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Body size from unconventional specimens: A 3D geometric morphometrics approach to fishes from Ancestral Pueblo Contexts

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ABSTRACT

Animal body size estimation from zooarchaeological specimens often relies on specific, one-dimensional (i.e., conventional) measures from skeletal elements. Here, we introduce an animal body size estimation technique for archaeological fishes that relies on 3D reference scans and the calculation of centroid size, a standard 3D geometric morphometric proxy measure for organism size. Centroid size-based estimations on whole caudal vertebrae are strongly correlated with a widely accepted measure (i.e., centrum width), but the scalability and flexibility of the centroid size-based approach allows for use on a wide variety of fragmented remains. We use zooarchaeological fish remains (subfamily Ictiobinae) from late pre-Hispanic period large village sites located in the Middle Rio Grande region of New Mexico. Informal reports suggest that fishes were large during this time, and we demonstrate that ictiobines were significantly large compared to modern specimens. The centroid size-based body size estimation technique indicates that Ancestral Pueblo fishing strategies were associated with energy maximizing foraging behavior.

1. Introduction

Animal body size estimation, where skeletal remains are measured to assess animal length or weight, has been used in zooarchaeological research to measure taxonomic abundance (Lyman 2008; Reitz et al., 1987), calculate human population size (Shawcross 1972), gauge foraging efficiency (Broughton 1997; Butler 2001), track human prey species health (Wolverton et al., 2007, 2008, 2009), infer the technological investment associated with different capture techniques (Eiselt 2020), and understand shifts in animal management practices that led to domestication (Rowley-Conwy et al., 2012; Zeder and Lemoine 2020), among others. This widespread use of animal body size estimates is related to how methodologically straightforward estimating body size is. However, the use of body size estimations in zooarchaeology has a major drawback: this method typically relies on one-dimensional measurements of specific skeletal elements that are good indicators of size. This approach limits the applicability of animal body size estimation to archaeofaunal assemblages (Orchard 2003; Thieren and Van Neer 2016 for typical measures on fishes). As fragmentation and a variety of skeletal elements are both typical in faunal assemblages (Lyman 1994), quantitative animal body size estimation using traditional techniques is difficult in many zooarchaeological contexts.

Fish remains from late pre-Hispanic (ca. 1300–1600 CE) archaeological sites of the Middle Rio Grande region of New Mexico (Fig. 1) are one example of this problem. Fish bones are ubiquitous across sites in this time and place. Approximately, 51% of sites where fishes have been recovered and reported in New Mexico occur in the Middle Rio Grande region, and 85% of those sites date to the late pre-Hispanic period (Dombrosky et al., 2020; Snow 2002). This pattern may be linked to a changing environment where increased aquatic habitat quality made fishes a more optimal resource (Dombrosky et al., 2020). One way to test the connection between environment and Pueblo foraging decisions involves fish body size. If environmental conditions were more favorable, then fish body size should be large. Unfortunately, however, ichthyofaunal assemblages from relevant sites often contain relatively low numbers of specimens, with little consistency in particular elements recovered; moreover, these assemblages are often fragmented. Typical animal body size estimation procedures are not designed for this context.

One potential solution to this problem, which may be applicable to

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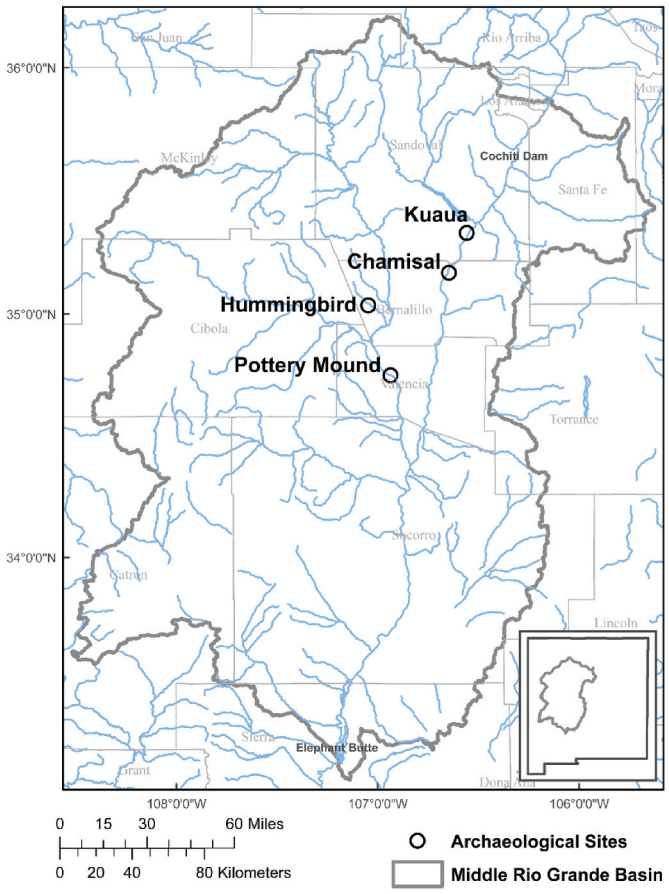

Fig. 1. New Mexico's Middle Rio Grande hydrological basin with the four sites discussed in this article.

other zooarchaeological contexts as well, is to use 3D geometric morphometric techniques. 3D geometric morphometrics allows for the objective comparison of shape and size between objects using multivariate digitized coordinates (Gunz 2020). In zooarchaeology, 3D geometric morphometrics is widely used to identify shape and size differences between domesticates and their wild counterparts (Drake et al., 2015; Hanot et al., 2017; Owen et al., 2014; Pelletier et al., 2020).

In this article, we present a 3D reference library for two commonly recovered and hard-to-skeletally-distinguish taxa in the Middle Rio Grande region: the smallmouth buffalo (*Ictiobus bubalus*) and river carpsucker (*Carpiodes carpio*). We then use this reference library as a part of a proposed new procedure for estimating animal body size: we measure zooarchaeological Ictiobinae specimens of interest using 3D geometric morphometric measures and then use the digital reference library of 3D skeletal element scans to calculate body size of the fish from which the zooarchaeological remains originated. We evaluate the robustness of this approach by comparing it to a common linear measure (i.e., centrum width) taken from caudal vertebrae. Finally, we use this procedure to evaluate whether Ancestral Pueblo people caught larger than average fishes during the late pre-Hispanic period (ca. 1300–1600 CE) in the Middle Rio Grande region of New Mexico and use these data to evaluate the connection between changing environment and Pueblo fishing decisions.

2. Background

2.1. Animal body size estimation

Animal body size estimation techniques are widely used in zooarchaeology, especially with fish remains (Reitz et al., 1987; Orchard 2003; West et al., 2020). These techniques rely on linear measurements taken from whole skeletal elements of individuals where biological information is known (such as age, sex, mass, and/or length). The strength of the allometric relationship between linear and body size measures is assessed with linear (sometimes curvilinear) regression. Animal body size is typically predicted by linear measures with the strongest length/weight relationship. The most common measurement used in body size reconstruction is the whole length of bone in a set dimension.

Body size estimation conducted in this way is simple to execute; it requires only a set of calipers and simple data analysis software (Rowley-Conwy et al., 2012:2). The low technological investment in estimating body size is one major reason why the technique is so widespread. Further, many analysts are in the habit of taking measurements on specimens for several different reasons, such as measuring the effects of recovery bias or the degree of fragmentation in an archaeofaunal assemblage (Nagaoka 2005; Wolverton 2002). Although such measures are susceptible to intra- and inter-analyst error (Lyman and VanPool 2009; Von den Driesch 1976), the impact of such error can be minimized when analysts take their own measurements on reference materials (Lyman 2010).

3D geometric morphometric techniques offer an alternative approach. Landmarks measure specimens by placement on describable parts of bones. Each landmark represents an x, y, z coordinate in space. The Generalized Procrustes Analysis (GPA) holds orientation, rotation, and scale constant, allowing an analyst to compare similar landmark configurations (Gower 1975; Rohlf and Slice 1990). The centroid, or average point in space equidistant to all landmarks in a configuration, is used to translate different objects to the same point. The configuration is fully aligned when landmarks are rotated and scaled as close together as possible. The scaling of different landmarks—so that each configuration approaches the same size—load onto one measure called centroid size (Klingenberg 2016:120). Centroid size is the standard size measure in 3D geometric morphometrics (*sensu* Mosimann 1970; see also Klingenberg 2016; Loy et al., 1998; Monteiro 1999). It can be used to calculate animal body size from skeletal remains (Halenar 2011). There are some potential issues in the application of centroid size-based animal body size estimation. The technique requires relatively expensive equipment and software; a digital reference library must be created (*sensu* Betts et al., 2011), which is labor-intensive; and replicable landmark configurations must be established (Hirst et al., 2018). In general, however, 3D geometric morphometrics solve more problems than they create. The cost of scanners and software continues to decrease, and the number of 3D libraries of comparative specimens is increasing (Betts et al., 2011; Manzano et al., 2015;Kuzminsky and Gardiner, 2012). Measurement error is roughly equivocal between specimens and their scans (Emery et al., 2016; Evin et al., 2016; Franklin et al., 2013). There are many methods to account for intra- and inter-analyst error (Hirst et al., 2018). In short, 3D scans resolve many data quality issues in animal body size estimation by bringing natural history collections to analysts (Lyman 2010; Wolverton 2013). Notably, centroid size can be used to reconstruct body size on fragments of skeletal specimens where only portions of skeletal features remain. A researcher must simply reconfigure landmark configurations according to the archaeological specimen at hand. 3D geometric morphometrics hold great promise for obtaining animal body size information from non-ideal contexts in which zooarchaeological specimens are limited or fragmented.

2.2. Fishing and fish size in the Middle Rio Grande

As mentioned earlier, fish remains are ubiquitous in zooarchaeological assemblages from this time and place, a pattern that contrasts with earlier assemblages. Although the number of specimens is not always large (the median number of identified fish specimens recovered across sites is around 20), the number of specimens can range from a couple of bones to around 1000 (Akins 1987, 1994, 1995, 2004, 2012; Brown 1999; Brown and Brown 1994, 1997; Clark 2007; Cordero 2010,

2013; Duncan 2010; James 1987; Mattson 2010; Sullivan and Akins 1994; Wands 2009). Thus far, archaeologists do not have a clear picture of why this temporal pattern exists.

The regional uptick in the representation of fishes could have several causes. One (not exclusive) potential cause relates to changing aquatic environmental conditions (Dombrosky et al., 2020). If aquatic environmental conditions improved during this time, then fishes could have represented reliable food for Pueblo fishers. Further, fishes may have also been large and represented large quantities of food. Qualitative assessments of bone size suggest that fish were large during this time and place (Gehlbach and Miller 1961; Snow 2002). Traditional techniques, however, are not a good option for investigating this possibility; the available specimens are relatively few in number, and they are largely both fragmented and not typical body size indicators (such as quadrates or hyomandibulars). Centroid size-based fish body size estimation may be a solution.

3. Methods and materials

3.1. The 3D reference library

The method proposed here relies on a reference library of 3D scans of two different species of ictiobines commonly recovered from Middle Rio Grande contexts: the river carpsucker (*Carpiodes carpio*) and the smallmouth buffalo (*Ictiobus bubalus*). Individual reference specimens were loaned from two different institutions: the Museum of Southwestern Biology Division of Fishes and the Tulane University Biodiversity Research Institute (Table 1). When possible, we scanned all vertebrae and an additional 12 skeletal elements (the basipterygium, cleithrum, entopterygoid, hyomandibular, maxilla, metapterygoid, opercle, pharyngeal teeth, preopercle, quadrate, subopercle, and urohyal) from each specimen. In total, 250+ 3D scans were made using an HDI Advance 3D Scanner R5X, which uses structured light. 3D models were assembled in and exported from the program FlexScan3D (LMI Technologies, Inc. 2015). Mesh density and resolution were set to maximum capabilities to capture as many possible describable landmarks on fish bones.

3.2. Centroid size-based body size reconstruction

Centroid size-based body size reconstruction requires at least three landmarks. Because sliding landmarks set multiple points at once, this means at least two describable portions of bone need to be present. We set landmark configurations for this analysis using Stratovan Checkpoint (Stratovan Corporation 2020), placed the same landmark configurations on both the archaeological and reference specimen scans, and exported landmark coordinates into a .txt datafile.

We uploaded datafiles into R (R Core Team 2020) and performed a Generalized Procrustes Analyses with the GeoMorph package (Adams et al., 2021). We used the linear model function in R with the centroid sizes of specimens and their corresponding body size measures (i.e., standard length). R^2 and Spearman's *rho* were used to evaluate the strength of the relationship between centroid size and body size. If we deemed the strength of the relationship appropriate (see section 5.2), we estimated body size from centroid size with the equation produced from the linear model.

We compared our centroid size-based estimates to those derived from more commonly used linear measures. Centrum width on caudal vertebrae typically exhibits a strong linear relationship with fish body size (Casteel 1976; Jelu et al., 2021; Orchard 2003; Samper Carro et al., 2018). We took centrum width measures in Meshlab (version 2020.02). Additionally, we use the known body size of reference specimens to calculate Prediction Error (PE) and Mean Prediction Error (MPE) within individuals (Halenar 2011). Prediction error is calculated using the following equation:

$$PE = \frac{actual\ standard\ length\ -\ estimated\ standard\ length\ \times\ 100}{estimated\ standard\ length}$$

3.3. Were late pre-Hispanic Middle Rio Grande fish large?

To investigate the question of whether late pre-Hispanic Middle Rio Grande fish were large, we calculated the body size of 60 zooarchaeological specimens from four late pre-Hispanic period archaeological sites: Chamisal (LA 22765), Hummingbird (LA 578), Kuaua (LA 187), and Pottery Mound (LA 416) Pueblos (Table 2). The archaeofaunal assemblages from these sites are curated at the Maxwell Museum of Anthropology or stored in the Zooarchaeology Laboratory at the University

Table 1
The 17 museum comparative specimens used to create the 3D reference library (raw data also available in the Supplementary Material). (TUBRI = Tulane University Biodiversity Research Institute, Royal D. Suttkus Fish Collection; MSB = Museum of Southwestern Biology, Division of Fishes).

Curating Institution	Species	Catalogue No.	Standard Length (mm)	Total Length (mm)
TUBRI	*Carpiodes carpio*	582	314	402
		671	297	383
		673	272	353
		677	257	333
		684	232	303
	Ictiobus bubalus	685	280	375
		686	266	350
		689	277	363
		690	292	380
		692	237	313
		696	247	325
		697	253	328
		702	204	273
		706	166	222
MSB	*Carpiodes carpio*	50.003	340	–
	Ictiobus bubalus	25.273	460	–
		50.002	325	–

Table 2
Site details for the late pre-Hispanic Middle Rio Grande fish specimens used in this study. (NSP = Number of Specimens used in this study.)

Site Name	Site Number (LA)	Dates (CE)	Screen Size[a]	NSP	Reference
Pottery Mound	416	1370–1475	–	50	Schaafsma (2007)
Kuaua	187	1425–1550	–	5	Franklin (2019)
Chamisal	22765	1300–1600	¼"	4	Jones et al. (2016, 2021)
Hummingbird	578	1275–1475	¼"	1	Eckert and Clark (2009)

[a] Pottery Mound and Kuaua went unscreened.

of New Mexico, and each collection was completely examined for fish remains.

Most specimens are from Pottery Mound Pueblo, which is a large village of approximately 400 rooms located near the Rio Puerco (a major Rio Grande tributary) known for its distinctive kiva murals (Hibben 1975; Schaafsma 2007). Fish remains analyzed here were recovered during Frank Hibben's 1954–1961 excavations; they derive from multiple locations within the Pueblo. Kuaua Pueblo is a massive village site of around 1200 rooms located next to the Rio Grande; the fish specimens used here were recovered by Dorothy Lurh's 1938 excavations of the North Plaza (Franklin, 2019). Neither fish sample from these two assemblages was recovered through screening (Table 2). Chamisal Pueblo, excavated in the 1980s by Kathryn Sargeant, is smaller, with approximately 200 rooms; fish remains were recovered from contexts that have been securely dated to the late Classic period. Finally, Hummingbird Pueblo is located near and was occupied approximately 100 years before Pottery Mound Pueblo. The single specimen used here was recovered from Michael Adler's excavations at the site during the early 2000s. Both these excavations screened using ¼ inch mesh (Table 2).

Just over half of the skeletal elements in this sample are caudal vertebrae. Some specimens are from similar or adjacent provenience, and it is possible they could be interdependent (though differences in body size do suggest separate individuals from the same contexts). The body size estimations presented here are likely best viewed at ordinal levels of interpretation (Grayson 1984; Lyman 2008).

A linear relationship between centroid size and standard length with a coefficient of determination (R^2) value of 0.50 and higher was deemed appropriate enough to derive a body size estimate (see section 5.2 for more elaboration on this choice). Landmark configurations for each skeletal specimen and linear equations used to calculate body size are reported in the Analyses RMD and PDF file in the Supplementary Material (also available on GitHub see the Data Availability section below).

We compare the zooarchaeological body size estimates developed here to the mean modern total length distribution of *Ictiobus bubalus* from Elephant Butte Lake in New Mexico between 1967 and 1970 (reported by Moody 1970:Table 4) and from 2011 to 2017 (data provided by the New Mexico Department of Game and Fish). There was an *Ictiobus* spp. commercial fishery at Elephant Butte during the 1960s, which has since ended. Thus, these two datasets represent the body size distribution of ictiobines under intense harvest pressure (1967–1970) and release/recovery from that pressure (2011–2017). We converted our standard length estimates on archaeological specimens to total length using the mean length-length conversion for *Ictiobus bubablus* and *Carpiodes carpio* from FishBase. This meant multiplying standard length estimates by 1.27 (see the Analyses RMD or PDF file in the Supplementary Material for further discussion; also available on GitHub). We rely on visual inspection to differentiate modern and archaeological fish size distributions as Moody (1970) only reported summary proportional data.

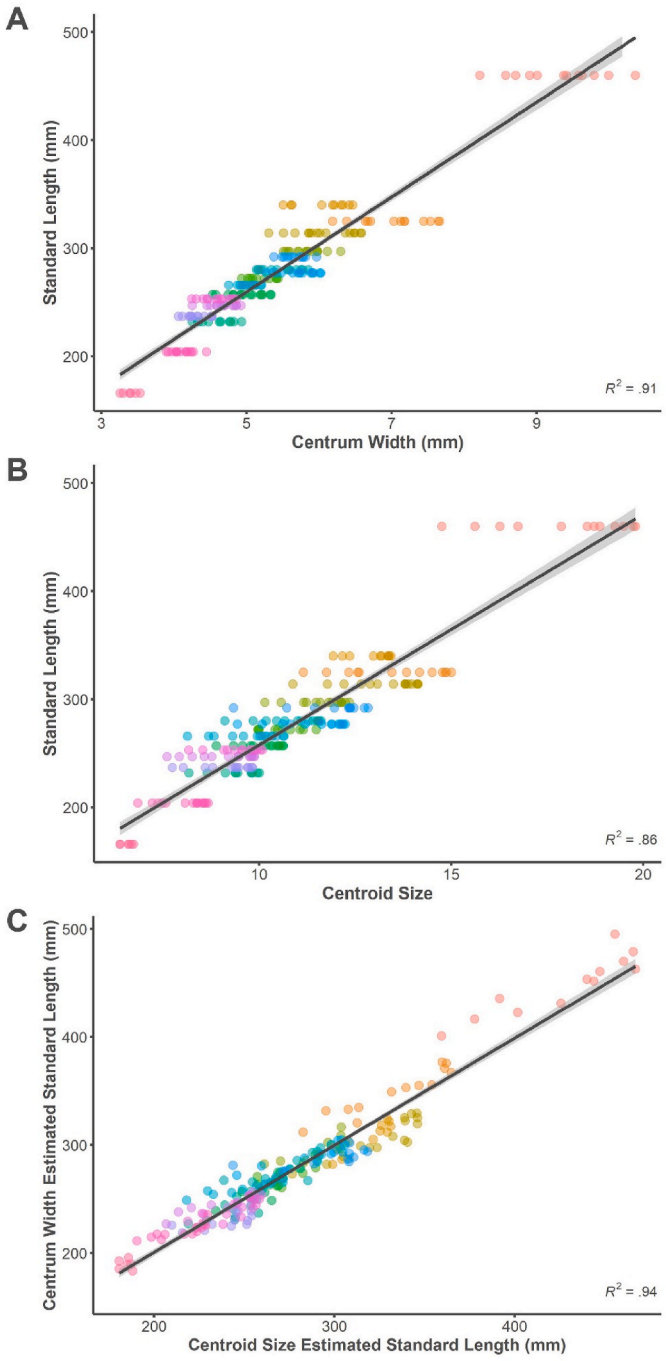

Fig. 2. Linear regressions between **A** caudal vertebrae centrum width and standard length, **B** caudal vertebrae centroid size and standard length, and **C** centrum width estimated standard length and centroid size estimated standard length from 17 individual ictiobine reference specimens (represented by distinct colors). (For interpretation of color in this figure, the reader is referred to the Web version of this article.)

4. Results

4.1. The 3D reference library

The 250+ 3D scans of *Ictiobus bubalus* and *Carpiodes carpio* specimens, along with each associated landmark file, are publicly available (see Data Availability section below). File structure and names indicates loaning institution, specimen identification number, and skeletal element.

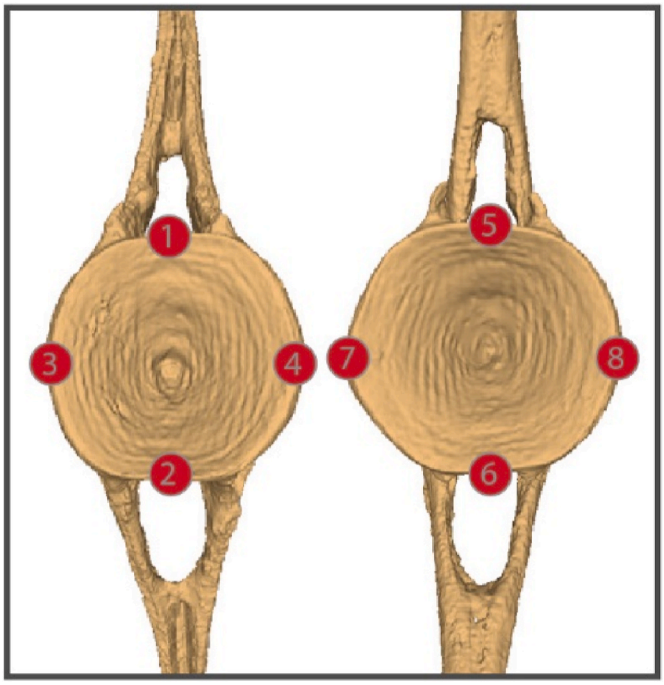

Fig. 3. Caudal vertebrae landmark configuration used to compare centroid size and centrum width body size estimates. The Landmark Configuration Profiles PDF in Supplementary Material provides all configurations per element used in this article.

4.2. Centroid size-based body size reconstruction

There is a strong correlation between caudal vertebrae centrum width and the standard length of ictiobine specimens in this sample (Fig. 2A). There is also a strong correlation between centroid size and standard length (Fig. 2B; Fig. 3). The body size estimations that result from using these two approaches are also strongly correlated (Fig. 2C), and nearly identical at an ordinal scale (*rho* = 0.96).

Fig. 4 shows that centroid size-based body size estimates on caudal vertebrae are slightly underestimated compared to their linear counterparts. The centroid-size based approach is slightly more conservative in assigning specimens to larger sizes. Prediction error is strongly correlated between linear- and centroid-based approaches ($R^2 = 0.56$; Fig. 4A). Mean prediction error of caudal vertebrae within individuals is also strongly correlated ($R^2 = 0.63$; Fig. 4B), and standard deviation is 4.64 for centroid size and 5.37 for centrum width. An important limitation of using vertebrae to predict fish body size is that their size varies along the vertebral column. Interestingly, mean prediction error suggests that the centroid size approach slightly reduces variation in prediction error from vertebrae within the same individual. Overall, our results suggest standard length estimations were both off by about ±5% of actual standard length measures.

Taken together, these results indicate that the centroid size-based approach can be at least similar to commonly accepted body size estimation techniques that use linear measures on whole bones. While including larger individuals would be ideal, we believe extrapolation of body sizes beyond 460 mm is warranted with the current model if interpretations are limited to ordinal size, given the strong linear relationship presented here and the fact that the centroid size-based approach tends to underestimate actual body size. Intra- and inter-analyst measurement error is virtually indistinguishable between replicates using the landmark configurations presented here (see Analyses RMD or PDF file in Supplementary Material for further discussion). The strength of relationships from fragmented remains (see Landmark Configuration Profiles PDF in Supplementary Material) demonstrates how flexible the technique is on unconventional remains.

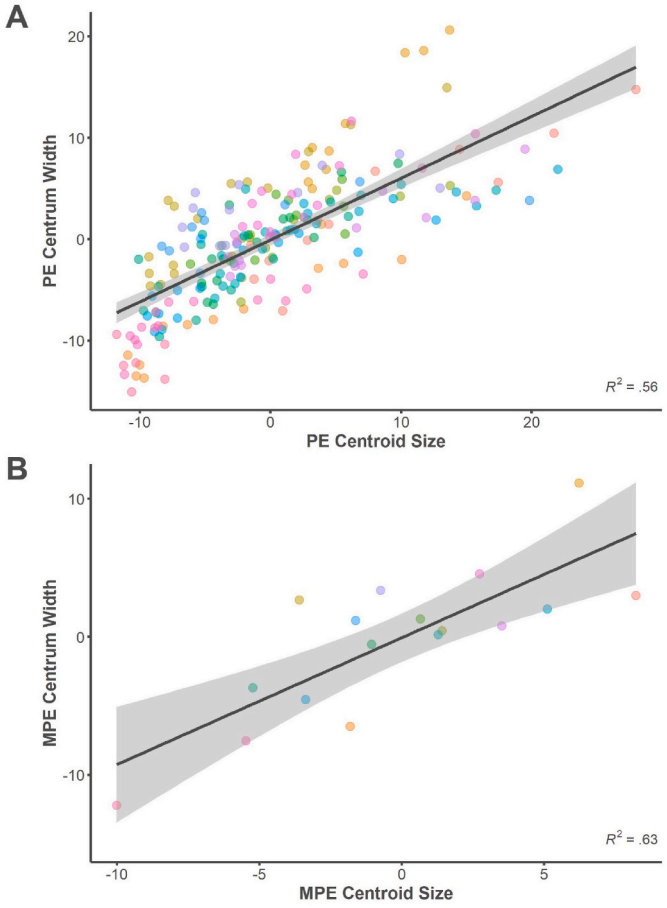

Fig. 4. Linear regressions on **A** caudal vertebrae Prediction Error (PE) for centrum width standard length estimation and centroid size standard length estimations, and **B** Mean Prediction Error (MPE) for caudal vertebrae within individuals between centroid size and centrum width standard length estimation. Estimations are based on 17 individual ictiobine reference specimens (represented by distinct colors). MPE is then calculated as mean PE per individual. (For interpretation of color in this figure, the reader is referred to the Web version of this article.)

4.3. Were late pre-Hispanic Middle Rio Grande fish large?

Ictiobines harvested by Pueblo fishers in the late pre-Hispanic Period were large (Fig. 5). The most common total length of *Ictiobus bubalus* was 450–499 mm when there was a commercial fishery for this taxon, and the archaeological size distribution resembles when ictiobines had recovered from intense harvest pressure (2011–2017). The archaeological and non-commercial fishery size distribution are both dramatically left-skewed, where the most common total length is 550+ mm. Interestingly, the most abundant smaller size class in the non-commercial fishery distribution (200–249 mm) is also represented in the archaeological fishery.

5. Discussion

5.1. Fishing and fish size in the Middle Rio Grande

Large-bodied fishes are associated with Ancestral Pueblo foraging in the late pre-Hispanic Middle Rio Grande, but what does the large size of fishes represent? While it is possible that Pueblo fishers were preferentially targeting large fishes using handlining or hook-and-line techniques, where small fishes could have been simply thrown back (see

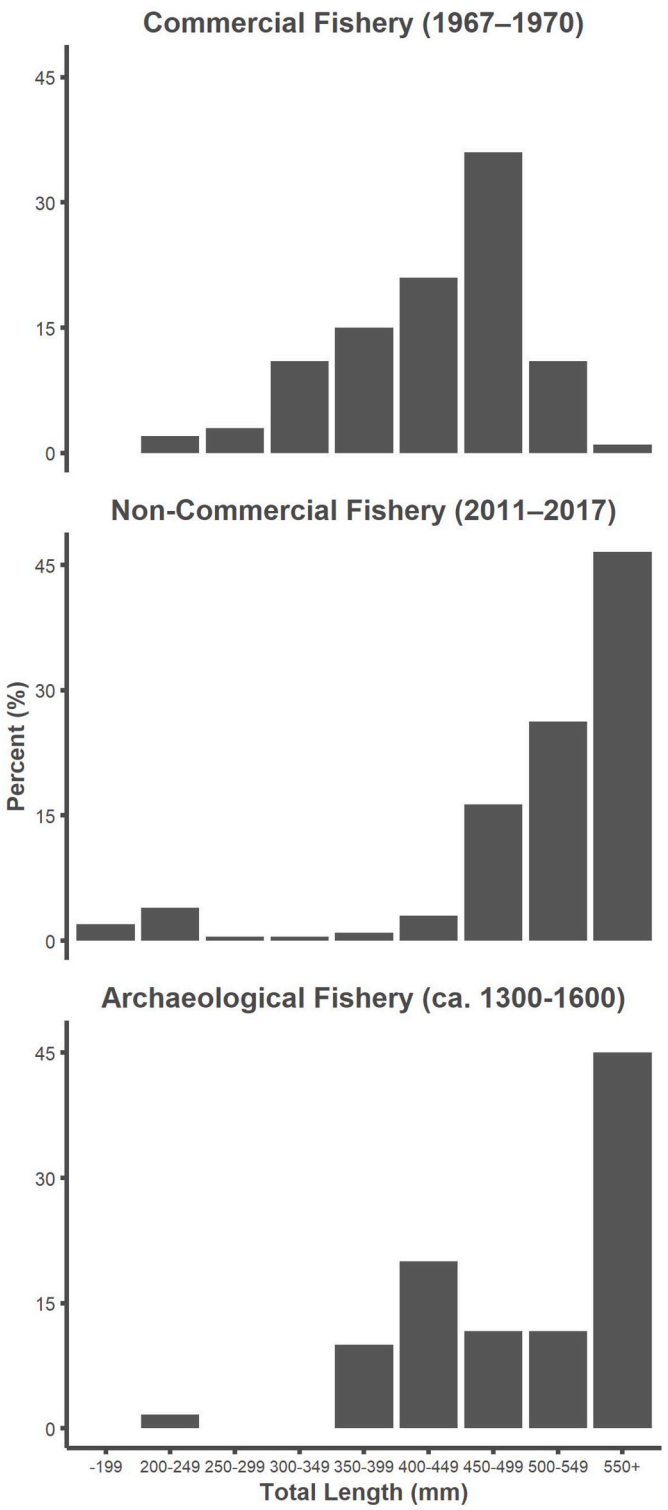

Fig. 5. Ictiobine size distribution from Elephant Butte, NM when there was a commercial fishery (mean values from Moody 1970:Table 4) and when there was not a commercial fishery compared to archaeological specimens recovered from late pre-Hispanic large village sites from the Middle Rio Grande region of New Mexico. All dates are CE.

Peacock et al., 2012 for more on the cultural filter problem), the ethnographic record suggests non-targeted fishing strategies were the most common along the Middle Rio Grande. Fishes were caught with weirs (Ford 1977:144, 1992:175; Harrington 1916:187), during communal seining events (Bandelier, 1892:149; Hill 1982:59–60), and by taking stranded fishes in the bottom of drained irrigation canals (Ford 1992:175; Ortiz 1969:112).

The efficacy of non-targeted fishing methods might be related to the reproductive life history of bottom dwelling fishes like ictiobines. Ictiobines typically reproduce from spring to early summer and use oxbows, backwaters, and other slow-flowing river habitats as spawning habitat. Large numbers of fishes of various ages congregate in these areas prior to spawning (Robison and Buchanan 2020). Fertilized eggs adhere to submerged vegetation, and larvae and early-stage juveniles usually remain in slow-flowing habitats to rear. Reproductive adults become trapped if water drops suddenly and isolates them from the river mainstem. This life history makes them vulnerable to non-targeted capture.

That the most abundant smallest size class from the non-commercial fishery is present in the archaeological fishery also suggests non-targeted methods were used in the late pre-Hispanic period. This size bin is represented by a single archaeological specimen that was recovered from Frank Hibben's 1954 excavations at Pottery Mound, which were unscreened (Ballagh and Phillips 2006). That the signal of this size class was preserved, from non-ideal recovery methods no less, reinforces the argument that archaeological specimens were captured using non-targeted methods. Further, recovery methods likely have not unduly influenced distribution shape within the archaeological sample. A range of size classes were successfully recovered, and yet most specimens fall within the 550+ size bin. The high proportion of large (at an ordinal scale) fishes analyzed here are likely indicators of environmental change.

The environmental connection between fish body size and Ancestral Pueblo fishing is also highlighted through stable isotope data. Ancestral Pueblo fishing in the Middle Rio Grande is associated with the ecological stability of fish communities; it appears that wetter stream conditions brought on by the end of the Medieval Warm Period (Routson et al., 2011; Woodhouse et al., 2010) enhanced habitat quality in the Middle Rio Grande and made stabilizing nutrients available to fish populations (Dombrosky et al., 2020). The greater bioavailability of nutrients, increased amount of habitat space, and greater habitat complexity linked to wetter stream conditions would also likely result in healthier, larger fishes (Post 2002; Pusey and Arthington 2003).

Fishing associated with environmental change is a key component of Ancestral Pueblo foraging behavior. If fishes represented "desperation foods" (*sensu* Arntzen and Speth 2004; Speth et al., 2004), then a whole range of body sizes in an even proportion would be anticipated from these sites. This would be the case whether fishes were caught using targeted or non-targeted techniques. Instead, our analysis suggests that fishing occurs when fish size is large. This in turn suggests that Pueblo people in the Middle Rio Grande actively sought to select predictable and nutrient-dense fishes in connection with ecological stability.

5.2. *Practically significant body size estimation*

The method outlined here is designed to maximize samples from which body size can be calculated to minimize error. One way to reduce error involves relying on high R^2 values. For instance, Thieren and Van Neer (2016) threw out two cleithrum measurements on sturgeon (*Acipenser* spp.) remains to calculate body length because R^2 values of 0.82 and 0.62 were deemed low. This type of selectivity is strategic if the archaeological record affords a large sample size of bones where measurements with higher R^2 values can be taken.

However, if the archaeological record does not afford such an ideal sample, then maximizing sample size altogether is another way to reduce error. The centroid size-based approach outlined here uses the sample maximizing strategy to reduce error, but such a strategy surrenders resolution. The length estimates provided here are likely ordinal scale measures of fish body size (as evidenced by Fig. 3). This means that R^2 values with generally high effect size may be used ($\geq$0.50; Cohen

1988) to estimate body size, but it is crucial to pair this method with non-parametric descriptive statistics and/or inferential tests. Non-parametric approaches are both robust and resistant to outlier effects and thus appropriately handle lower resolution data (Wolverton et al., 2016).

5.3. Pluses and minuses of the centroid size-based approach

There is a trade-off related to time and money investment in the centroid size-based body estimation approach. If taking linear measurements with a set of calipers is considered "low technology" (Rowley-Conwy et al., 2012), then taking 3D centroid-size based measures is certainly "high technology." The price of 3D modeling technology has decreased over the years, and museums are rapidly adopting such technology for several tasks. Nevertheless, the price, portability, and ease of use of calipers is unrivaled. Further, producing digital 3D models of scans takes far more time on the frontend then does taking linear measurements.

For this reason, there are many situations in which analysts may choose to stick with traditional linear measurement-based body estimation. Sometimes, however, the advantages to the centroid size-based approach will outweigh the costs. A library of 3D scans can be used to calculate body size on an almost limitless variety of skeletal fragments. Creating new landmark configurations that scale well with body size is a time-consuming task, but certain configurations could become well-known as reliable indicators of body size if this approach is adopted in different contexts. The time investment in 3D scanning and landmarking might be a detraction in the immediate future, but it is ultimately a long-term investment. It is possible that body size could be calculated from a larger variety of specimens with standardized and freely available reference materials for specific regions, which could greatly enhance between analyst comparisons of body size information and increase data quality.

5.4. Global applications

When the technology is available, and the question is reliant on body size, the approach we outline here may well be worth the investment. Centroid size-based body size estimation has potential for archaeology globally. For example, the technique is well-suited for early hominid fishing research considering ichthyofaunal samples are often nonideal (i.e., poorly preserved, fragmented, and from limited skeletal elements). Body size estimation with centroid size can be applied in a variety of contexts and could help reveal the opportunity costs and benefits associated with human fishing strategies across the globe.

6. Conclusion

We have introduced one way to estimate body size with unconventional skeletal specimens, a method that can widen the application of animal body size estimation to a larger number of archaeological contexts. Our demonstration of this method shows that fishes recovered from late pre-Hispanic sites in Middle Rio Grande region of New Mexico are significantly large, something previously hinted at but never formally tested. This finding supports a connection between Ancestral Pueblo foraging decisions and favorable environmental conditions.

Ultimately, centroid size-based animal body size estimations can help answer a host of anthropological questions related to human subsistence practices including the goal of human foraging decisions, technology used in hunting, and different animal management practices. Animal body size reconstruction is a versatile tool in the zooarchaeological toolkit. We hope to have increased its versatility to answer new questions in a range of archaeological situations.

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Declarations of interest

None.

Data Availability

The supplementary files associated with this work are available on GitHub: https://github.com/jdombrosky/Body-Size-from-Unconventional-Specimens. The library of 3D scans and landmark files are available here: https://digitalrepository.unm.edu/anth_fsp/6/. The file was compressed using 7-Zip and must be extracted. Many scans have corresponding landmark files (CKPT files) associated with them. Landmark configurations per specimen are viewable in Stratovan Checkpoint and coordinates can be manually exported. Archaeological scans have "Error" files associated with them, which correspond to the section entitled "Intra- and Interindividual Error" in the Supplementary Material. Files in "Error" folders ending in 1–5 are replicates associated with Analyst 1 (Alexandra Harris), and files ending in JD1–5 are replicates associated with Analyst 2 (Jonathan Dombrosky).

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