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Fishboneviz: Enhancing the availability of zooarchaeological fish reference collections through an open access 3D database

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ABSTRACT
Fish remains are a common component of coastal and inland archaeological assemblages from Australia and the Pacific Islands. Physical reference collections are the primary tool that researchers use to taxonomically identify fish bones but given the high biodiversity of fishes in this region, collections are frequently not complete at the genus- and species-level. Adjunct resources, such as online photograph repositories of fish bone reference collections and illustrated technical guides, provide useful supplementary aids. However, such 2D photographs and illustrations offer fixed perspectives of the bone and do not allow for ready manipulation and detailed examination of the specimen. Here, we introduce Fishboneviz, the first open access 3D fish bone reference collection, which was developed to reduce inequitable access to physical reference collections in line with the FAIR principles of data management (findable, accessible, interoperable, reusable). A 'best-practice' methodology was established to facilitate fast and effective segmentation (i.e. isolate regions of interest such as elements) of fish Computed Tomography (CT) scans. This way, fish bone elements of interest were segmented to allow digital manipulation and viewing of the complete element. To examine the effectiveness of the approach, image segmentation procedures were applied to a representative sample of 10 bone elements per fish: dentary, premaxilla, maxilla, articular, quadrate, hyomandibular, opercle, preopercle, last precaudal vertebra, and first caudal vertebra. For species within the family Labridae, the three pharyngeal grinding plates were also segmented. These elements were selected as they represent different regions of the skeleton, variable morphologies, and commonly recovered elements from archaeological sites. To date, the collection contains the skeletal elements of 26 fish species (18 families). In the future, it is hoped that the collection will be further expanded by a broader network of interested collaborators to ensure it grows according to the changing needs of research and teaching communities.

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Introduction

Fish remains are ubiquitous in the coastal and inland archaeological record of Australia and the Pacific Islands (Allen 2017; Balme 1995; Bouffandeau et al. 2019; Butler 1994; Campbell and Nims 2019; Disspain et al. 2018; Lambrides et al. 2019, 2022; Manne and Veth 2015; Weisler and McNiven 2016). Yet, the taxonomic resolution is frequently low, particularly from tropical fish bone assemblages, owing to poor bone preservation, high biodiversity, and morphological overlap at the genus- and species-level. These factors make identifications below the family-level challenging (Lambrides and Weisler 2016). Furthermore, access to quality physical fish bone comparative collections can be difficult globally, and is challenging for many researchers across Australia. For example, to the authors' knowledge only four Australian institutions (James Cook University, Australian National University, University of Queensland, and University of Western Australia) have purpose-built collections of varying coverage of Australian and Pacific Ocean fish taxa adequate to support archaeological research (e.g. Tomkins et al. 2013), and there is patchy availability of dry specimens in museum collections (e.g. the Queensland Museum fish osteology collection is limited compared to the wet whole fish collection). Accessing these existing physical collections can be costly when

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travel is necessary, and over time continuous handling can be destructive to the specimens. Furthermore, these physical comparative collections are not readily accessible to the public, which limits the audience that can benefit from this often publicly funded research infrastructure (e.g. Davies et al. 2017, raises similar concerns about access to three-dimensional [3D] digital datasets).

3D data acquisition, such as CT (Computed Tomography) scanning, photogrammetry, or surface scanning (collectively termed '3D images' herein), can offer researchers an alternative option to physical specimen access. Digital representations of osteological material also frequently reveal features that are not as discernible by direct examination of the physical specimen (Ristevski 2022; Ristevski et al. 2023), provide a greater analytical potential (e.g. Geometric Morphometrics, Viacava et al. 2023), and offer both an adjunct and supplement to physical collections. Each of these factors sees interactive 3D images as expanding on comparative material to help address the frequent taxonomic gaps in physical reference collections (Davies et al. 2017; Kerr et al. 2024; Mein et al. 2022; Prideaux et al. 2022; Ristevski et al. 2020; van Zoelen et al. 2023).

Given the inequities in access to comparative fish bone collections in Australia, a project was developed to (1) develop a 'best practice' methodology for fish CT scan segmentation to support taxonomic identifications of archaeological bone; (2) publish these outcomes open access to facilitate broader communication, reuse and, if and where required, refinement of the methodology and retention of expertise into the future; and, (3) establish an open access virtual fish bone reference collection on the MorphoSource digital platform. The aim of this paper is to introduce Fishboneviz, the first open access 3D fish bone reference collection, to those interested in Australian and Pacific Islands ichthyoarchaeology, and the broader implications of 3D comparative reference collections for archaeological and palaeontological research and teaching efforts. A discussion of the recent history of fish bone reference collection digitisation and dissemination will be provided, as well as a consideration of the benefits of open access 3D data, including the FAIR principles of data management (findable, accessible, interoperable, reusable). Finally, an overview of the data sources, storage, fish bone segmentation methods, accessibility, and future collaborative opportunities to expand the Fishboneviz collection will be discussed.

Background

Digitising modern fish bone comparative collections

There is a need for adjunct osteological resources to be available alongside traditional physical specimen collections to facilitate the taxonomic identification of archaeological bones. It is common practice in many disciplines – ranging from field ecology, taxonomy, zooarchaeology to palaeontology – to use a combination of published identification keys, reference imagery and physical collections when identifying bones. For those interested in fish bones, a wide range of resources are available, and they can be divided into three main categories: (1) 2D photographs of physical collections housed in online repositories; (2) 2D photographs of physical collections published as volumes and guides; and, (3) volumes and manuals containing 2D technical illustrations for identification purposes. There are a variety of such resources that researchers will use depending on the geographic location of interest, but below is a representative list:

1. 2D photographic reference databases (available online):
   - *OsteoBase* (Tercerie et al. 2022): A collaboration between National Museum of Natural History, National Centre for Scientific Research, and Sorbonne University, all in France, and the international FishBase database. The database features cranial and postcranial remains of 106 fish families. It is accessible here: <https://osteobase.mnhn.fr/>.
   - *Pictorial Skeletal Atlas of Fishes* (McEwan et al. 2005): This atlas was established by the Florida Museum of Natural History, in the USA. The collection includes select cranial elements of 101 fish families. It is accessible at: <https://www.floridamuseum.ufl.edu/fish-atlas/>.
   - *Archaeological Fish Resource* (Sykes and Saddler 2023): This collection is managed by the University of Nottingham, in the UK, and features cranial and postcranial remains of 25 fish families. It is accessible at: <http://fishbone.nottingham.ac.uk/>.
   - *Archaeological Fish-Bone Images of Australia* (Colley 2010): This collection was established by The University of Sydney, in Australia. It features select cranial and postcranial elements of nine fish families. It is accessible at: <https://fish.library.usyd.edu.au>.

2. 2D photographic reference databases (hardcopy volumes and manuals):
   - *A Manual for the Identification of Fish Bones* (Barnett 1978): This manual, the first volume of the Australian National University's Technical Bulletins, was written for the identification of tropical archaeological fish bones. While richly illustrated with

photographs of fish bones, it was from the onset recommended to be ideally used in conjunction with comparative collections. This manual contains images of the neurocranium, dentary and premaxilla of 27 fish families.

- *Manual of Hawaiian Fish Remains Identification Based on the Skeletal Reference Collection of Alan C. Ziegler and Including Otoliths* (Dye and Longenecker 2004): This manual was produced to support the identification of fish remains from Hawaiian Island archaeological sites. This manual contains images of select cranial elements (including otoliths) of 38 fish families.
- *North Sea Fish and their Remains* (Camphuysen and Henderson 2017): This volume contains detailed information regarding species life history traits and descriptive accounts of unique morphological features of select cranial and post cranial elements. More than 100 fish families are featured in the manual.
- *Les Otolithes des Poissons de l'Indo-Pacifique* (Rivaton and Bourret 1999): Seminal manual of Indo-Pacific fish otoliths, with coverage of over 150 fish families.

3. Technical illustrations:
   - *A Guide to the Identification of Fish Remains from New Zealand Archaeological Sites* (Leach 1997): A targeted guide to support researchers working on archaeological fish bone assemblages recovered from sites in New Zealand. A select range of cranial remains are illustrated from 39 fish families.
   - *Marine Fish Osteology: A Manual for Archaeologists* (Cannon 1987): Primarily a fish osteology guide, but it provides all elements from the complete skeleton of fish, with individual fish bone elements illustrated using four type families.
   - There are also various academic papers that provide illustrated fish bone element guides to aid taxonomic identification (e.g. Yeomans and Beech 2021).

Despite their utility, these resources are routinely not cited in academic publications when they have been consulted for taxonomic identifications. It is imperative that these resources are acknowledged in the methods sections of publications to recognise their value, but also to help support funding cases for their continued development. The examples that were listed here are all exceptional and well-used resources by ichthyoarchaeologists, and they will continue to play an important supporting role in faunal analysis. However, being collections of 2D photographs and illustrations, there is limited capacity to interact with the images, such as rotate or zoom to view different perspectives. Additionally, a number of these resources were produced decades ago, and as such image quality can be variable. Access to seminal volumes can also be challenging when a number of these resources are out of print. 3D representations of fish bones can provide a practical solution to some of the limitations of 2D data, but still sit alongside these existing identification resources by providing communities an additional tool to support their research and teaching.

3D data and FAIR principles

In recent years, the benefits of 3D images of osteological materials have been widely recognised, particularly as a useful means of viewing collections when there are challenges associated with developing and accessing physical collections (e.g. Boyer et al. 2017; Copes et al. 2016; Mulligan et al. 2022). While we understand that digital resources are also not necessarily accessible by everyone, open access online databases are nevertheless increasingly accessible globally. Furthermore, more comprehensive information can be derived from scanned specimens (e.g. Butler et al. 2021), which is critical for many disciplines such as archaeology, palaeontology and evolutionary biology. However, there are significant costs, both in time and resources, to digitise comparative reference collections. Such costs can become problematic if they act as a disincentive for data sharing. For example, because of perceived ownership of imagery in a highly competitive research environment, the resourcing required to curate, store and present digitised collections, or lack of understanding on how 3D imagery can be made accessible (Hipsley and Sherratt 2019). In many circumstances, the result is that 3D images become housed in internal repositories and not made widely accessible (e.g. Davies et al. 2017; Mulligan et al. 2022). Lack of open access equality slows the pace of research (e.g. Davies et al. 2017), and is not in line with the objectives of the mostly public-owned collections and government/philanthropic funding agencies that scientific digitisation is widely conducted under (Australian Research Council 2021; Mulligan et al. 2022). There are many initiatives, such as the USA's National Science Foundation funded oVert consortium that are addressing these issues (see below). Such initiatives operate to provide 3D imagery as a service to the global scientific community and provide broader access for the community at large. As detailed in the 'FAIR Guiding Principles for scientific data management and stewardship', this aspires to more open access and argues that data should be findable, accessible, interoperable, and

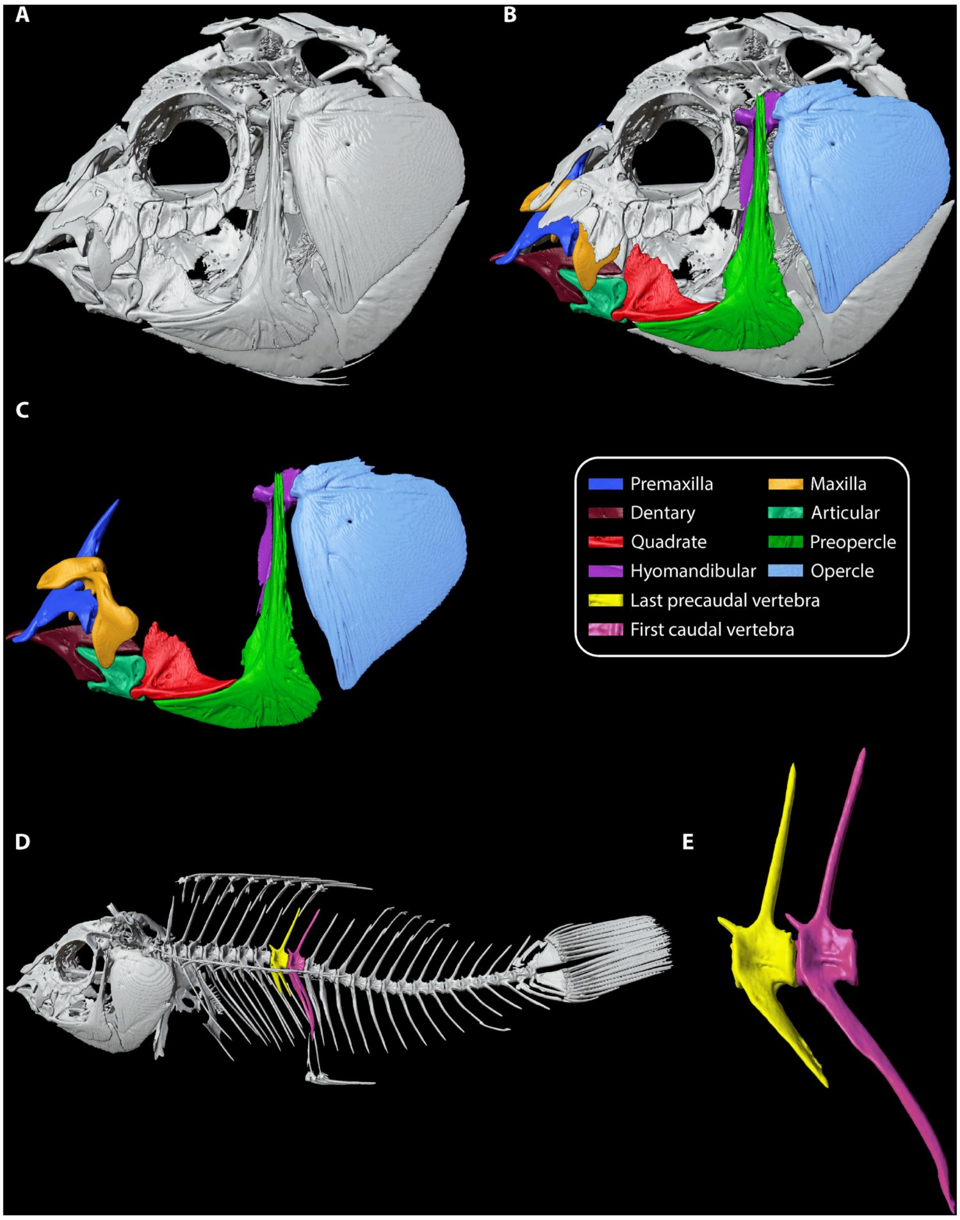

Figure 1. Digital model of *Anampses caeruleopunctatus* (UF Fish 9937), in left lateral views. (A) Digital model of the skull without the eight target craniomandibular elements highlighted; (B) Digital model of the skull with the eight target craniomandibular elements highlighted; (C) Digital models of the eight craniomandibular elements isolated; (D) Digital model of the skeleton with the two target vertebrae highlighted; and, (E) Digital models of the last precaudal and first caudal vertebrae. *Note*: The upper and lower pharyngeal grinding plates are not visible. These elements are in the throat of a fish and aid in food processing (see Figure 6).

reusable (Wilkinson et al. 2016). The creation of open access 3D reference collections, including the publication of the methods used, is therefore an excellent means of ensuring the widest accessibility to scholarly data and the retention of expertise into the future. Fishboneviz adds to these aspirations in the specific context of Australasian zooarchaeology, providing both a useful database for the identification of key fish species and a use case for FAIR data in the field.

Data sources and storage

oVert

The oVert project is a multi-institutional undertaking tasked with generating high-resolution digital three-dimensional data of vertebrate animals representing over 80% of all vertebrate genera (Blackburn et al. 2024; Cross 2017). The project commenced in 2017 and has aimed to produce more than 20,000 CT scans of vertebrate specimens housed in museum collections globally. One of the core objectives of oVert has been the open access availability of the scans and 3D-generated models to researchers across the world. Given the commitment to open access data sharing, Fishboneviz was able to use existing CT scans produced by oVert that are available on MorphoSource, an online 3D collections database. The oVert-generated CT data were used to segment select skeletal elements of relevant Australian and Pacific Ocean fish taxa to test the

Table 1. Summary of represented taxa and segmented craniomandibular and vertebral elements.

Family	Species	Number of segmented elements	Access status of 'raw' CT scans on MorphoSource	MorphoSource media ID(s)	MorphoSource DOIs
Acanthuridae	*Naso unicornis*	10 standard elements	Open download	000067764	https://doi.org/10.17602/M2/M67764.
Carangidae	*Selar crumenophthalmus*	10 standard elements	Open download	000091770 and 000091789	https://doi.org/10.17602/M2/M91789. https://doi.org/10.17602/M2/M91770.
Caesionidae	*Caesio caerulaurea*	8 standard elements[a]	Download request required	000085190	https://doi.org/10.17602/M2/M85190.
Cirrhitidae	*Cirrhitichthys aprinus*	10 standard elements	Download request required	000085165 and 000085173	https://doi.org/10.17602/M2/M85173. https://doi.org/10.17602/M2/M85165.
Coryphaenidae	*Coryphaena hippurus*	8 standard elements[a]	Open download	000049143	https://doi.org/10.17602/M2/M49143.
Diodontidae	*Diodon hystrix*	13 elements[b]	Open download	000437992 and 000438009	https://doi.org/10.17602/M2/M437992. https://doi.org/10.17602/M2/M438009.
Istiophoridae	*Makaira nigricans*	10 standard elements	Open download	000461585 and 000461579	https://doi.org/10.17602/M2/M461579. https://doi.org/10.17602/M2/M461585.
Kyphosidae	*Kyphosus bigibbus*	10 standard elements	Download request required	000483667 and 000483666	https://doi.org/10.17602/M2/M483666. https://doi.org/10.17602/M2/M483667.
Labridae	*Anampses caeruleopunctatus*	10 standard elements + 3 grinding plates	Open download	000159147 and 000159146	https://doi.org/10.17602/M2/M159147. https://doi.org/10.17602/M2/M159146.
Labridae	*Bodianus mesothorax*	3 grinding plates	Download request required	000058181	https://doi.org/10.17602/M2/M58181
Labridae	*Cetoscarus bicolor*[c]	10 standard elements + 3 grinding plates	Download request required	000078050	https://doi.org/10.17602/M2/M78050.
Labridae	*Cheilinus fasciatus*	3 grinding plates	Download request required	000058190	https://doi.org/10.17602/M2/M58190.
Labridae	*Chlorurus bleekeri*[c]	Lower pharyngeal grinding plate[d]	Download request required	000056584	https://doi.org/10.17602/M2/M56584
Labridae	*Choerodon anchorago*	3 grinding plates	Download request required	000057755	https://doi.org/10.17602/M2/M57755.
Labridae	*Coris gaimard*	3 grinding plates	Download request required	000057759	https://doi.org/10.17602/M2/M57759.
Labridae	*Halichoeres hortulanus*	3 grinding plates	Download request required	000058197	https://doi.org/10.17602/M2/M58197.
Labridae	*Thalassoma lunare*	3 grinding plates	Download request required	000057853	https://doi.org/10.17602/M2/M57853.
Lutjanidae	*Pinjalo pinjalo*	10 standard elements	Open download	000072062	https://doi.org/10.17602/M2/M72062.
Mugilidae	*Crenimugil crenilabis*	10 standard elements	Open download	000085109 and 000085103	https://doi.org/10.17602/M2/M85109. https://doi.org/10.17602/M2/M85103.
Platycephalidae	*Rogadius asper*	10 standard elements	Download request required	000436983 and 000436966	https://doi.org/10.17602/M2/M436966. https://doi.org/10.17602/M2/M436983.
Plotosidae	*Plotosus lineatus*	10 standard elements + vomer	Download request required	000436900 and 000436865	https://doi.org/10.17602/M2/M436865. https://doi.org/10.17602/M2/M436900.
Pomacanthidae	*Chaetodontoplus mesoleucus*	10 standard elements	Download request required	000482860 and 000482865	https://doi.org/10.17602/M2/M482860.

(*continued*)

Table 1. Continued.

Family	Species	Number of segmented elements	Access status of 'raw' CT scans on MorphoSource	MorphoSource media ID(s)	MorphoSource DOIs
					https://doi.org/10.17602/M2/M482865.
Pomacentridae	*Neoglyphidodon melas*	10 standard elements	Open download	000460130 and 000460131	https://doi.org/10.17602/M2/M460130. https://doi.org/10.17602/M2/M460131.
Scombridae	*Katsuwonus pelamis*	10 standard elements	Download request required	000483385 and 000483381	https://doi.org/10.17602/M2/M483381. https://doi.org/10.17602/M2/M483385.
Serranidae	*Plectropomus maculatus*	10 standard elements	Open download	000486167 and 000483511	https://doi.org/10.17602/M2/M486167. https://doi.org/10.17602/M2/M483511.
Sillaginidae	*Sillago sihama*	10 standard elements	Download request required	000473244 and 000473243	https://doi.org/10.17602/M2/M473243. https://doi.org/10.17602/M2/M473244.

Notes: [a]The vertebrae for *Caesio caerulaurea* and *Coryphaena hippurus* could not be segmented. [b]Due to the peculiar craniomandibular morphology of *Diodon hystrix,* which is characterised by fusion of the premaxillae, fusion of the dentary-anguloarticular complex as well as presence of ossified spines, a deviation from the standard segmentation of craniomandibular elements was required. [c]Parrotfish were formerly family Scaridae, but are now designated as a subfamily (Scarinae) of the wrasses (Labridae), yet their skeletal elements remain distinct and useful for archaeological identification. [d]Due to the CT scan quality, only the lower pharyngeal grinding plate of *Chlorurus bleekeri* could be segmented reliably. The 10 standard elements comprise of eight craniomandibular bones (left articular, dentary, hyomandibular, maxilla, opercle, premaxilla, preopercle, and quadrate) and two vertebrae (last precaudal and first caudal). The three grinding plates are exclusive to species within the family Labridae, and comprise the lower and the left and right upper pharyngeal grinding plates. *Note*: All digital models generated by Fishboneviz can be accessed open access via the project ID (000568470) and are permanently associated on MorphoSource with the 'raw' CT scans that can be accessed via the DOIs listed in the table.

efficacy of the approach and utility of such segmentations for archaeological applications. The 3D digital library of skeletal fish elements created by Fishboneviz is also of relevance to zoological and palaeontological research.

MorphoSource

MorphoSource (https://www.morphosource.org/) is an online data repository of 'raw' CT and microCT scans as well as 3D models (mesh files generated from CT and/or microCT scans, laser surface-scan renderings, structured light or photogrammetry) and 2D digital photographs of museum specimens (Boyer et al. 2017). One of the key goals of MorphoSource is reliable archiving and ease of storing, sharing, and accessibility of digital data of extinct and extant organisms. MorphoSource has been active since April 2013 and has grown rapidly thanks to the continuous addition of data by numerous researchers and institutions worldwide. At the time of writing (January 2024), MorphoSource has 189,271 media files from 1,371 collection and facilities and over 19,000 users. Most of the current data on MorphoSource is readily available for in-browser visualisation, and open access data can be downloaded by anyone with a free MorphoSource account. Some data may require pre-approval by the appointed data reviewer(s) or manager(s) on MorphoSource by sending a written download request. All pre-existing oVert CT scans used by the Fishboneviz project were obtained from MorphoSource. Thus, the skeletal fish elements segmented by Fishboneviz are also stored on MorphoSource where they are available for in-browser visualisation as well as free downloads. The MorphoSource viewer can also be embedded as an inline frame elsewhere, such as collating bone meshes in a learning management system for online learning.

Methods

Target taxa, skeletal elements, and 'raw' CT data sources

Fishboneviz has so far targeted representatives of the most common marine fish families recovered from Australian and Pacific Islands archaeological sites. In general, 10 elements from the craniomandibular and post-cranial skeleton that are commonly recovered from archaeological sites were selected for segmentation. These 10 elements are eight craniomandibular bones (left articular, dentary,

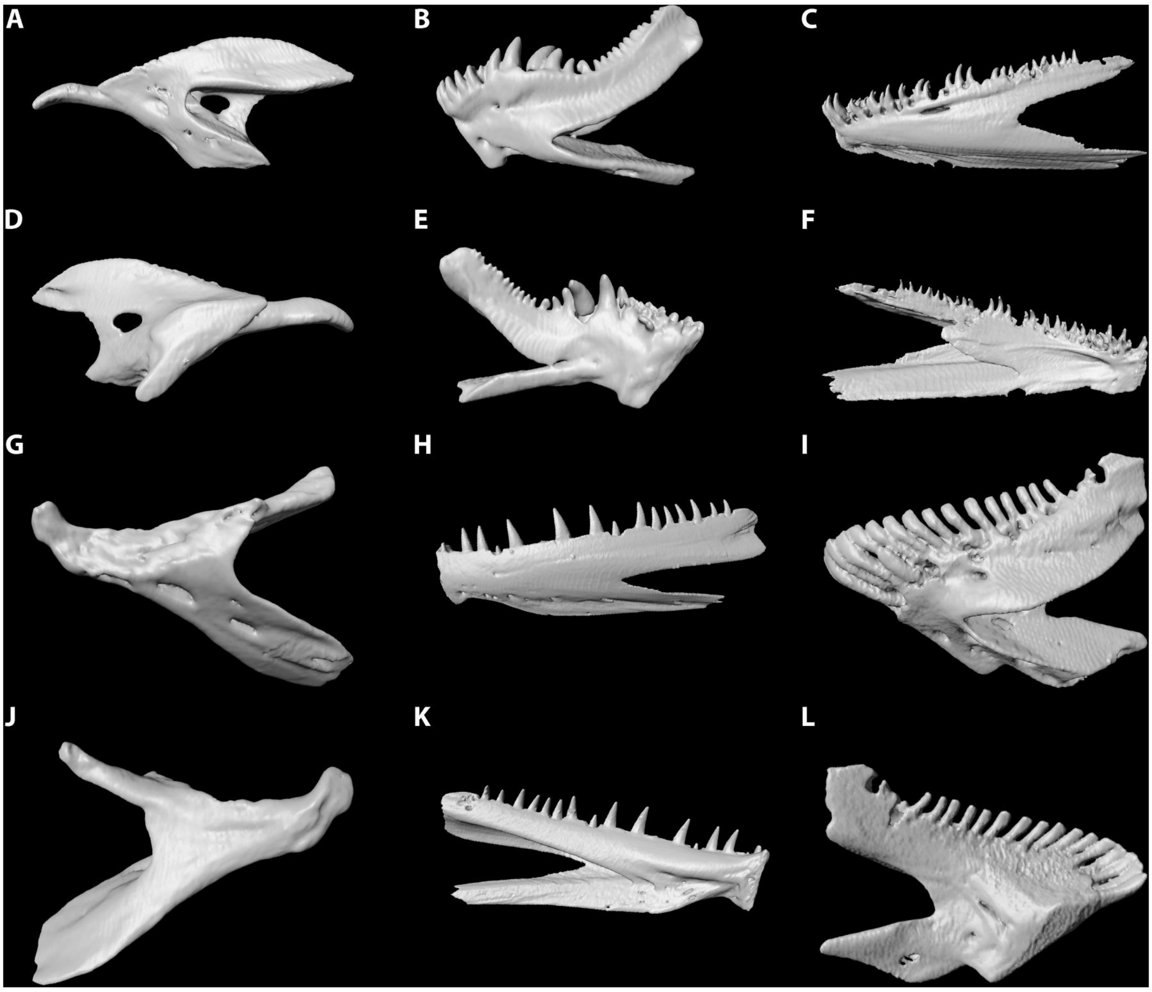

Figure 2. Digital models of left dentaries of select fishes. *Anampses caeruleopunctatus* (UF Fish 9937), left dentary in (A) lateral and (D) medial views; *Cirrhitichthys aprinus* (KU KUI 41159), left dentary in (B) lateral and (E) medial views; *Coryphaena hippurus* (UF Fish 163454), left dentary in (C) lateral and (F) medial views; *Crenimugil crenilabis* (UF Fish 42481), left dentary in (G) lateral and (J) medial views; *Katsuwonus pelamis* (KU KUI 14067), left dentary in (H) lateral and (K) medial views; and, *Neoglyphidodon melas* (UF Fish 120791), left dentary in (I) lateral and (L) medial views. Not to scale.

Figure 3. Digital models of left maxillae of select fishes. *Anampses caeruleopunctatus* (UF Fish 9937), left maxilla in (A) lateral, (B) medial, and (C) anterior views; *Caesio caerulaurea* (KU KUI 31980), left maxilla in (D) lateral, (E) medial, and (F) anterior views; and *Neoglyphidodon melas* (UF Fish 120791), left maxilla in (G) lateral, (H) medial, and (I) anterior views. Not to scale.

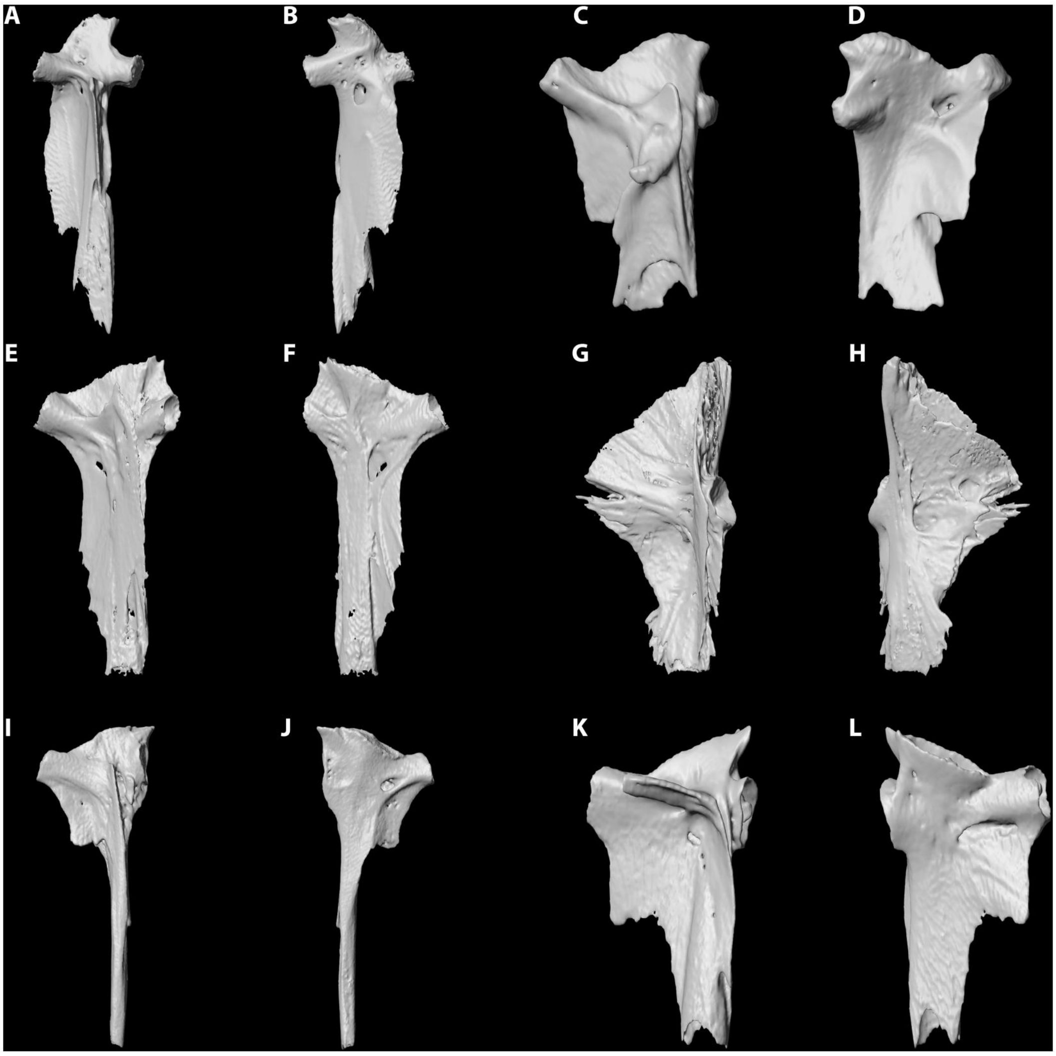

Figure 4. Digital models of left hyomandibulars of select fishes. *Anampses caeruleopunctatus* (UF Fish 9937), left hyomandibular in (A) lateral and (B) medial views; *Cirrhitichthys aprinus* (KU KUI 41159), left hyomandibular in (C) lateral and (D) medial views; *Coryphaena hippurus* (UF Fish 163454), left hyomandibular in (E) lateral and (F) medial views; *Diodon hystrix* (UF Fish 116860), left hyomandibular in (G) lateral and (H) medial views; *Katsuwonus pelamis* (KU KUI 14067), left hyomandibular in (I) lateral and (J) medial views; and, *Makaira nigricans* (UF Fish 166699), left hyomandibular in (K) lateral and (L) medial views. Not to scale.

hyomandibular, maxilla, opercle, premaxilla, preopercle, and quadrate) and two vertebrae (the last precaudal and first caudal) (Figure 1). For species within the family Labridae, the three pharyngeal grinding plates (the lower grinding plate and the left and right upper grinding plates) were also segmented. The aim of using these scans and digital models is to test their usefulness for distinguishing between genera on the basis of their morphologies. In total, 215 skeletal elements derived from 26 fish species were segmented (18 families, but 19 if 'Scaridae' is included). Parrotfish were formerly considered to be of the family Scaridae, but are now designated as a subfamily (Scarinae) of the wrasses (Labridae), yet their skeletal elements remain distinct and useful for archaeological identification. A summary of all the CT scans of the represented taxa and their elements accessible on MorphoSource is given in Table 1.

Digital segmentation

All 3D skeletal models were segmented from preexisting CT scans created by oVert and available on MorphoSource. The CT data were selected not only for their relevance (i.e. they had to be of Australian or Pacific Ocean fish taxa) but also their resolution. Because the bones of the skull and mandibles of actinopterygian (ray-finned) fishes tend to be quite thin, it was important that the CT data were of sufficient resolution relative to the size of the specimen to successfully segment the target elements. Some CT scans were excluded because of low resolution, which prevented reliable segmentation.

The downloaded CT data were processed in the 3D imaging software Mimics 24 (Materialise NV, Belgium), but the steps involved could also be performed with many other softwares (e.g. Dragonfly, which has a free educational version at the time of writing). Following import, the grey values in the 2D

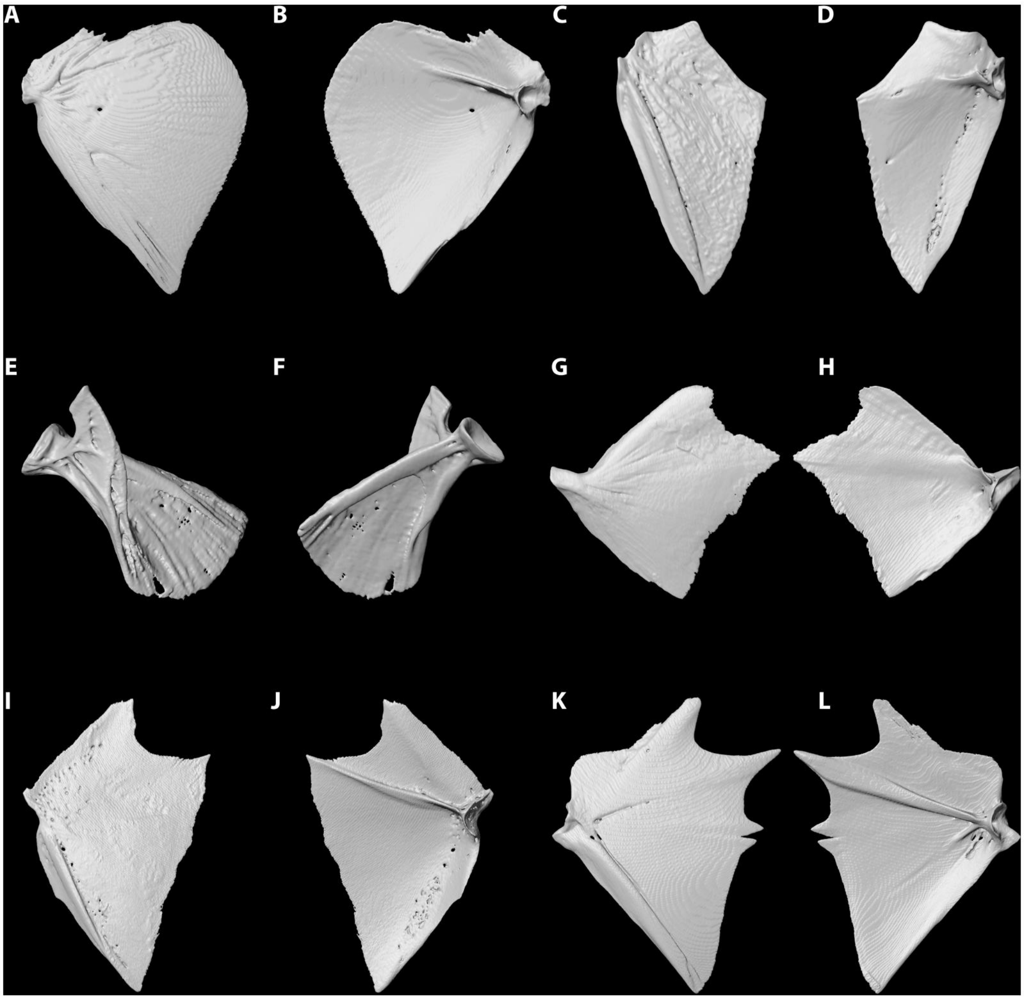

Figure 5. Digital models of left opercles of select fishes. *Anampses caeruleopunctatus* (UF Fish 9937), left opercle in (A) lateral and (B) medial views; *Chaetodontoplus mesoleucus* (KU KUI 41084), left opercle in (C) lateral and (D) medial views; *Diodon hystrix* (UF Fish 116860), left opercle in (E) lateral and (F) medial views; *Makaira nigricans* (UF Fish 166699), left opercle in (G) lateral and (H) medial views; *Neoglyphidodon melas* (UF Fish 120791), left opercle in (I) lateral and (J) medial views; and, *Plectropomus maculatus* (UF Fish 146334), left opercle in (K) lateral and (L) medial views. Not to scale.

slices representing bone density were manually determined for thresholding in order to best visualise the relevant skeletal elements. Due to the different parameters and resolution for each scan, the thresholding values had to be determined on a case-by-case basis. Most of the segmentation was performed manually (or sometimes semi-automatically by interpolating thresholding values across multiple slices) in the 2D previews of the CT scans. Other procedures that were used as part of the segmentation process were Region Grow (e.g. to delete floating pixels), Edit Masks (e.g. to edit an active mask in 2D or 3D preview) and Boolean Operations (e.g. to subtract or unite masks). Following segmentation, the thresholded grey values were reconstructed into three-dimensional surface meshes for each bone of interest. In certain cases, meshes were smoothed within Mimics. The smoothing was done exclusively for models with rough surface textures and was applied only as a cosmetic measure without compromising the information content of the model. This was double-checked by comparing the smoothed model with its non-smoothed counterpart. Once the above steps were completed, the segmented elements were exported as individual 3D meshes in PLY format. All segmented elements were then uploaded open access to the Fishboneviz project page on MorphoSource (https://www.morphosource.org/projects/000568470), where they can be viewed and downloaded. See the section 'Notes for users' below, for a detailed explanation of how to access and cite Fishboneviz.

Fishboneviz outcomes, future directions, and taxonomic expansion

Successful segmentation of the cranial and post-cranial fish elements demonstrated the efficacy of our protocols to produce a useable digital 3D comparative reference collection. The Fishboneviz project was initiated to assess the suitability of these oVert-based scans for distinguishing between key Australasian fish families. At the family-level, differences between

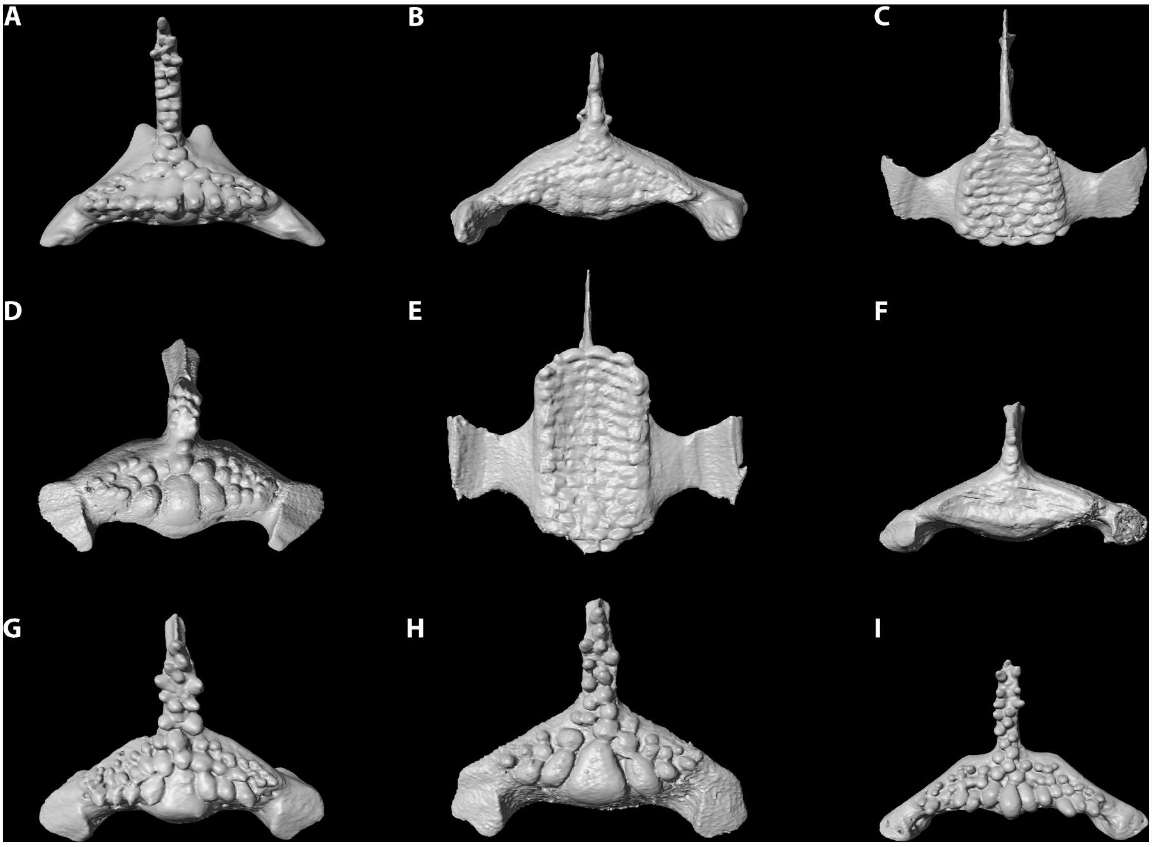

Figure 6. Digital models of the lower pharyngeal grinding plates of select labrids in dorsal views. (A) *Anampses caeruleopunctatus* (UF Fish 9937); (B) *Bodianus mesothorax* (FMNH Fishes 126755); (C) *Cetoscarus bicolour* (UW 040661); (D) *Cheilinus fasciatus* (FMNH Fishes 124051); (E) *Chlorurus bleekeri* (FMN Fishes 118756); (F) *Choerodon anchorago* (FMNH Fishes 119442); (G) *Coris gaimard* (FMNH Fishes 110684); (H) *Halichoeres hortulanus* (FMNH Fishes 126864); and (I) *Thalassoma lunare* (FMNH Fishes 120214). Not to scale.

elements were observable. Hence, the upper and lower pharyngeal grinding plates of wrasse and parrotfish (Labridae) were segmented to test the possibility of observing genus-level differences. The results suggested that the CT scans are able to capture genus-level differences in the surface morphology of fish bone elements. This has allowed a viable reference dataset to be produced. Unsurprisingly, however, the outcomes were heavily influenced by the quality of the CT scan data available for segmentation. Representative examples of the segmented dentary (Figure 2), maxilla (Figure 3), hyomandibular (Figure 4), opercle (Figure 5), lower pharyngeal grinding plate (Figure 6) and last precaudal vertebra (Figure 7), illustrate the high visibility of morphological features useful for taxonomic identification. While only limited perspectives can be viewed in the static Figures (i.e. when the 3D scans are viewed in a fixed 2D plane), full 3D visualisations are available via the Fishboneviz project page on MorphoSource, which facilitates 3D manipulation and viewing.

Given the successful implementation of the segmentation procedures and high useability of the 3D fish bone elements to support both research and teaching, we encourage ongoing collaborations to facilitate the expansion of the collection into the future. Currently, marine fish species have been prioritised, but only one representative species per fish family commonly identified in Australian and Pacific Islands archaeological sites has been segmented to provide a foundational methodology for broader application. In the future, expansion of the database to include freshwater species, the incorporation of additional fish bone elements, and more comprehensive genus- and species-level taxonomic coverage would benefit the development of the collection. A significant time investment is required to learn the process of segmentation, as well as requiring access to appropriate software. Scan quality also greatly influences the time it takes to segment the fish bone elements. For example, if the scan was of exceptionally high quality, the 10 elements segmented per scan could be achieved in a matter of hours, but if the quality was poor or the bone morphology was more complex, this process could take four to five days. There is also the potential to explore the utility of other scanning methods, such as structured light scanning or photogrammetry, to expand the range of media available for the collection. Moving forward, we anticipate that a range of

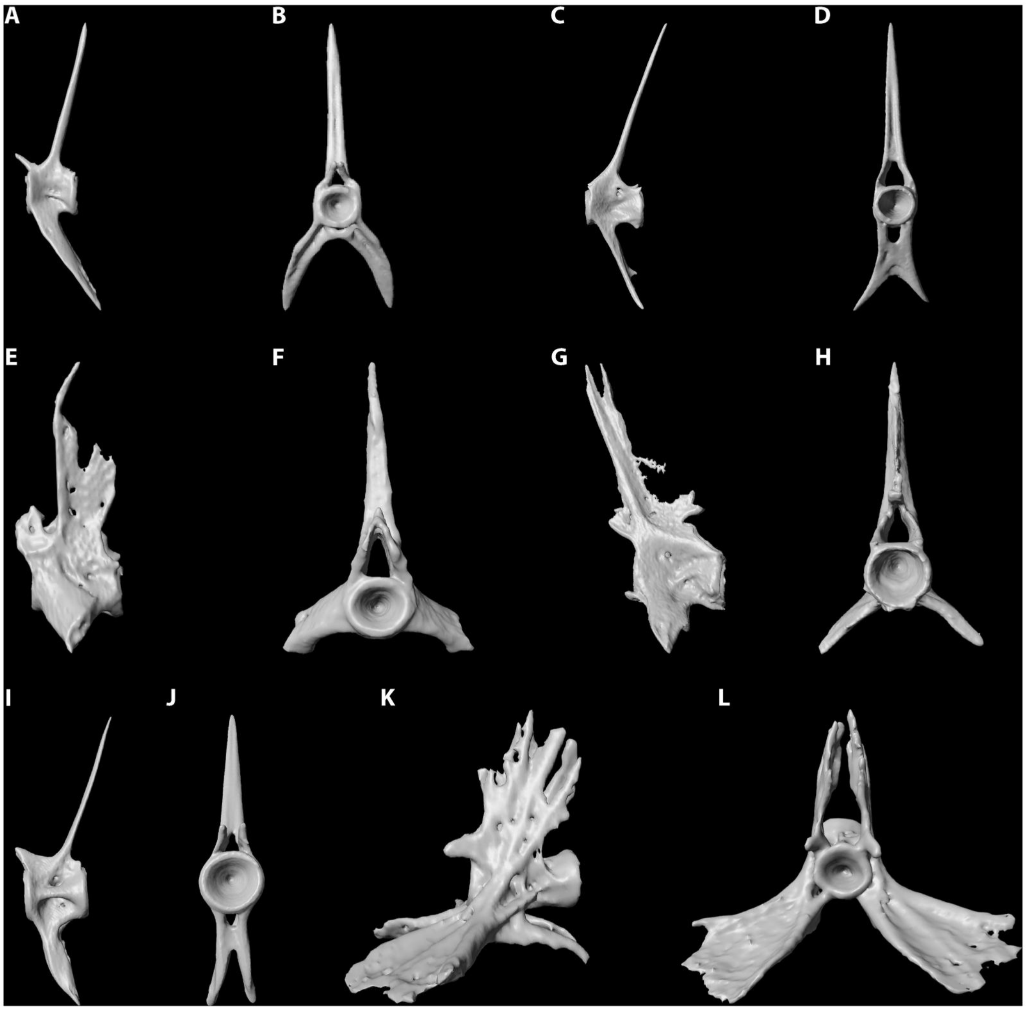

Figure 7. Digital models of last precaudal vertebrae of select fishes. *Anampses caeruleopunctatus* (UF Fish 9937) last precaudal vertebra in (A) left lateral and (B) anterior views; *Cetoscarus bicolour* (UW 040661), last precaudal vertebra in (C) left lateral and (D) anterior views; *Chaetodontoplus mesoleucus* (KU KUI 41084), last precaudal vertebra in (E) left lateral and (F) anterior views; *Naso unicornis* (UW 009507), last precaudal vertebra in (G) left lateral and (H) anterior views; *Plectropomus maculatus* (UF Fish 146334), last precaudal vertebra in (I) left lateral and (J) anterior views; and, *Diodon hystrix* (UF Fish 116860), last precaudal vertebra in (K) left lateral and (L) anterior views. Not to scale.

interested research communities will utilise the published protocols and contribute to Fishboneviz, which in turn would allow the collection to grow into a broader disciplinary initiative by which to support changing research and teaching needs. Supplementary Information 1 provides a guideline for contributing 3D media (CT scans or meshes) to Fishboneviz. The guidelines outline specimen eligibility, data formats, metadata requirements, and upload instructions.

Conclusions

Fishboneviz is the first open access 3D fish bone reference collection that has been developed to support ichthyoarchaeologists working on assemblages from Australia and the Pacific Islands. It is also of relevance to those broadly interested in zooarchaeology and palaeontology. The collection, accessible via MorphoSource, allows the user to view the segmented bones on an internet browser without download. Alternatively, full open access download is available to allow the full range of 3D manipulations. This facilitates ready-use as a quick research reference, but also, given recent emphasis on online academic teaching, provides a resource that could be incorporated into online zooarchaeology practicals or incorporated into lecture content when interaction with physical specimens may not be possible. The establishment of this online collection is a first step towards addressing the limitations currently experienced when trying to access physical fish bone reference collections across Australia and the Pacific Islands. The continued expansion of Fishboneviz is now expected to be underpinned by a broader disciplinary network of interested collaborators, so that the collection can grow according to the broader needs of research and teaching communities into the future.

Notes for users

Accessing Fishboneviz

All digital models generated by Fishboneviz can be accessed on MorphoSource via the project ID (000568470). Since all Fishboneviz 3D models are open access, they can be freely visualised on MorphoSource within an internet browser – no download or registration is necessary. Downloading the 3D models is also available, however a MorphoSource account is a prerequisite. Creating a MorphoSource account is free. Despite being open access, a brief statement (minimum 50 characters) for the purpose of the download of the data is required, as per MorphoSource rules. The statement should briefly explain the reason(s) for downloading the data (such as personal reference, research, education, etc.).

There are many software options that can be used to visualise the downloaded PLY file(s). Two popular examples of freeware that can open PLY files (among many other 3D file formats) are MeshLab (Cignoni et al. 2008; http://www.meshlab.net/) and Blender (Blender Foundation; https://www.blender.org/). Both are available for major operating systems like Windows, macOS, and Linux. Due to the relatively small file size of the individual meshes (most being under 7 MB), it is possible to visualise them with ease on virtually any modern computer with average hardware specifications.

Citation of Fishboneviz

Publications using the Fishboneviz collection for research should (1) cite this publication; (2) adhere to the citation requirements of the original scans that meshes are associated with on MorphoSource; and, (3) include the following statement in the acknowledgements: ‘Fishboneviz was funded by the ARC Centre of Excellence for Australian Biodiversity and Heritage (project number CE170100015)’.

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