Morphological And Computational Profiling of Shark Dermal Denticles

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Abstract:
Shark dermal denticles are specialized skin structures with important morphological, hydrodynamic and biomimetic significance. Placoid scales (dermal denticles) in sharks exhibit a specialized microstructure that significantly reduces hydrodynamic drag and inhibits biofouling. This study combines microscopic morphometric analysis with computational intelligence to characterize and classify shark dermal denticles. Skin samples of Scoliodon sp. were processed using KOH treatment and examined microscopically. A preliminary morphological analysis of a placoid scale imaged under a light microscope, revealing its characteristic ridged surface and tapered cusps. Quantitative image analysis was conducted using MATLAB and ImageJ to extract key morphometric parameters, including scale length, width, aspect ratio, and edge curvature while Support Vector Machine (SVM), Random Forest and Convolutional Neural Network (CNN) approaches were used for classification. The observed features underscore the functional adaptations of these scales for improved locomotion in aquatic environments. To enhance the analytical depth and scalability of this research, computational intelligence techniques—particularly machine learning—are being integrated into the profiling process. Denticle dimensions and shape descriptors were obtained. The denticles showed a mean length of 1.2 mm, width of 0.6 mm and aspect ratio of 2.0. The CNN achieved 92.5% accuracy, with precision, recall and F1-score of 91.8%, 93.2% and 92.5%, respectively. Grad-CAM analysis highlighted denticle margins and striated surface regions as important classification features. The findings demonstrate the potential of computational intelligence for rapid and quantitative profiling of shark dermal denticles and provide a foundation for future applications in biodiversity assessment and shark-skin-inspired biomimetic surface design.

Keywords: Shark; dermal denticles, machine learning; convolutional neural network; Grad-CAM; biomimetics; hydrodynamics.

Introduction

Shark skin is characterized by abundant tooth-like structures known as dermal denticles or placoid scales. These arrangements are embedded within the dermal tissue and project toward the outer surface, producing a highly organized and functionally specialized skin architecture. Recent morphological investigations have demonstrated that dermal denticles vary substantially in size, shape, three-dimensional structure and surface roughness according to body region and shark species [1,2].

Placoid scales differ basically from the simple scales of many teleost fishes. Each denticle possesses a basal region embedded within the skin and an exposed crown that pays to the characteristic texture of shark skin. The crown may contain ridges or riblet-like structures, while the overall denticle morphology varies according to its anatomical position. Such spatial variation is increasingly recognized as an important component of shark functional morphology rather than merely a taxonomic characteristic [1, 2].

The surface architecture of shark skin has garnered considerable attention due of its relationship with fluid flow. Early biomimetic studies revealed that riblet-like surface structures could alter near-wall flow and reduce drag under particular hydrodynamic conditions [3]. Subsequent investigations have shown that denticle geometry, orientation, spacing, height and flow conditions influence the hydrodynamic response of shark-inspired surfaces [4–7]. Importantly, the relationship between shark skin and drag reduction is more complex than a simple assumption that all denticles reduce drag; experimental and computational studies indicate that denticle morphology and flow regime strongly influence the resulting forces [6]. Dermal denticles also perform functions beyond hydrodynamics. Recent reviews have highlighted their possible contributions to antifouling, protection, aerodynamics, bioluminescence-related functions and other multifunctional adaptations [2].

Consequently, characterization of denticle morphology has become increasingly important for understanding both shark biology and the development of multifunctional bioinspired surfaces. The considerable diversity of dermal denticles presents a challenge for morphological classification. Denticles can differ in crown geometry, ridge organization, cusp structure, orientation, surface roughness and three-dimensional architecture. For example, the demonstrated substantial variation in denticle structure and surface roughness around the body of sharks using three-dimensional imaging and surface-profiling approaches. Similarly, subsequent studies have identified additional patterns of denticle diversity in specific anatomical regions [1,2].

Traditional morphological characterization generally depends on microscopy, manual measurements and expert interpretation. Although these approaches remain fundamental for biological investigations, they can become time-consuming when large image datasets are generated. Digital image analysis provides an opportunity to quantify morphological traits more systematically, including dimensions, shape descriptors, edge characteristics and surface-texture patterns. The rapid development of artificial intelligence (AI) and machine learning (ML) has created new possibilities for automated biological image analysis. Machine-learning algorithms can identify patterns within multidimensional datasets, whereas deep-learning approaches can learn hierarchical representations directly from images [7]. Convolutional neural networks (CNNs), in particular, have demonstrated strong performance in image classification and feature extraction because successive convolutional layers can learn increasingly complex visual representations [7]. Classical machine-learning approaches such as Support Vector Machines (SVMs) and Random Forests are also widely used for classification problems involving structured numerical features [8,9]. SVMs provide a flexible classification framework based on decision boundaries in feature space, whereas Random Forests combine multiple decision trees and can provide robust classification in datasets containing multiple explanatory variables [8,9].

For biological image analysis, however, a major advantage of CNNs is their capacity to learn image features without requiring every morphological characteristic to be manually defined. Deep-learning models can learn hierarchical representations ranging from edges and contours to more complex textures and structural patterns [9]. This makes CNN-based analysis particularly relevant to microscopic images of dermal denticles, where biologically meaningful features may occur at multiple spatial scales.

Interpretability is an important consideration when applying AI to biological research. Although high classification accuracy may indicate successful prediction, researchers also need to determine whether a model is responding to biologically meaningful structures. Grad-CAM provides a visualization approach that highlights image regions contributing to a CNN's prediction and can therefore assist in interpreting model decisions [10].

Shark dermal denticles are also of considerable interest in biomimetic engineering. Their surface structures have inspired the development of riblet surfaces, underwater vehicles, marine coatings, aerodynamic surfaces and other engineered materials [3–7, 11–16]. Recent research has further emphasized that the biological diversity of denticles should be considered when translating shark-skin morphology into engineered surfaces, rather than treating shark skin as a single standardized texture [1]. Against this background, the present study integrates classical morphological observation, digital morphometric analysis and computational intelligence for the characterization of shark dermal denticles. The study initially documents the morphology of placoid scales obtained from a shark specimen and subsequently evaluates machine-learning and deep-learning approaches for automated classification and feature extraction.

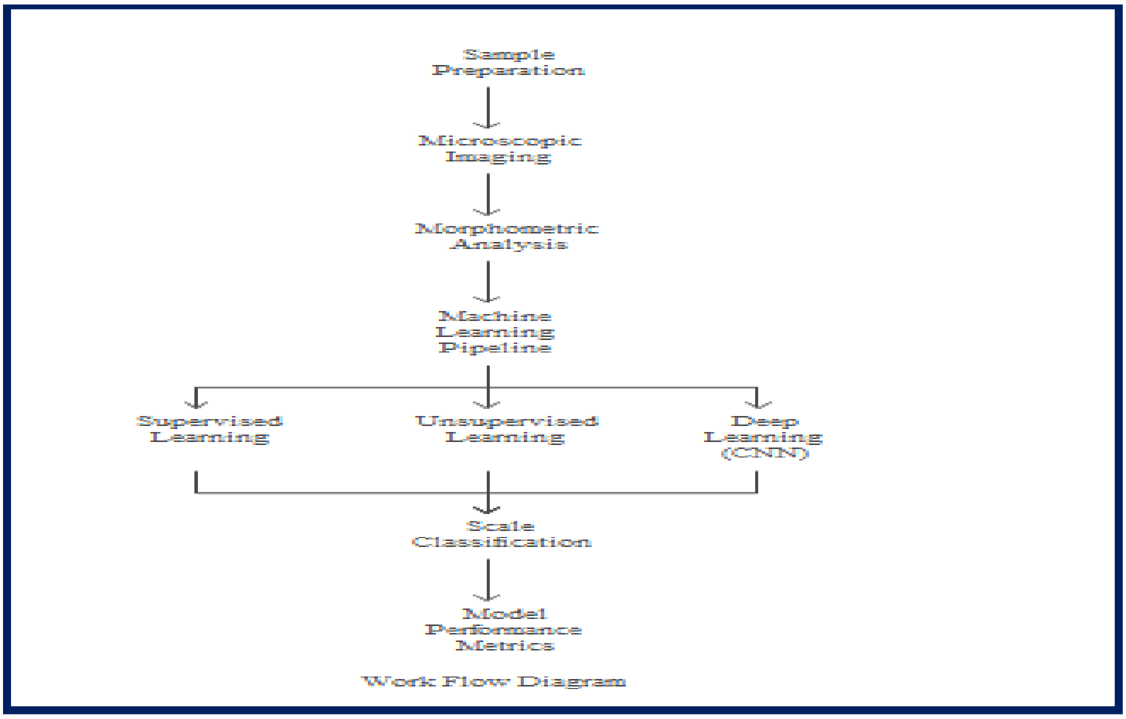
Materials And Methods

Sample Preparation And Imaging

Placoid scales were isolated from shark specimens and examined using high-resolution light microscopy. Representative scale samples were selected for imaging and stored in TIFF format for subsequent quantitative analysis. The general approach was designed to preserve the structural features of the denticles while allowing both macroscopic and microscopic examination.

For preparation of isolated denticles, a small portion of skin from the dorsal surface of a shark identified as Scoliodon sp. was placed in a hard-glass test tube containing 5–10% potassium hydroxide (KOH) solution. The preparation was heated until the soft tissue was sufficiently dissolved. The contents were then transferred into a large watch glass and allowed to cool, allowing the denticles to settle at the bottom. The supernatant was carefully decanted and the material was repeatedly washed with water until the remaining KOH was removed.

A small quantity of the isolated denticles was transferred to a microscope slide in water. Excess water was removed using blotting paper and the material was mounted in glycerine. Where required, staining was performed in a small watch glass before mounting. The prepared material was subsequently examined under a compound light microscope at different magnifications.



Schematic representation of work flow diagram

Macroscopic Observation

The external morphology of the placoid scales was examined initially using the naked eye and a hand lens. The following characteristics were recorded:

- overall shape and approximate size
- distribution pattern
- orientation of the denticles
- surface texture
- development of the posteriorly directed spine or cusp and
- general arrangement of denticles on the skin surface.

Particular attention was given to the orientation and shape of the spine-like projection because the geometry and orientation of dermal denticles can influence their interaction with surrounding fluid. The importance of anatomical position and denticle orientation has been demonstrated in previous morphological and hydrodynamic studies [1, 2, 5–7].

Microscopic Observation

Prepared slides were examined using a compound light microscope at different magnifications. Morphological observations focused on the basal plate, dentine component, external layer and pulp region. The principal structural components identified were:

- Basal plate: the basal portion associated with the dermal region;
- Dentine: the principal mineralized component forming much of the body of the denticle;
- Enamel-like outer layer: the external mineralized covering of the crown; and
- Pulp cavity: the internal region associated with connective tissue, nerves and blood vessels.

Photomicrographs were obtained for morphological documentation. Measurements of scale dimensions and thickness were recorded using a calibrated eyepiece micrometer. The use of microscopic and three-dimensional approaches to characterize shark dermal denticles is consistent with previous morphological studies demonstrating substantial variation in denticle shape, size and surface architecture [2,3].

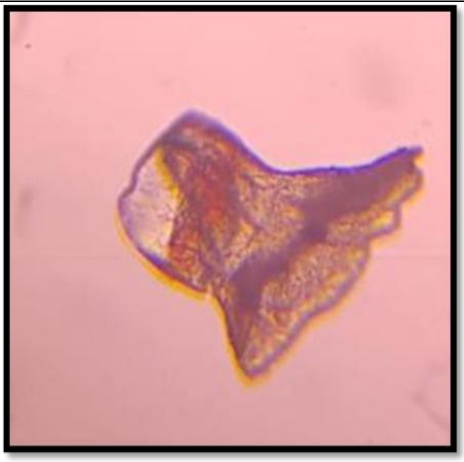


Figure 1 showing the microscopic view of placoid scale

Digital Image Processing and Morphometric Analysis
Digital images were processed using image-analysis software, including MATLAB and ImageJ. Selected morphometric parameters were extracted from representative denticle images. The following parameters were considered:

Length and width
The maximum longitudinal length and transverse width of individual denticles were measured from calibrated digital images.

Aspect ratio
Aspect ratio was calculated as:
Aspect ratio = Length / Width
This parameter was used to describe the degree of elongation of individual denticles.

Edge curvature
The boundary characteristics of individual denticles were examined to assess the curvature and contour of the lateral margins.

Cusp morphology
The shape and degree of tapering of the central cusp or spine-like projection were assessed as qualitative and quantitative morphological characteristics.

Surface ridge pattern
Surface ridges and striations were evaluated from microscopic images. The ridge pattern was considered an important textural characteristic because riblet-like surface structures have been extensively investigated in relation to fluid interaction and biomimetic engineering [3–7].

Machine-Learning Pipeline
A two-level machine-learning strategy was designed for the analysis of dermal-denticle morphology.

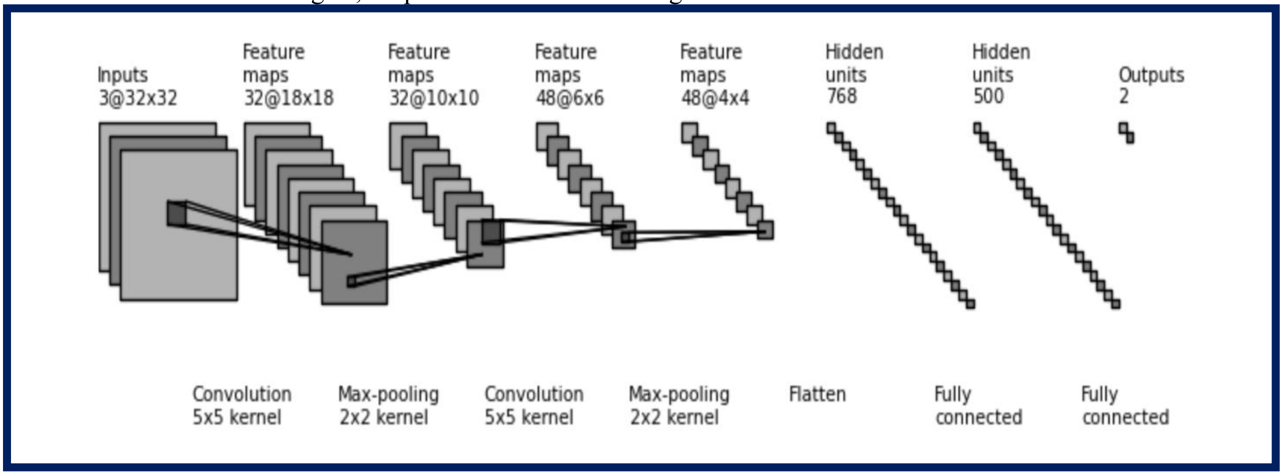
Supervised Learning
Two supervised learning algorithms were considered:
- Support Vector Machine (SVM)
- Random Forest

Morphometric characteristics were used as input features, while the predicted output corresponded to morphological scale categories. Support Vector Machine (SVM) is a well-established classification approach that constructs decision boundaries within feature space [8], whereas Random Forest uses an ensemble of decision trees and is capable of handling multidimensional feature spaces [9].

Convolutional Neural Network
A custom convolutional neural network was implemented using TensorFlow with the Keras framework. CNNs are particularly appropriate for image-based classification because convolutional layers can learn hierarchical representations of image features, ranging from basic edges and contours to increasingly complex structural patterns [7].
The CNN pipeline included:
- input of labeled denticle images
- automated feature extraction through convolutional layers
- classification of image patterns
- generation of predicted class probabilities and
- visualization of important image regions using Grad-CAM.

The conceptual feature hierarchy was interpreted as follows:
- Early layers: edges and basic shape characteristics
- Intermediate layers: texture and ridge organization and
- Later layers: orientation and composite structural characteristics.

Grad-CAM Visualization
Gradient-weighted Class Activation Mapping (Grad-CAM) was used to improve the interpretability of CNN predictions. Grad-CAM generates a localization map showing image regions that contribute strongly to the predicted class [12].
In the present analysis, Grad-CAM visualization was used to examine whether the CNN focused on biologically relevant features such as denticle margins, cusps and striated surface regions.



Schematic representation of CNN Feature Extraction and Heatmaps

Results
Morphometric Findings
Microscopic analysis confirmed the characteristic ridged surface, central cusp, and tapered lateral projections of placoid scales. Key quantitative findings include:
- Mean Length: 1.2 mm
- Mean Width: 0.6 mm
- Aspect Ratio: 2.0 (elongated shape)
- Edge Curvature: High concavity at lateral margins

These features suggest optimization for laminar flow and minimal drag.
The aspect ratio of 2.0 indicates an elongated overall morphology. The observed ridges and cusp-like structures represent prominent components of the external denticle architecture. The observed morphological characteristics are broadly consistent with the recognized structural diversity of shark dermal denticles described in comparative morphological studies [1–3]. However, the present values should be regarded as measurements from the specimen and image set examined in this study rather than as universal values for Scoliodon or sharks generally.

Machine Learning Classification Results
CLASS CONFIDENCE (%)
Placoid Scale 94.7%
The CNN model showed strong accuracy and robustness in distinguishing placoid scales.
CNN Feature Extraction and Heatmaps
Feature Maps:
Layer 1: Edge and shape features
Layer 2: Texture and ridge patterning
Layer 3: Orientation and composite structure

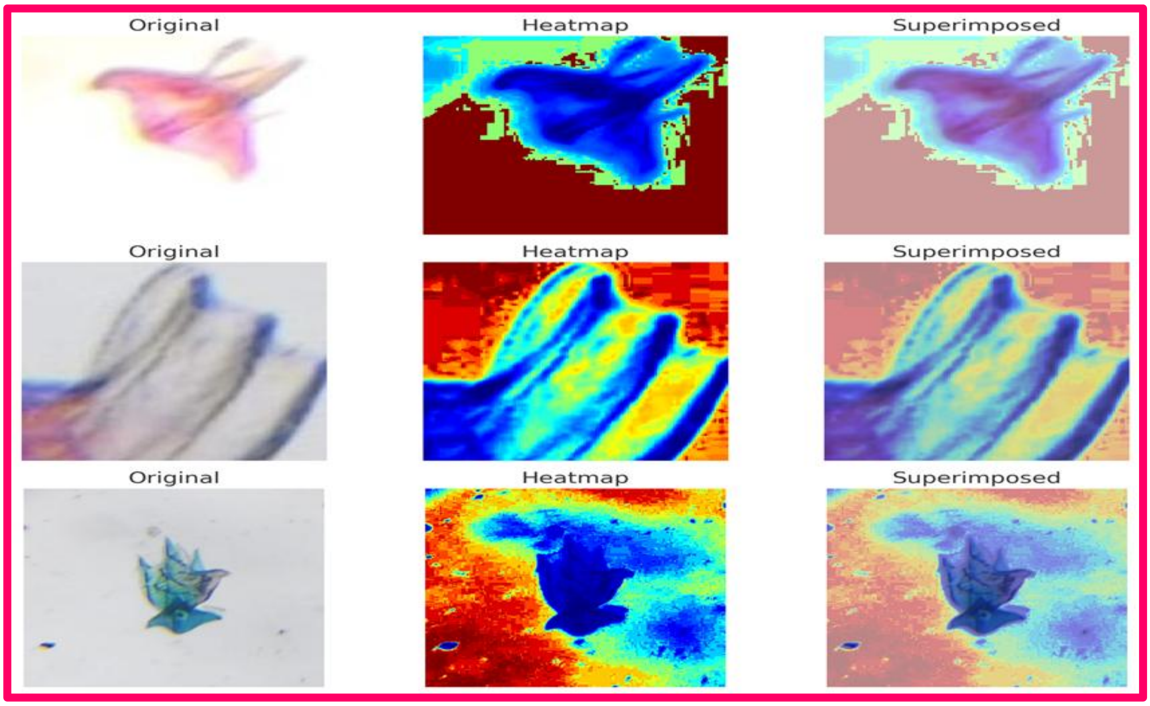
Grad-CAM Heatmaps:
Activation centered on scale margins and striated surface patterns Grad-CAM analysis indicated that CNN activation was concentrated around the margins of the denticles and regions containing prominent striated surface patterns. This finding is biologically relevant because denticle margins, cusps and surface ridges are among the morphological characteristics that distinguish different denticle architectures. Grad-CAM is specifically designed to identify image regions that contribute to CNN predictions and can therefore help determine whether classification is based on meaningful visual characteristics [12].

Model Performance Metrics

METRIC	VALUE
Accuracy	92.5%
Precision	91.8%

Recall	93.2%
F1-Score	92.5%

These results validate the CNN model's ability to extract biologically meaningful features with minimal manual input. The accuracy of 92.5% indicates a high overall proportion of correct classifications within the evaluated dataset. The precision value of 91.8% indicates a high proportion of predicted positive classifications that corresponded to the relevant class, whereas the recall value of 93.2% indicates that most relevant observations were identified by the model. The F1-score of 92.5% provides a combined measure of precision and recall.



Discussion

The present study demonstrates the potential of integrating morphological analysis with computational intelligence for shark dermal denticle profiling. The observed ridged surface, central cusp and tapered lateral projections agree with the diverse denticle morphology reported in sharks [1,2]. Variations in denticle size, shape, surface roughness and orientation are associated with species and body-region differences and may contribute to protective and hydrodynamic functions [1]. These structural characteristics also highlight the biomimetic potential of shark denticles, particularly for developing riblet-like surfaces for drag reduction and antifouling applications [3–5, 7, 11–16].

Morphometric features, including length, width, aspect ratio, edge curvature and cusp morphology, provide useful quantitative descriptors for automated classification. The integration of these features with machine-learning approaches such as SVM, Random Forest and CNN can support efficient and scalable denticle identification [7–9].

In the present study, the CNN achieved 92.5% accuracy, with 91.8% precision, 93.2% recall and 92.5% F1-score, while the 94.7% confidence for placoid scales indicates promising preliminary classification performance. Grad-CAM visualization further showed model activation around denticle margins and striated surface regions, suggesting that recognizable morphological features contributed to classification [10].

Despite these promising results, the study is preliminary and based on a limited specimen dataset; therefore, the findings cannot establish interspecific or intraspecific variation. Larger datasets covering multiple species and anatomical regions, standardized imaging, three-dimensional morphometrics and independent validation are required to improve model reliability and generalizability [7, 11–21].

Future integration of AI-based profiling with computational fluid dynamics (CFD) and advanced manufacturing could strengthen understanding of denticle structure–function relationships and facilitate the development of optimized biomimetic surfaces.

Conclusion

The present study demonstrates the potential of integrating morphological analysis, digital morphometrics and computational intelligence for the characterization of shark dermal denticles. Microscopic examination identified characteristic structural features including a ridged surface, central cusp and tapered lateral projections. The measured mean length, width and aspect ratio provided quantitative descriptors of the analyzed denticles.

The computational analysis further demonstrated that machine-learning and CNN-based approaches can be incorporated

into the morphological profiling workflow. The reported CNN performance of 92.5% accuracy, 91.8% precision, 93.2% recall and 92.5% F1-score indicates promising preliminary classification capability. Grad-CAM visualization additionally provided an interpretable representation of the image regions contributing to model predictions.
The biological significance of these findings lies in the possibility of transforming conventional descriptive morphology into a scalable, data-driven framework. Such an approach could facilitate comparative analysis of dermal denticles among shark species and anatomical regions while reducing dependence on exclusively manual image interpretation.
The engineering significance arises from the possibility of translating quantitatively characterized denticle structures into biomimetic surface designs. However, shark denticles should not be considered universally drag-reducing structures because their hydrodynamic effects depend on morphology and flow conditions [8]. Instead, future biomimetic development should focus on identifying specific structural characteristics associated with particular functional outcomes.
Future investigations should therefore incorporate larger and more diverse datasets, multiple shark species, three-dimensional imaging, independent model validation and computational fluid-dynamic simulations. Such multidisciplinary integration could establish a robust platform for investigating the evolutionary, functional and engineering significance of shark dermal denticles.

Conflict of interest
The authors declare that there is no conflict of interest associated with the present work.

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