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Testing osteometric species determination on zooarchaeological dolphin remains from Late Neolithic and Early Bronze Age sites in Ash-Sharqiyyah, Sultanate of Oman

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ABSTRACT

Different Late Neolithic and Early Bronze Age sites located in the Ras al-Hadd cape and Ras al-Jinz Bay area (Ash-Sharqiyyah South Governorate, Sultanate of Oman) have provided thousands of zooarchaeological dolphin remains suggesting a strong reliance on the exploitation of these animals. Dolphins are hard to identify to the species level due to a highly comparable interspecies osteological morphology as well as a general lack of extensive osteological reference collections. As a result, such remains are frequently identified as "dolphin", without any further species identification being undertaken. In this study, we assess whether an osteometric method for distinguishing the nine dolphin species that are present in Omani waters can be used to identify the zooarchaeological specimens. Zooarchaeology by Mass-Spectrometry (ZooMS) was also undertaken on a subset of the specimens but proved ineffective due to the poor preservation of the material in an arid climate. This evidence strengthens the need for effective species identification methods based on traditional zooarchaeological methods. This research is based on our ongoing analysis of the thousands of dolphin remains from the Omani zooarchaeological assemblages.

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Introduction

Cetacean remains deriving from archaeological contexts are frequently merely identified as "dolphin," "whale," "cetacean," or even "marine mammal" (Smith and Kinahan 1984). The lack of species identification undertaken on cetacean remains can be explained by the limited number of diagnostic skeletal elements. Cetaceans have an extended vertebral column, but due to morphological variation in vertebrae along the column, these are not frequently

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used in the field of zooarchaeology for species identification practices. Additionally, they lack hind limbs, which are frequently used for species identification in the field of zooarchaeology. Furthermore, over 90 cetacean species are recognized, which makes the identification of cetacean remains even harder. Moreover, the lack of extensive osteological cetacean reference collections and the often fragmented state of cetacean remains add to the problem. These aspects combined have led to few attempts being undertaken to optimize species identification practices for cetacean remains.

This lack of pursuit of cetacean species identification practices is also the case for the Ras Al-Hadd cape and the Ras Al-Jinz bay area in the easternmost region of the Sultanate of Oman, where thousands of dolphin remains have been recovered at sites dating from the Late Neolithic (ca. 4500–3200 BCE) to the Early Bronze Age (ca. 3200–2000 BCE). Dolphins make up an extraordinary large proportion of the zooarchaeological assemblages of these sites, representing one of the major taxonomic groups. This suggests a heavy reliance on the exploitation of marine fauna (Mosseri-Marlio 2002; Borgi et al. 2012; Genchi and Maiorano 2019).

Species identification of the archaeological remains is necessary to reconstruct the dynamics of human–cetacean relationships in Neolithic and Bronze Age Oman and the changing rates of exploitation. Additionally, as various species require different methods of hunting (e.g. coastal or pelagic hunting), taxonomic identification will contribute to our understanding of these early dolphin hunting strategies (Mosseri-Marlio 2002). Moreover, this will potentially allow reconstructing the past spatiotemporal ranges of various cetacean taxa and to what degrees they have been targeted by hunters.

New methods have been developed for distinguishing osteologically comparable species, including Zooarchaeology by Mass-Spectrometry (ZooMS) and aDNA analysis. Unfortunately, these methods are not always feasible due to financial costs, required access to dedicated laboratories, and their destructive nature. This paper explores the possibility to perform osteometric analysis on dolphin specimens to accomplish species identification in an accessible, reproducible, and nondestructive manner. A similar approach has been applied on the atlas of different cetaceans by Thongcharoenchaikit and Eda (2020) and showed promising results. This paper focuses on additional skeletal elements and different taxa. The identifications based on the osteometric comparison were tested using ZooMS. The application of the method on archaeological material will provide a better understanding of ancient human–cetacean interaction in the region.

Material and methods

Over 4000 dolphin bone fragments have been recovered in archaeological excavations at the main Late Neolithic and Early Bronze Age sites along the coastal stretch from Ras Al-Hadd to Ras al-Jinz (Figure 1). The area marks the easternmost jut of the Arabian Peninsula. The sites considered include Ras Al-Hadd HD-1, Ras Al-Hadd HD-2, Ras Al-Hadd HD-5, Ras Al-Hadd HD-6, Ras Al-Jinz RJ-2, and Ras Al-Jinz RJ-3. Dolphin remains were collected during different excavation seasons that span over 40 years of research (Cleuziou and Tosi 2020b). All the archaeological finds were collected employing dry sieving of the sand sediment with a screen mesh of 5 mm.

The zooarchaeological studies have been completed for Ras Al-Jinz RJ-2 and Ras Al-Hadd HD-2, while research is still underway for Ras Al-Hadd HD-1, HD-5 and

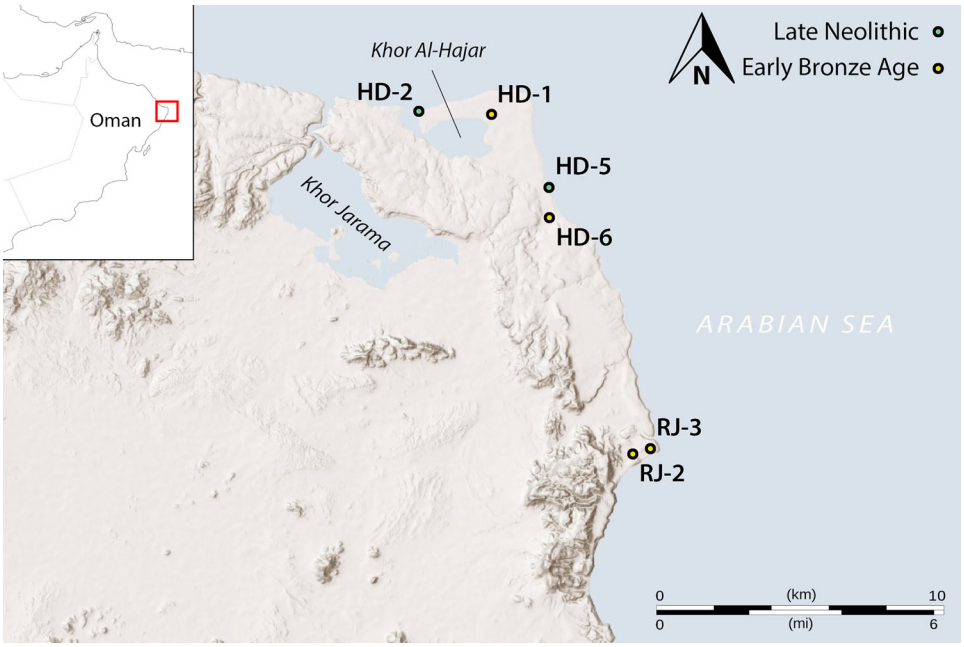

Figure 1. Location of sites discussed within the eastern tip of Oman.

Table 1. Overview of sites analyzed as part of this study, estimated cetacean bone fragments collected (* ongoing studies ° ongoing excavations), number of identified Specimens (NISP) considered so far, and number of specimens sampled for ZooMS analysis.

Site	Chronology	Period	Quantity of dolphin remains collected	NISP considered	ZooMS samples
HD-1*	2600 BCE – 2000 BCE	Umm an-Nar	ca. 2500 frag.	428	25
HD-2	3700 BCE – 3200 BCE	Late Neolithic II	20 frag.	20	4
HD-5*	4000 – 3200 BCE/ 2500 – 2000 BCE	Late Neolithic and Umm an-Nar	ca. 500 frag.	229	14
HD-6*	3100 BCE – 2700 BCE	Hafit	ca. 20 Kg	12	7
RJ-2	2500 BCE – 2000 BCE	Umm an-Nar	ca. 200 frag.	44	9
RJ-3*°	2500 BCE – 2000 BCE	Umm an-Nar	ca. 1000 frag.	346	20
TOTAL			**ca. 4000 fragments**	**1079**	**79**

HD-6, for which the faunal remains of marine mammals have simply been separated from the others (see estimated quantity). For these latter sites, only a small part has so far been considered and constitutes the archaeological dataset for this study (see the Number of Identified Specimens – NISP) (Table 1). Only the faunal assemblage of Ras Al-Jinz RJ-3 increases in size every year due to the continuation of archaeological excavation.

Our ongoing work on the dolphin remains and its contextualization will be described in a future publication. This paper will focus solely on the osteometric analysis and its potential for improving our understanding of ancient dolphin exploitation in Oman.

Ras Al-Hadd HD-1

The HD-1 site at Ras Al-Hadd has provided local copper fishing gear, local and imported ornaments, and a large number of ceramics from the Indus Civilization

(present-day Pakistan and North-west India) dating to the second half of the third millennium BCE. Thanks to its strategic location on a narrow sandy bar separating the deep ocean waters from the shallow Al-Hajar lagoon, the site was an ideal shelter for mooring large fishing and cargo ships. HD-1 has been interpreted as a workshop and processing area for fishermen and a seasonal trading station (Cattani et al. 2019).

Ras Al-Hadd HD-2

The HD-2 site is located at Ras Al-Hadd at the very entrance of Al-Hajar lagoon. It has been dated to the fourth millennium BCE, from the Late Neolithic II to the beginning of the Early Bronze Age. The site has been identified as a flint-knapping area and potentially represented a temporary settlement or encampment (Genchi and Maiorano 2019). Numerous shell remains as well as fishing gear (net sinkers and fishhooks made of shells) have been uncovered. The only faunal remains collected at the site were 20 dolphin vertebrae, from the Late Neolithic II levels discovered, which is by far the lowest amount among the sites considered.

Ras Al-Hadd HD-5

The HD-5 site is located on a small rocky hill facing the ocean. It had two separate occupation phases. The first phase dates to the Late Neolithic in the fourth millennium BCE. The site was abandoned at the end of the fourth millennium BCE and resettled during the second half of the third millennium BCE. The material culture and the faunal remains show the site was oriented toward the exploitation of marine resources during both occupational phases (Borgi et al. 2012).

Ras Al-Hadd HD-6

The HD-6 site is located 1.3 km to the south of HD-5. It was a large and complex walled settlement dating to the first phase of the Early Bronze Age in Oman, the so-called Hafit period, spanning the late fourth millennium and the early centuries of the third millennium BCE (Azzarà and Cattani 2020). New food production techniques relating to the introduction of oasis farming and breeding and the large-scale introduction of copper working stimulated the nucleation of small groups of fisherfolks and gatherers into larger, more permanent settlements supporting craft specialization. Subsistence was based on the exploitation of marine resources, including various species of pelagic and coastal fish, but also mollusks, turtles, and dolphins.

Ras Al-Jinz RJ-2 and RJ-3

The two Ras al-Jinz Bay sites, although considered archaeologically independent, were likely compounds of a single settlement that was occupied from the second half of the fifth millennium BCE onward. Excavations at RJ-2 have revealed a short Late Neolithic phase followed by the foundation of a large Early Bronze Age settlement dating to the Umm an-Nar period (second half of the third millennium BCE) (Cleuziou and Tosi

2000a). Recent excavations at RJ-3 showed a continuous occupation from the Neolithic to the end of the Early Bronze Age instead (De Rorre et al. 2020). For these sites, dolphin remains make up a considerable part of the zoo archaeological assemblage.

While high numbers of dolphin remains have been recovered from the sites, taxonomic identification to the species level has not been attempted. Based on the size of the specimens, the vast majority belong to small to medium-sized dolphin taxa (up to the size of the common bottlenose dolphin (*Tursiops truncatus*)/Risso's dolphin (*Grampus griseus*)). Moreover, based on the morphology, three specimens (a mandible, rib, and vertebral fragment) from HD-6 (square US812) belong to a very large dolphin species, tentatively identified as pilot whale (*Globicephalinae* sp.). This indicates that larger taxa were also occasionally taken, though the smaller taxa appear to be more frequently targeted.

The majority of the zooarchaeological specimens were vertebrae, which due to variation along the vertebral column are hard to identify to the species level. Future studies should attempt to assess to what extent vertebral remains can be useful for species identification purposes. Moreover, the crania and the mandibles were highly fragmented, and though these elements, together with teeth, are useful for species identification, the focus of this study was put on skeletal elements which showed lesser signs of fragmentation and allowed for multiple measurements to be undertaken on them. Therefore, the atlases, scapulae, humeri, radii, and ulnae, were selected in order to assess what these skeletal elements can contribute to reconstructing ancient dolphin hunting practices. The sites combined provided seven atlases, 13 scapulae, 15 humeri, 12 radii, and 13 ulnae that allowed for measurements to be undertaken.

Baldwin et al. (2021) report that the common bottlenose dolphin (*T. truncatus*), Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), common dolphin (*Delphinus delphis*), spinner dolphin (*Stenella longirostris*), pantropical spotted dolphin (*Stenella attenuata*), striped dolphin (*Stenella coeruleoalba*) Risso's dolphin (*G. griseus*), Indian humpback dolphin (*Sousa plumbea*), and rough-toothed dolphin (*Steno bredanensis*) are present in Omani waters. Even though different species might have occurred in the area in the past, it was decided for this study to focus on these nine dolphin species. For the size, weight, pod size, modern-day distribution in Omani waters, and feeding behavior of the nine taxa, see Baldwin et al. (2021).

Standardized measurements on the selected skeletal elements (four on the atlas, five on the scapula, seven on the humerus, five on the radius, and six on the ulna) were undertaken on the modern specimens of these selected nine dolphin species and on the zooarchaeological specimens. Measurements were exclusively taken on specimens for which the epiphyses were fused. These measurements are based on those developed by Von den Driesch (1976) and adapted by author YvdH for cetaceans (see Supplementary File S1). Measurements on modern specimens were taken at various museums, including measurements on 1434 skeletal elements at the Smithsonian Institution, 29 at the Natural History Museum Rotterdam, six at the National Museums of Scotland, 17 at the Muséum National d'Histoire Naturelle Paris, six at the Naturalis Biodiversity Center Leiden, 100 at the Natural History Museum of Oman, 84 at the Zoologisk Museum Copenhagen, 20 at the Museu Nacional de História Natural e da Ciência Lisbon, 20 at the Cambridge Zoology Museum, and nine at the Cambridge Zooarchaeology laboratory

at the University of Cambridge. While ample material was available for some species, limited material was available for others, limiting our ability to fully assess the osteometric potential for all nine species.

Moreover, as the establishment of various species and the redefining of full species and subspecies is still a topic of debate, the labels at various museum collections are likely no longer up to date which makes research even harder. For example, *D. delphis* and *Delphinus capensis* are now thought to be one species, *Tursiops truncatus* and *T. aduncus* were separated in 1998, and the genus *Sousa* was split recently into four species (*Sousa plumbea*, *Sousa chinensis*, *Sousa teuszii*, and *Sousa sahulensis*) (Würsig, Thewissen and Kovacs 2018). Because of this taxonomic flux, we decided to include any *Delphinus* sp. specimen into a "*Delphinus* sp." category and any *Sousa* sp. specimen into a "*Sousa* sp." category.

Statistical analyses were conducted using the software PAST version 4.11 (Hammer, Harper, and Ryan 2001), except for the Linear Discriminant Analysis (LDA), which was run in R (R Core Team 2022). All measurements were natural log-transformed. Two-tailed two-sampled paired t-tests were used to compare left- and right-sided elements of the same individuals for the different taxa. Using this test, means were compared from the sums of all measured variables per specimen. The test predicts the probability of equality among the measurements with an alpha of 0.05 indicating significant differences. For variables for which lower than ten paired measurements were present, the non-parametric Wilcoxon signed-rank test was also employed.

Subsequently, we undertook metric evaluation based on taxonomic separation by testing the significance of patterning among the nine taxa using one-way PERMANOVA to evaluate between-group significance. This was done for the atlas, scapula, humerus, radius, and ulna. When available, both left- and right-sided elements were incorporated. PERMANOVA was chosen since the sample size for some taxa and elements was low (<10). A similar analysis was undertaken by Emery et al. (2016) in their study on testing osteometric turkey species determination.

Following this, we undertook two-tailed two-sample pairwise t testing of the equality of means between the different taxa, to evaluate interspecies significance. This was done using all the measurements taken for the five elements for the nine taxa.

To assess a more robust model of individual variation among specimens per group and the factors influencing metric distributions, we subjected the complete set of measurements per element to principal component analysis (PCA) labeled by taxa. PERMANOVA and PCA tests require excluding any specimens for which not all measurements could be taken. As a result, specimen numbers vary between tests. Next, LDA was undertaken using the R package 'mass' (Venables and Ripley 2002 to assign the zooarchaeological specimens to species). The model accuracy was assessed based on leave-one-out cross-validation.

While multivariate analysis is promising and allows for some species separation, the method will likely only rarely allow for implementation on actual zooarchaeological material. Due to various taphonomic factors, the zooarchaeological specimens are often fragmented and will not allow for the full sweep of measurements to be taken. Therefore, we attempted to compare each separate measurement taken on archaeological specimens with the reference material to assess whether species identification is possible.

To assess the univariate measurements taken, the range of measurements obtained for each taxon and each element in the modern reference specimens dataset was considered. Outliers, defined as measurements falling 1.5 x IQR beyond the first and third quartiles, were excluded from each set of measurements. Subsequently, all measurements undertaken on the zooarchaeological specimens were individually compared to the modern measurement ranges. If a measurement of a zooarchaeological specimen fell within a range of a modern taxa it was counted as a match. The number of matches per zooarchaeological specimen were counted and the specimen was assigned to the taxon with the highest number of matches.

While heavily influenced by the sample size for the modern specimens, this univariate method permits us to include specimens for which the full sweep of measurements could not be obtained. This is beneficial for sample size since the bulk of the zooarchaeological material was heavily weathered or fragmented. The results were subsequently compared to the multivariate approach.

Subsequently, ZooMS was undertaken to identify the specimens to the species or genus level. ZooMS provides taxonomic identifications based on the differences in the mass of the peptides which arise due to sequence differences between the species (Buckley et al. 2014). From each selected specimen 0.1 gram was sampled. ZooMS was performed at the BioArCh-Center, University of York, UK, following the methods outlined in (Rodrigues et al., 2018)Rodrigues et al. (2018) for collagen extraction, purification, mass spectrometry, and peptide mass fingerprinting identified. Demineralization was accomplished by using 0.6 M hydrochloric acid, and subsequent gelatinization through incubation in 100 μL of 50 mM ammonium bicarbonate at 65 °C for one hour. The collagen was digested through incubation with 0.4 μg of trypsin overnight at 37 °C and subsequently purified using a 100 μL C18 resin ZipTip® pipette tip (EMD Millipore). The samples were spotted in triplicate with a matrix of α-cyano-4-hydroxycinnamic acid on a 384 spot MALDI target plate, with calibration standards and run on a Bruker ultraflex III MALDI TOF/TOF mass spectrometer. Averaged spectra were created from the replicates for each specimen using mMass software (Strohalm et al. 2008).

Results

Multivariate analysis

For the osteometric comparison of modern specimens, we took measurements for the nine taxa in the museums and institutions visited. We used two-tailed two-sampled paired t-tests to compare metrics between left and right-sided elements. The full results can be found in Supplementary Tables S1-S4. Overall, the *P*value indicate the null hypothesis of equality cannot be rejected for most measurements and indicate left and right-sided elements can be considered metrically equal. However, the pair-wise testing on groups with $a > 10$ sample size suggested statistically significant differences between the sides for the following measurements: Breadth of the proximal head (Bp) and smallest breadth of the diaphysis (SB) for the humerus of *G. griseus*; SB and greatest length of the lateral side (GLl) for the humerus of *T. truncatus*; proximal depth (Dp) for the humerus of *S. bredanensis*; greatest length (GL) for the radius of *Delphinus* sp.; and proximal depth (Dp) and smallest breadth of the diaphysis (SB) for the ulna of

G. griseus. Due to the large number of tests and the low number of statistically significant results, these results are unlikely to represent any large, statistically significant differences. Only *Grampus griseus* had more than one or two metrics with significant differences between left and right.

Subsequently, we undertook one-way PERMANOVA testing. For all five skeletal elements, the PERMANOVA probability (p) that the specimens were randomly distributed was very low (0.0001; Table 2). Two-tailed two-sample pairwise t testing of the equality of means between the nine taxa indicated significant separation for almost all skeletal elements (Table 2). Only a small number of groups showed no significant separation, likely due to a relatively small sample size. Therefore, these tests indicate that the different taxa are separate groups, and the spread of the measurements are statistically different for all the elements. Thus, we are reasonably confident that specimens can be identified using these measurements.

The PCA analysis indicated that the first two components explained at least 94% of the variation among the metrics in all cases (see Figure 2; Supplementary Figures S1–S8; Supplementary Table S5). The PCA for principal component 1 and 2 for the atlas provided in Figure 2, indicates that most taxa overlap with several others. *S. longirostris* only slightly overlaps with *S. attenuata*, while *G. griseus* only overlaps with *Tursiops truncatus* and *T. aduncus*. The PCA plots for the other skeletal elements (Supplementary Figures S1–S8) show similar trends.

In the PCAs, we have also plotted the archaeological specimens that allowed for the full sweep of measurements to be performed. This was only possible for two atlases, five humeri, two radii, and one ulna, of which most derive from Ras Al-Hadd 1. All plotted within or close to the *Stenella* taxa clusters.

LDA results for the ten specimens for which the full sweep of measurements were available are displayed with a posterior probability of group membership displayed to two decimal places in Table 3. For seven specimens, the posterior probability was highest for *S. longirostris*, while for the remaining three it was highest for *S. attenuata*.

We assessed the model's accuracy using leave-one-out cross-validation (Supplementary Table S6-8). The accuracy of the cross-validation of the LDA model overall was good with the majority of data points being self-assigned (between 69.5–74.2% for the various elements). However, for the less strongly represented taxa in our dataset (*Sousa* sp., *S. attenuata*, *S. longirostris* and *T. aduncus*) the accuracy was expectably lower.

While few zooarchaeological specimens could be subjected to this multivariate method, of those that could, the majority appear to belong to smaller species, most likely *S. longirostris* or *S. attenuata*. If each measurement is only considered separately in a univariate manner, more data could potentially be extracted from the zooarchaeological specimens. This will be explored in the next section.

Univariate analysis

To assess the univariate measurements, the range of measurements taken on the modern reference specimens dataset for each taxon and each element were compared with the archaeological specimens. The ranges are provided in Supplementary Table S9 and the measurements for the archaeological specimens in Supplementary Table S10. When

Table 2. PERMANOVA and pairwise test results for selected taxa (P.N.: permutation N; TSOS: total sum of squares; WGSOS: within-group sum of squares).

				Pairwise (bold = significant)								
PERMANOVA (Permutation N: 9999)				Delphinus sp.	Grampus griseus	Sousa sp.	Stenella attenuata	Stenella coeruleoalba	Stenella longirostris	Steno bredanensis	Tursiops aduncus	Tursiops truncatus
ATLAS			N	53	26	6	6	43	10	23	12	37
Total N	194	*Delphinus* sp.	53		**0.0001**	**0.0003**	**0.001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
P. N	9999	*Grampus griseus*	26	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0002**
TSOS:	19.33	*Sousa* sp.	6	**0.0003**	**0.0001**		**0.0021**	**0.0007**	**0.0003**	**0.0271**	0.0705	**0.0016**
WGSOS:	4.863	*Stenella attenuata*	6	**0.001**	**0.0001**	**0.0021**		**0.0001**	**0.0045**	**0.0001**	**0.0001**	**0.0001**
F:	73.98	*Stenella coeruleoalba*	43	**0.0001**	**0.0001**	**0.0007**	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**
p (same):	**0.0001**	*Stenella longirostris*	10	**0.0001**	**0.0001**	**0.0003**	**0.0045**	**0.0001**		**0.0001**	**0.0001**	**0.0001**
		Steno bredanensis	23	**0.0001**	**0.0001**	**0.0271**	**0.0001**	**0.0001**	**0.0001**		**0.0001**	**0.0001**
		Tursiops aduncus	12	**0.0001**	**0.0001**	0.0705	**0.0001**	**0.0001**	**0.0001**	**0.0001**		**0.0221**
		Tursiops truncatus	37	**0.0001**	**0.0002**	**0.0016**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0221**	
SCAPULA			N	65	46	8	13	80	16	36	14	83
Total N	361	*Delphinus* sp.	65		**0.0001**	**0.0001**	**0.0001**	**0.0023**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
P. N	9999	*Grampus griseus*	46	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
TSOS:	102.6	*Sousa* sp.	8	**0.0001**	**0.0001**		**0.0002**	**0.0001**	**0.0001**	0.1347	0.1345	**0.0019**
WGSOS:	20.47	*Stenella attenuata*	13	**0.0001**	**0.0001**	**0.0002**		**0.0001**	**0.0006**	**0.0001**	**0.0001**	**0.0001**
F:	151.1	*Stenella coeruleoalba*	80	**0.0023**	**0.0001**	**0.0001**	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**
p (same):	**0.0001**	*Stenella longirostris*	16	**0.0001**	**0.0001**	**0.0001**	**0.0006**	**0.0001**		**0.0001**	**0.0001**	**0.0001**
		Steno bredanensis	36	**0.0001**	**0.0001**	0.1347	**0.0001**	**0.0001**	**0.0001**		**0.0018**	**0.0001**
		Tursiops aduncus	14	**0.0001**	**0.0001**	0.1345	**0.0001**	**0.0001**	**0.0001**	**0.0018**		**0.0096**
		Tursiops truncatus	83	**0.0001**	**0.0001**	**0.0019**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0096**	
HUMERUS			N	61	44	7	10	72	12	44	11	49
Total N	310	*Delphinus* sp.	61		**0.0001**	**0.0002**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
P. N	9999	*Grampus griseus*	44	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
TSOS:	102.6	*Sousa* sp.	7	**0.0002**	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0076**	0.1066	**0.0005**
WGSOS:	20.47	*Stenella attenuata*	10	**0.0001**	**0.0001**	**0.0001**		**0.0002**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
F:	151.1	*Stenella coeruleoalba*	72	**0.0001**	**0.0001**	**0.0001**	**0.0002**		**0.0001**	**0.0001**	**0.0001**	**0.0001**
p (same):	**0.0001**	*Stenella longirostris*	12	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**		**0.0001**	**0.0001**	**0.0001**
		Steno bredanensis	44	**0.0001**	**0.0001**	**0.0076**	**0.0001**	**0.0001**	**0.0001**		0.177	**0.0207**
		Tursiops aduncus	11	**0.0001**	**0.0001**	0.1066	**0.0001**	**0.0001**	**0.0001**	0.177		**0.0088**
		Tursiops truncatus	49	**0.0001**	**0.0001**	**0.0005**	**0.0001**	**0.0001**	**0.0001**	**0.0207**	**0.0088**	
RADIUS			N	30	30	7	10	20	11	22	10	52
Total N	192	*Delphinus* sp.	30		**0.0001**	0.0662	**0.0001**	**0.0003**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
P. N	9999	*Grampus griseus*	30	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
TSOS:	45.65	*Sousa* sp.	7	0.0662	**0.0001**		**0.0001**	**0.0002**	**0.0001**	**0.0008**	**0.0189**	**0.0001**
WGSOS:	8.392	*Stenella attenuata*	10	**0.0001**	**0.0001**	**0.0001**		**0.0001**	**0.0276**	**0.0001**	**0.0001**	**0.0001**
F:	101.5	*Stenella coeruleoalba*	20	**0.0003**	**0.0001**	**0.0002**	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**

(*continued*)

Table 2. Continued.

				Pairwise (bold = significant)								
PERMANOVA (Permutation N: 9999)				Delphinus sp.	Grampus griseus	Sousa sp.	Stenella attenuata	Stenella coeruleoalba	Stenella longirostris	Steno bredanensis	Tursiops aduncus	Tursiops truncatus
p (same):	**0.0001**	*Stenella longirostris*	11	**0.0001**	**0.0001**	**0.0001**	**0.0276**	**0.0001**		**0.0001**	**0.0001**	**0.0001**
		Steno bredanensis	22	**0.0001**	**0.0001**	**0.0008**	**0.0001**	**0.0001**	**0.0001**		0.0698	**0.0067**
		Tursiops aduncus	10	**0.0001**	**0.0001**	**0.0189**	**0.0001**	**0.0001**	**0.0001**	0.0698		**0.0205**
		Tursiops truncatus	52	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0067**	**0.0205**	
ULNA			N	29	25	7	10	18	11	22	11	44
Total N	177	*Delphinus* sp.	29		**0.0001**	0.1884	**0.0001**	**0.0009**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
P. N	9999	*Grampus griseus*	25	**0.0001**		**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
TSOS:	49.97	*Sousa* sp.	7	0.1884	**0.0001**		**0.0007**	**0.037**	**0.0001**	**0.0006**	**0.0107**	**0.0001**
WGSOS:	9.867	*Stenella attenuata*	10	**0.0001**	**0.0001**	**0.0007**		**0.0002**	**0.0031**	**0.0001**	**0.0001**	**0.0001**
F:	85.34	*Stenella coeruleoalba*	18	**0.0009**	**0.0001**	**0.037**	**0.0002**		**0.0001**	**0.0001**	**0.0001**	**0.0001**
p (same):	**0.0001**	*Stenella longirostris*	11	**0.0001**	**0.0001**	**0.0001**	**0.0031**	**0.0001**		**0.0001**	**0.0001**	**0.0001**
		Steno bredanensis	22	**0.0001**	**0.0001**	**0.0006**	**0.0001**	**0.0001**	**0.0001**		0.1384	**0.0001**
		Tursiops aduncus	11	**0.0001**	**0.0001**	**0.0107**	**0.0001**	**0.0001**	**0.0001**	0.1384		**0.003**
		Tursiops truncatus	44	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.003**	

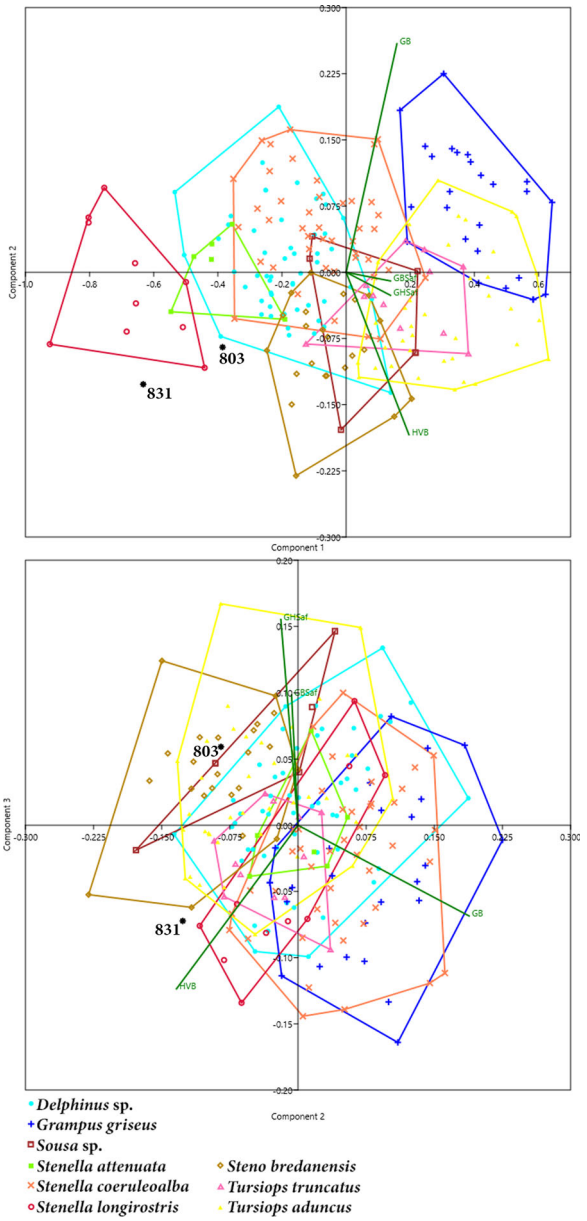

Figure 2. PCA for atlas, components 1 and 2; 2 and 3. Specimen 803 from Ras al-Hadd 1 and specimen 831 from Ras al-Hadd 5 plotted as well.

a measurement on an archaeological specimen fell within the range of the modern measurements it was considered a match. A specimen could match with multiple taxa. A total of 163 measurements on 60 specimens were compared this way. This method is flawed as it relies heavily on the sample size of each measurement per skeletal element per taxon. Therefore, taxa for which fewer skeletal materials were available will be heavily underrepresented. It does, however, provide an idea of which taxa were potentially caught, although future more robust analysis building on a larger sample size will have to be undertaken to confirm these hypotheses.

Table 3. Linear discriminant analysis results are displayed with a posterior probability of group membership.

Skeletal element	Site	Specimen	*Delphinus* sp.	*Grampus griseus*	*Sousa* sp.	*Stenella attenuata*	*Stenella coeruleoalba*	*Stenella longirostris*	*Steno bredanensis*	*Tursiops aduncus*	*Tursiops truncates*
Atlas	HD-1	803	0.27	0.00	0.01	**0.39**	0.00	0.03	0.29	0.00	0.00
	HD-5	831	0.01	0.00	0.00	0.24	0.00	**0.74**	0.00	0.00	0.00
Humerus	HD-1	75	0.01	0.00	0.00	**0.65**	0.02	0.31	0.00	0.00	0.00
	HD-1	103	0.01	0.00	0.00	**0.65**	0.03	0.32	0.00	0.00	0.00
	HD-1	737	0.01	0.00	0.00	0.42	0.01	**0.56**	0.00	0.00	0.00
	HD-1	806	0.01	0.00	0.00	0.16	0.03	**0.81**	0.00	0.00	0.00
	HD-1	818	0.05	0.00	0.00	0.27	0.09	**0.59**	0.00	0.00	0.00
Radius	HD-1	102	0.02	0.00	0.01	0.05	0.25	**0.67**	0.00	0.00	0.00
	HD-1	630	0.02	0.00	0.00	0.05	0.45	**0.48**	0.00	0.00	0.00
Ulna	HD-1	805	0.02	0.00	0.00	0.39	0.04	**0.55**	0.00	0.00	0.00

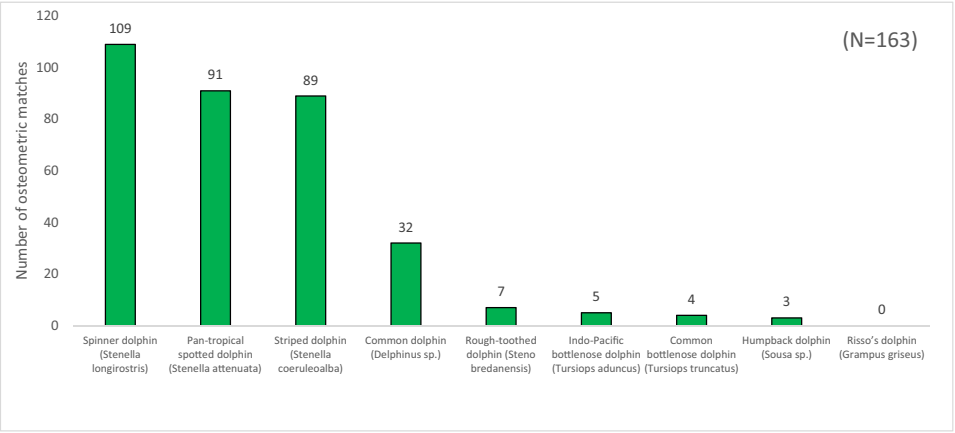

Figure 3. Number of matches per measurement undertaken on the 60 specimens for which measurements (total of 163 measurements) could be undertaken.

Based on this method, *S. longirostris*, *S. attenuata*, and *S. coeruleoalba* have the most matches with the reference material (Figure 3). This aligns with the multivariate analysis results. *G. griseus* has no matches with any of the zooarchaeological material, while a considerable set of reference measurements were available for this species. The other medium to large taxa (*Delphinus* sp., *S. bredanensis*, *Sousa* sp., *T. aduncus*, and *T. truncatus*) display a similar trend as *G. griseus* and only have limited matches with the modern dataset, suggesting a stronger reliance on the smaller dolphin taxa.

A second method was undertaken by assigning the archaeological specimens to the taxon with which they have the highest number of matches. If three measurements could be obtained on one specimen and two taxa shared the highest number of osteometric matches, they received half a match. If three taxa matched, they received a third, etc. Again, *S. longirostris*, *S. attenuata*, and *S. coeruleoalba* matched most frequently with the zooarchaeological material (Supplementary Figure S9). A total of 23 specimens had the highest number of matches with just one taxon (19 *S. longirostris*, two *S. coeruleoalba*, and two *S. attenuata*). Five specimens did not match with any taxa, which might result from a lack of data for some species and the impact of fragmentation of precluding more than one or two measurements on the archaeological specimens. One

Figure 4. Morphological comparison of four humeri (specimens 818, 75, 806, and 809) to their LDA taxa identifications (*S. longirostris* (left humerus specimen 1981-159 part of the Muséum national d'Histoire naturelle, Paris), *S. attenuata* (right humerus specimen 571515 part of the Smithsonian Institution) *T. truncatus* (left humerus specimen 550097 part of the Smithsonian Institution collection).

large humerus (unfused proximally) could be measured on the distal end but did not match with *Stenella* spp. Instead, it had matches with *T. truncatus*, *T. aduncus*, *Delphinus* sp., and *S. bredanensis*, indicating that this juvenile individual was larger than the *Stenella* taxa and must have belonged to a larger species (Figure 4). While this is only one specimen, it suggests that the dolphin hunters more frequently targeted smaller dolphins, but also occasionally took larger species.

The ten specimens that were subjected to Linear Discriminant Analysis (Table 3) were compared to the univariate results (Supplementary Table S11). In comparison, the univariate method showed mixed results with the multivariate method. Five specimens were identified to the same taxon, three specimens were identified to two or three taxa using the univariate method of which one matched the LDA results, while the univariate method identified two specimens as another taxon. This is likely affected by the varying sample size for the reference specimens for the different taxa, making the multivariate method the stronger method.

ZooMS analysis

ZooMS analysis was undertaken to test the results of the univariate and multivariate osteometric analysis. For this study, 79 dolphin specimens from the six sites were selected (Supplementary Table S12). A variety of skeletal elements were selected, including vertebrae, scapulae, humeri, radii, ulnae, and mandibles. These specimens represent all sites and a wide range of time periods. Unfortunately, due to the arid environmental conditions, the collagen preservation proved to be poor and not a single specimen provided any results.

Discussion

Species-level identification of zooarchaeological specimens can be a significant challenge for zooarchaeologists. Techniques such as ZooMS and ancient DNA analyses are often not viable for poorly preserved specimens, highlighting the need to develop alternative methods of species identification. Osteometric approaches can potentially fill this need. We evaluated osteometric methods for dolphin species identification, statistically testing the viability of this approach by assessing intra- and interspecies variation among selected skeletal elements to determine which metric traits are useful for species separation. The PERMANOVA, pairwise tests, LDA, and leave-one-out cross-validation tests employed as part of this study indicate that osteometric analysis employing the designed measurements is a valid tool to identify archaeological dolphin remains to the species level for all the skeletal elements considered. Between 69.5% and 74.2% of the elements were self-assigned using the cross-validation of the LDA model. The accuracy was less for the less strongly represented taxa in this study (*Sousa* sp., *S. attenuata*, *S. longirostris* and *T. aduncus*). Therefore, the reference sample size needs to be expanded for some of the taxa in order to fully make use of the method's potential. Additionally, sexual dimorphism might have affected the results of the analysis (Caspar and Begall 2022). However, to assess sexual dimorphism an even larger dataset of both male and female individuals is required. This should be explored in the future.

Lateralized variation between left and right-sided elements was assessed. When performing two-sampled paired t-tests on the various taxa, only one or two of the full sweep of measurements for all the skeletal elements considered proved statistically significantly larger for one side. This indicates that there is no statistical variation between left and right-sided elements. The only exception is the *G. griseus* for which a total of four metric traits indicated a statistically significant lateralized difference. Visser et al.

(2021) determined that Risso's dolphins perform dives with intense stroking and right-sided lateral rotation. This might have affected the osteology of the pectoral flippers of the dolphins, which expressed itself during the osteometric analysis.

Despite these shortcomings of this proof of concept study, the results for both multivariate and univariate approaches on the archaeological remains demonstrate that at least three species were hunted by the residents of the sites of Ras al-Hadd and Ras al-Jinz: *S. longirostris*, *S. attenuata*, and another larger species based on the finding of one large humerus. The results of this study provide a foundation for future efforts to employ osteometric analysis in order to achieve species identification for cetacean remains.

Conclusion

Dolphin remains from Ras al-Hadd and Ras al-Jinz have proven to be hard to identify to species based on traditional zooarchaeological morphological comparisons using museum reference specimens because of the limited diagnostic features useful for species identification as well as the often fragmented state of archaeological specimens. The testing of univariate and multivariate osteometric methods for species identification has indicated that the methods can be used to differentiate closely related species and are potentially valuable alternatives for destructive biomolecular methods. It can be concluded that multiple dolphin species were targeted, but that the majority of the specimens derived from the smaller taxa, i.e. *S. longirostris* or *S. attenuata.*

Future studies should strive to increase sample sizes and apply additional statistical analyses to fully assess the potential of osteometric species identification of dolphin remains. This will subsequently allow for an improved understanding of early dolphin hunters in Oman and other regions globally. The archaeology of the sites in relation to dolphin hunting will be considered more in depth in a future study.

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