged animals (Anderson & Goldman, 1996).

When starting a photo ID catalogue, it is essential to obtain photographs of both the left and right sides of the dorsal fin for each individual. This approach ensures that the catalogue can effectively accommodate future submissions of photographs from either side, maximizing the chances of accurate matching. The findings on the asymmetry of pigmentation patterns, akin to those observed in *C. carcharias* (Domeier & Nasby-Lucas, 2007), are crucial for accurate photo ID, as photographs taken from the left side cannot be matched with those taken from the right side. Despite this limitation, using dorsal-fin patterns is advantageous because it allows researchers to easily discern whether a photo depicts the right or left side of the dorsal fin, minimizing confusion during initial categorization. This result emphasizes the importance of ensuring that comparisons are made between photos taken from the same side of the individual, which is particularly relevant for citizen science initiatives. Additionally, with only a record of the left side of a shark, when a photograph of the right side of the same shark is received later, it may mistakenly be identified as a different individual. Because the asymmetry prevents us from easily matching the two sides, there is currently no method to confidently associate the right side with the previously recorded left side, potentially leading to duplicate entries in the identification catalogue.

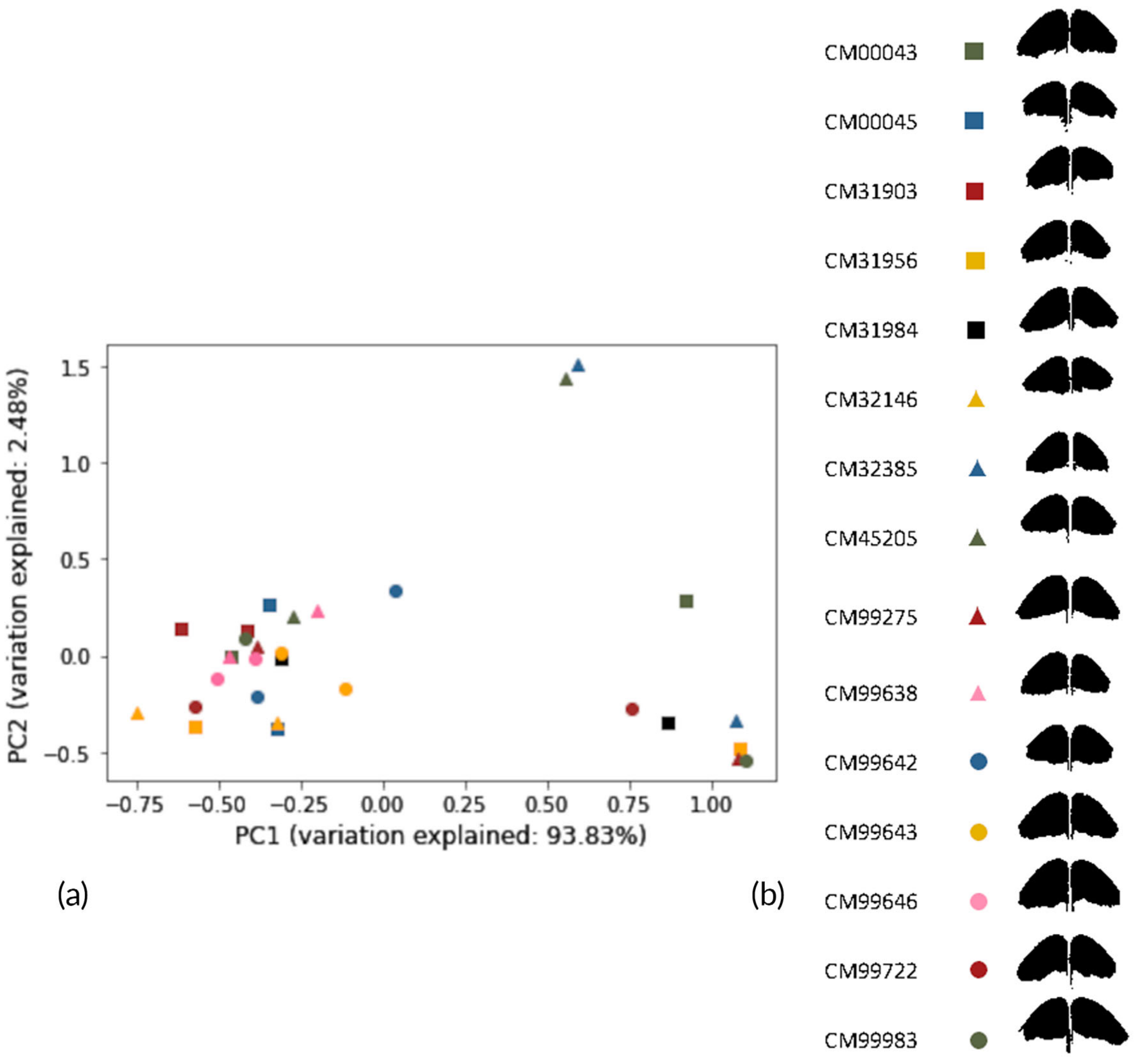


FIGURE 4 (a) Projection of 15 dorsal fins' left- and right-side images on PC1 (*x*-axis) and PC2 (*y*-axis) from the principal component analysis (PCA) based on the elliptical Fourier analysis (EFA). Left and right sides of the same dorsal fin match in shape and colour. (b) Left- and right-side silhouettes of dorsal fins.

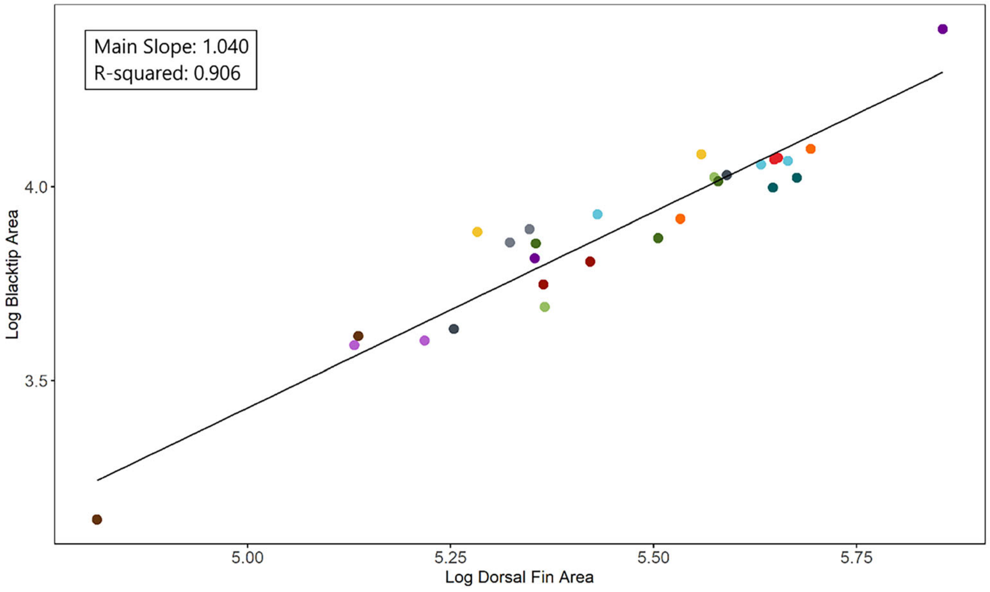


FIGURE 5 A plot of log-transformed values of dorsal-fin area (*x*-axis) on log-transformed blacktip area (*y*-axis). The 13 sharks considered in this analysis have been captured at least twice. Every shark is depicted in a different colour on the plot.

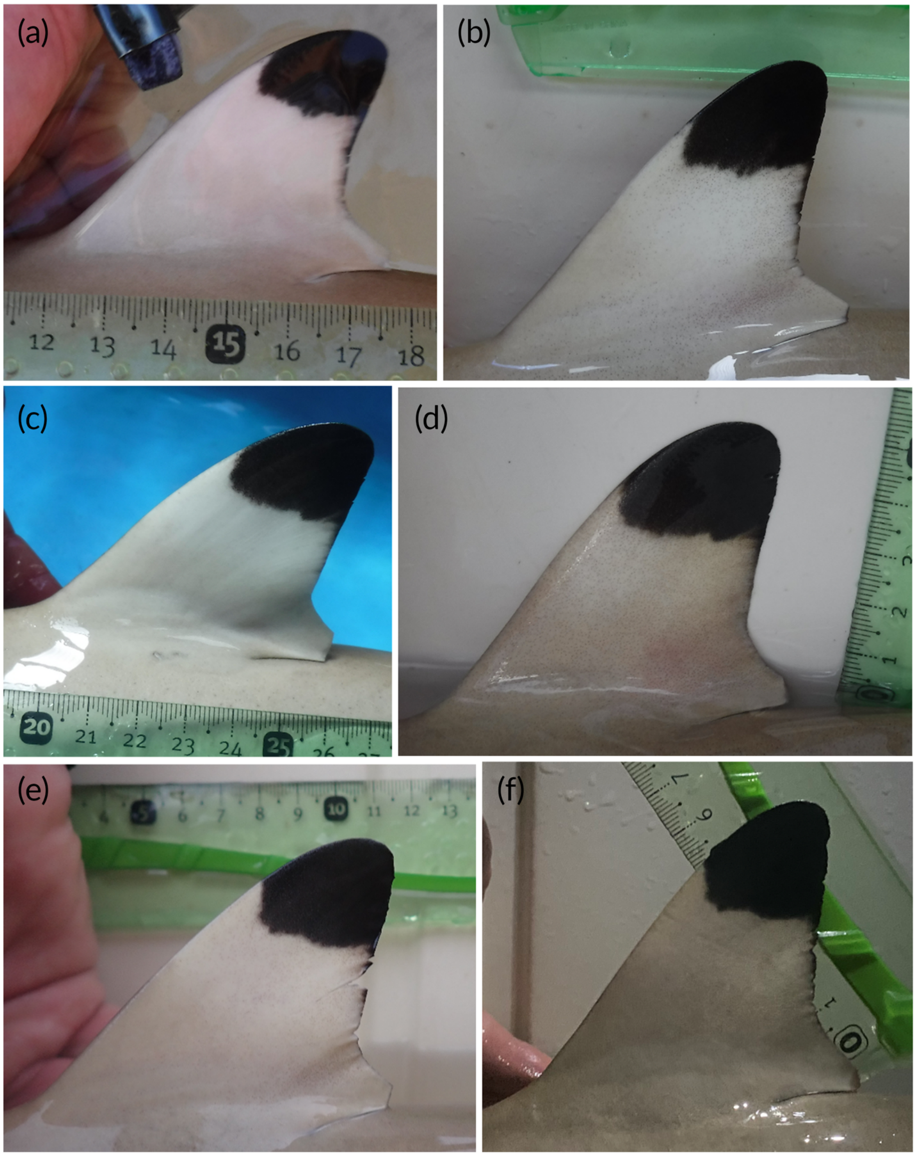


FIGURE 6 Comparison of the dorsal-fin patterns of CM31885 with an interval of 9 months (a and b), of CM99338 with an interval of 41 days (c and d), of CM99778 with an interval of 3 months (e and f).

The proportional growth of the dorsal-fin area and length to the body (PCL), however, as evidenced by the analysis, supports the long-term reliability of dorsal-fin patterns for identification, despite potential changes from predation or injury. The analysis indicates that, even throughout ontogeny, the changes in dorsal-fin shape exhibited by neonatal and juvenile sharks are not significant enough to alter the dorsal-fin pattern. These results support the previous findings of Irschick and Hammerschlag (2015) in their research on tiger sharks (*Galeocerdo cuvier* Péron & Lesueur 1822), bull sharks (*Carcharhinus leucas* Valenciennes 1839), blacktip sharks (*Carcharhinus limbatus* Valenciennes 1839) and nurse sharks (*G. cirratum*), which demonstrated that dorsal-fin dimensions exhibit isometric relationships with the PCL. Previous studies have demonstrated that the pattern of the blacktip on the dorsal fin could be consistent over at least 10 years in adult sharks (Mourier et al., 2012). However, it was uncertain whether this stability was also present during the early stages characterized by rapid growth rates and morphological changes. On the contrary, the largest interval of time between recaptures in this study is only 9 months, and *C. melanopterus* are known to mature after 4–8 years (Chin et al., 2013). Although the results of this study provide valuable insights into the stability of dorsal-fin patterns during early life stages, future studies should aim to explore the changes in dorsal-fin patterns over longer time frames, particularly as sharks approach sexual maturity. Gaining more information on the development of these patterns across different life stages would be crucial for enhancing the accuracy of long-term photo ID efforts, especially in juvenile and subadult *C. melanopterus*.

Literature suggests that other factors, such as predation, can also contribute to changes in dorsal-fin shape among young sharks. Neonatal and juvenile sharks are particularly vulnerable to predation from larger conspecifics and other shark species (Chin et al., 2015); yet, their capacity for regeneration (Chin et al., 2015; Debaere et al., 2025) suggests that dorsal-fin patterns remain a reliable identification feature over time. However, if a portion of the dorsal fin is removed due to injury or predation, the identification process may be compromised. It would be interesting to incorporate the caudal fin into the photo ID catalogue as a second physical feature to ensure the accuracy of identification matches. Nevertheless, there is no support that the pigmentation pattern or patch on the caudal fin would remain consistent over time, especially if a section of the fin were damaged or lost. However, the dorsal fin remains better suited due to its relative stability when the animal is swimming. Given the potential applications of these findings for citizen science research, it may be impractical to rely on the caudal fin as a feature, as the constant undulations may lead to increased distortion in the photographs (Song et al., 2021).

The broader implications of this study are substantial, as expanding the photo ID technique to track individuals from neonates to adults can provide invaluable insights into the effectiveness of French Polynesia as a shark sanctuary and broader shark conservation efforts. This approach may prove key to increasing our understanding of crucial aspects such as breeding grounds, gestation periods and parturition sites while also addressing fundamental questions about shark movement patterns. Moreover, the accessibility of photography encourages public participation in research, thereby enhancing citizen science initiatives in shark conservation (Davies et al., 2012; Séguigne et al., 2023).

In the realm of marine animal identification, advancements in artificial intelligence (AI) and deep learning present promising opportunities. Recent research in related fields, spanning various species, including undulate skates (*Raja undulata* Lacepède 1802; Gómez-Vargas et al., 2023), multiple cetaceans (Blount et al., 2022; Maglietta et al., 2023; Patton et al., 2023), epaulette sharks (*H. ocellatum*; Lonati et al., 2024) and *C. carcharias* (Hughes & Burghardt, 2017), has showcased the efficacy of these methodologies. These studies utilized deep learning-based approaches to analyse specific features captured in images, such as the outlines of dorsal fins (Hughes & Burghardt, 2017; Maglietta et al., 2023; Patton et al., 2023), caudal fins (Blount et al., 2022), pigmentation patterns (Gómez-Vargas et al., 2023; Lonati et al., 2024) or distinct markings like scars on their bodies (Blount et al., 2022; Maglietta et al., 2023). These AI models not only demonstrate high accuracy in individual identification but also showcase adaptability to new subjects with limited data, employing techniques such as few-shot learning and transfer learning (Gómez-Vargas et al., 2023; Patton et al., 2023).

In the context of *C. melanopterus*, employing AI and deep learning methodologies could enable swift and accurate identification of individuals from photographic data, streamlining population monitoring, behavioural investigations and species conservation initiatives. Moreover, leveraging AI has the potential to automate and accelerate the identification process, thereby alleviating the workload for researchers and organizations engaged in shark population monitoring. Integrating these technological innovations into research and management frameworks can enhance comprehension and capacity to safeguard these pivotal components of marine ecosystems.

However, it is important to acknowledge the potential challenges that can arise from citizen science data. Photographs taken by the public may be of lower quality compared to those taken by professionals, or may be captured from incorrect angles, leading to distorted data for analysis (Davies et al., 2012). Additionally, the choice of dive and snorkelling sites by participants may be influenced by the abundance of fauna or site accessibility, resulting in biases and certain sites being overrepresented in terms of data (Huveneers et al., 2009; Séguigne et al., 2023). Although these challenges exist, the benefits of public involvement in shark research are significant, including increased awareness and potential for self-funded conservation efforts (Hussey et al., 2013; Silvertown, 2009).

This study highlights the potential of using dorsal-fin patterns for shark identification, particularly in the context of neonatal and juvenile *C. melanopterus*. Although the findings demonstrate the feasibility of photo ID methods based on images captured during controlled conditions, such as when individuals are captured and precisely positioned for photography, the reliability of this approach under natural and varied conditions remains to be fully assessed. Future research should focus on evaluating the reliability and applicability of photo ID techniques for sharks in different environments and life stages, including individuals photographed in situ and under less-controlled conditions. Moreover, this study underscores the importance of long-term monitoring and data collection to better understand the stability of dorsal-fin patterns as sharks grow and develop. The analysis of recaptured individuals provides valuable insights, but the limited number of recaptures and short time intervals between captures highlight the need for more extensive and prolonged monitoring efforts to assess the long-term stability of shark identification using dorsal-fin patterns. The integration of AI for photo matching and the inclusion of caudal-fin photographs offer potential for improving the effectiveness of photo ID methods (Hughes & Burghardt, 2017; Maglietta et al., 2023; Patton et al., 2023). However, further research is needed to validate and optimize these approaches. Ultimately, this research contributes to the growing knowledge on shark population dynamics, providing valuable insights for conservation strategies and policymaking in marine ecosystems. By acknowledging the limitations of this study and emphasizing the need for continued research, the advancement of effective shark conservation measures can be ensured.

AUTHOR CONTRIBUTIONS

Conceptualization: L.A.M.G. Lionnet, S.F. Debaere, J.L. Rummer. Investigation: L.A.M.G. Lionnet, S.F. Debaere, H. Heuls, J. Mourier, J.L. Rummer. Data curation & formal analysis: L.A.M.G. Lionnet. Resources: S. Planes, J.L. Rummer. Writing – original draft: L.A.M.G. Lionnet. Writing – reviewing and editing: all authors.

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SUPPORTING INFORMATION

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

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