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3D sagittal otolith reconstruction from spherical Fourier descriptors

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1 Introduction

Otoliths, also known as ear stones, are calcified structures found in the inner ears of fish, playing a crucial role in fish hearing and balance [1]. They are valuable tools in fisheries research, used for age determination, stock identification, and understanding fish population dynamics [2, 3, 4]. The shape of otoliths provides insights into a fish's life history and environment [4]. While traditional methods for studying otoliths involve manual measurements and visual examination, recent technological advancements have introduced automated techniques, such as image processing and mathematical modelling, enabling more efficient and accurate analysis of otolith shape and structure.

Currently, these analyses are predominantly conducted using two-dimensional (2D) images [2, 3, 4], offering only a partial representation of the otolith's shape. This paper introduces a novel technique focusing on three-dimensional (3D) sagittal otolith reconstruction from spherical harmonics decomposition descriptors [9]. By utilising advanced imaging technology to capture 3D models of otoliths and applying mathematical descriptors, such as Fourier transforms, the method aims to provide a standardised and reproducible characterisation of otolith shape. This approach enables the standardisation, alignment, and extraction of otolith shape parameters, crucial for ensuring data quality and comparability across different 3D models.

This study aims to demonstrate how to standardise and extract the 3D shape information of fish otoliths. This innovative approach holds promise in improving the accuracy and efficiency of age determination, stock identification, and enhancing our understanding of fish populations, thereby supporting sustainable fisheries management. To apply this analytic protocol, otoliths from 20 commercial fish species from the Eastern Channel were used.

2 Extraction of 3D otolith shape

2.1 3D image acquisition

The acquisition of 3D sagittal otolith images involved the use of an X-ray microtomograph, which captures two-dimensional X-ray images of the otolith from various angles. These images reveal differences in density between the otoliths and the surrounding air.

Subsequently, reconstruction was conducted using Nrecon software (Bruker, Kontich, Belgium) to convert the X-ray images into virtual slices, followed by segmentation with 3D Slicer to extract otolith isosurfaces as 3D meshes. To ensure symmetry between the left and right otoliths, a mirror transformation was applied to the right otoliths (by multiplying one of the three mesh vertex coordinate dimensions by -1), ensuring accurate comparative analysis between both sides.

2.2 3D meshes standardisation

Prior to further analyses, six landmarks had to be placed manually on each mesh (Figure 1, Part 1); these were used to pre-align otolith meshes. In this shape analyses, measures could be taken to prevent under or over-representation of a population or species. This involved duplicating individuals from the same population or species to ensure equal representation across categories.

A mesh decimation process was then applied to all otoliths to ensure they had the same number of triangles per 3D object. Decimation reduces the number of triangles in the mesh while preserving its overall shape. Depending on the required level of detail, decimation can be adjusted as follows. For a high level of detail, the meshes were standardised to 10,000 triangles with 5,002 vertices per otolith. With 1,000 triangles and 502 vertices, otolith reconstruction was already completed (Figure 1, Part 2). Isolated vertices resulting from decimation were removed to prevent potential issues during the projection onto a sphere. Furthermore, the landmarks were readjusted after mesh decimation by associating them with the vertices closest to the new decimated mesh. The centroid size was resized to 1 for all meshes to ensure uniform size.

2.3 Fourier spherical harmonics with SPHARM

Three-dimensional otolith models were filtered to include only individuals without structural holes. This selection was necessary because the SPHARM (spherical harmonics) analysis [5, 6], which projects 3D shapes onto a reference sphere, cannot process data with holes. Indeed, as one of the SPHARM analysis step consists of mapping between a reference spherical surface (*i.e.* genus-zero surfaces and with no holes or handles) and object surfaces under study, it was crucial to ensure that the selected otolith surfaces were suitable for analysis [6]. MATLAB functions for SPHARM analysis were also translated into R language for further processing.

To align all 3D otoliths and compute Fourier coefficients [7, 8], was utilised through an (Figure 1, Part 3). Initially, a random individual was selected to align all others using corrected landmarks, initiating the iterative process. Subsequently, a global mean shape was calculated from all aligned otoliths, and the mean shape was recalculated from these new alignments iteratively until convergence was achieved, and the mean shape stabilised.

During each iteration, all 3D meshes were mapped onto a sphere and aligned using landmarks (Figure 1, Part 3). The meshes were projected onto a unit sphere under a bijective mapping to minimise area and topology distortion. The CALD spherical parameterisation algorithm was employed, combining local and global smoothing methods alternately until convergence was achieved [9]. Local smoothing aimed to minimise area distortion and worst-case length distortion at the level of a local sub-mesh, while global smoothing attempted to distribute area distortions evenly over the entire sphere [6, 9].

Fourier coefficients were calculated at each iteration, and, finally, the coefficients from the last iteration were considered when convergence occurred. The surface of each mesh was described by a series of points using three parameterized variables: $x(\theta, \varphi)$, $y(\theta, \varphi)$, and $z(\theta, \varphi)$, where θ represents the polar colatitudinal coordinate with $\theta \in [0, \pi]$, and φ represents the azimuthal longitudinal coordinate with $\varphi \in [0, 2\pi]$ (Figure 1, Part 3) [6]. Standardisation and mesh alignment by landmarks are crucial in this context as comparisons are made point by point. Variations in these three coordinates along the sphere are then treated as signals using Fourier functions, where these coefficients represent combinations of sinusoids at different frequencies. Low frequencies describe general aspects of the shape while high frequencies depict fine details, and the combination of these terms at different frequencies comprehensively describes the 3D shape, capturing both general aspects and local details.

All three parameters could be expressed as Fourier spherical harmonic (SPHARM) functions like [10]

$$Y_l^m(\theta, \varphi) = \sqrt{\frac{2l+1(l-m)!}{4\pi(l+m)!}} P_l^m(\cos\theta) e^{-im\varphi}$$

$P_l^m(\cos\theta)$ are Legendre polynomials known as $P_l^m(x) = \frac{(-1)^m}{(2^l l!)} (1+x^2)^{\frac{m}{2}} \frac{d^{l+m}}{dx^{l+m}} (x^2-1)^l$

Each parameters is autonomously decomposed with respect to spherical harmonics [6] as

$$x(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-1}^l c_{lx}^m Y_l^m(\theta, \varphi) \quad ; \quad y(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-1}^l c_{ly}^m Y_l^m(\theta, \varphi) \quad ; \quad z(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-1}^l c_{lz}^m Y_l^m(\theta, \varphi).$$

All these functions can be combined into a single vector-valued function [6] as

$$v(\theta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-1}^l c_l^m Y_l^m(\theta, \varphi)$$

where $v(\theta, \varphi) = (x(\theta, \varphi), y(\theta, \varphi), z(\theta, \varphi))^T$ and $c_l^m = (c_{lx}^m, c_{ly}^m, c_{lz}^m)^T$. The coefficients c_l^m are calculated through conventional least-squares estimation [6]. The SPHARM objective function is to compute c_{lx}^m , c_{ly}^m and c_{lz}^m up to the number of harmonics (degrees) defined [6].

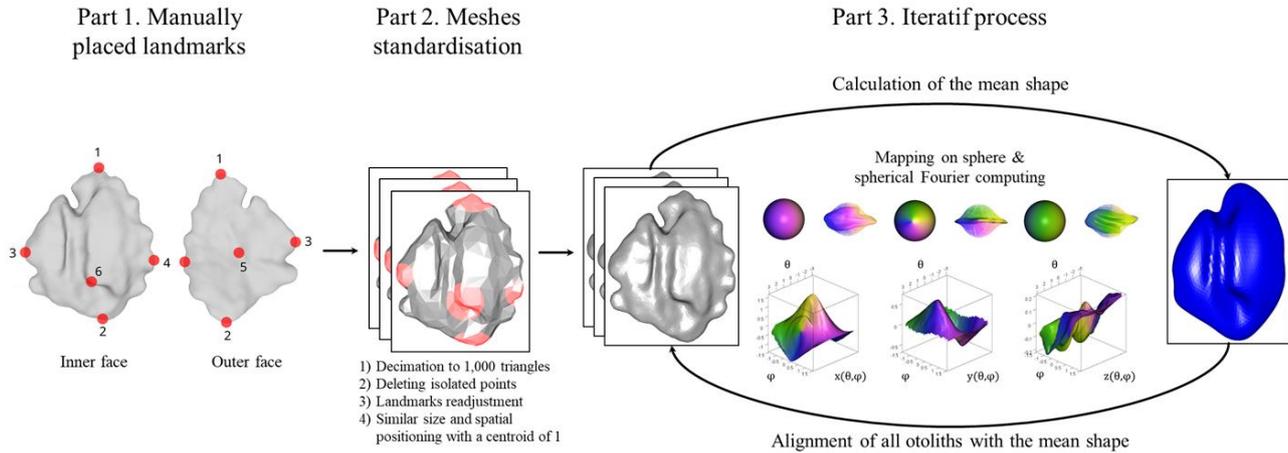


FIGURE 1 – Analytic protocol for standardisation, alignment, and calculation of spherical Fourier coefficients from 3D sagittal otoliths using SPHARM. Part 1 – 3D otolith mesh showing inner and outer faces with six landmarks (red points, 1 on the *rostrum*, 2 on the *postrostrum*, 3 at the end of dorsal, 4 at the tip of ventral, 5 on the middle of outer face of the otolith, 6 on top of the *sulcus acusticus*). Part 2 – Otoliths decimated to 1,000 triangles, with red parts on the meshes indicating the readjustment of landmarks. Part 3 – During each iteration, the meshes are projected onto a sphere, and Fourier coefficients are calculated for the aligned otoliths.

3 Discussion

This study introduces the application of the SPHARM method [6] for describing otolith shape, from 20 fish species, through the computation of spherical harmonics. A novel technique for 3D sagittal otolith reconstruction was introduced using spherical Fourier descriptors. This innovative approach overcomes the limitations of traditional 2D methods, providing a comprehensive characterisation of otolith shape. 3D analysis allows for the handling of asymmetry in otolith

shape based on the inner ear side. This important factor can influence otolith shape and is not adequately captured by 2D analysis. The analytic protocol in this study proved highly effective, automatically identifying and removing problematic meshes with holes, isolated points, or non-manifolds, which are the main 3D meshes where the SPHARM analysis finds the projection onto a sphere impossible. Leveraging advanced imaging technology and mathematical descriptors like Fourier transforms, the analytic protocol enables the standardisation, alignment, and extraction of otolith shape parameters, essential for ensuring data quality and comparability across different meshes.

Whether analysing 2D images or 3D meshes shape, standardisation of inputs is essential as it allows for comparison between each input. Standardisation is a vital process ensuring the quality and comparability of data by adjusting the dataset's distribution through normalisation, zero-centering, and standardisation [11]. This step accelerates machine learning time and achieves good generalisation in inference, improving data quality for activities like data cleaning, profiling, and matching. Moreover, alignment in morphometric analysis involves superposing shapes to minimise differences in position, orientation, and scale, a necessary preliminary step before meaningful shape comparisons [12, 13].

The next step will involve applying classification or multivariate analysis to this standardised otolith shape data. Using this comprehensive otolith shape holds potential to improve the accuracy and efficiency of age and stock identification classification.

The process of acquiring 3D images and standardisation is, however, time-consuming. It is advisable to reduce or optimise scan parameters according to the otolith size and study objectives. For instance, to reduce scanning time, X-ray with a smaller rotation step and a larger voxel size could be used (but risk losing quality and resolution). In this analytic protocol, decimation can be reduced to 1,000 triangles (11 harmonics) for small otoliths.

One avenue for further exploration lies in the automated identification of the six landmarks within the process. Additionally, addressing the challenge of managing holes in otoliths, a characteristic feature of certain fish species, presents another promising direction for study. While our case study focused on fish otoliths, this analytic protocol could be used in other areas of 3D shape analysis without holes or isolated elements.

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