ORIGINAL RESEARCH ARTICLE

The Changing Shape of Empire: A Morphological Study of Curated Chimú Jars and Bottles

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ABSTRACT
After centuries of looting along Peru's North Coast, archaeologists acknowledge that the pottery of the Chimú Empire is one of the most collected Andean artifacts, but also one of the most poorly understood. Much of the enduring classificatory uncertainty comes from the problematic provenance of most Chimú vessels, and the fact that the distinctive blackware identified as Chimú represents the production of workshops from across an extensive area, during periods of regional political decentralization (c. 900-1200 CE), imperial growth (c. 1200-1450), and foreign conquest by the Inca (c. 1450-1535) and Spanish (after 1532) empires. This chapter builds on previous seriations and field observations, using geometric morphometric analysis of a sample of 3D-scanned Chimú bottles from publicly held collections at the University of Texas (Austin) and the American Museum of Natural History. Since Chimú bottles were formed in workshops using molds, variations in vessel shape can serve as indicators of variable practices. We compare a sample of common Chimú blackware bottles with a sample of *Inca-Chimú* vessels that carry features typical of the short Inca occupation of the North Coast. Differences between the two samples offer new lines of evidence that can guide more precise classifications of these vessels, as well as new interpretations of the imperial history of Peru's North Coast.

KEYWORDS
Sections; lists; figures; tables; mathematics; fonts; references; appendices

1. The Collecting History of an Imperial Ware

The distinctive blackware pottery of the Chimú Empire of Peru's north coast is one of the most intensively collected Andean styles, but also one of the least-defined. Thousands of well-preserved vessels occupy the shelves of museums in South America, North America, and Europe, from the vast collections of famous institutions like Berlin's Ethnologisches Museum to local museums that possess a single vessel of unknown provenance. It is impossible to know when Europeans first began to collect Chimú blackwares, although published illustrations date back as far as the early eighteenth

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century (Figure 1; Frézier 1716).

[Figure 1 about here. Frézier image of north coast blackwares in an image of "Inca" culture]

By that time, Spaniards had already been plundering Peru's coastal huacas for nearly two centuries, mining them to extract the gold and silver found in rich burials. Nineteenth-century collecting shifted the emphasis from precious metals, toward the recovery of well-preserved human crania that could be used to buttress European beliefs in their own racial superiority. Over time, Chimú ceramics (and other artifacts) were caught up in the new collecting regime as public museums grew in the global North (e.g., Hrdlička 1914:50-51). By the early twentieth century, large numbers of unauthorized diggers were working full-time excavating tombs at Chan Chan, the ruined Chimú capital (Kroeber 1926:15), and Chimú pottery could be purchased from shops in the Peruvian city of Trujillo (Figure 2). Beuchat (1918:570) noted at that time that the blackware vessels of Peru's north coast were already "very well represented in most ethnographic collections." Since then, coastal blackwares have continued to be excavated and trafficked by illicit diggers who target more valuable metal artifacts and polychrome textiles (e.g., Atwood 2004), and today they can be readily found at internet auction sites for modest prices.

[Figure 2 about here. Map of the north coast of Peru]

The history surrounding the collection of Chimú blackwares helps to explain why this ubiquitous artifact class remains poorly understood by professional archaeologists. When viewed as a byproduct of other collecting activities that unfolded over almost a half millennium, the Chimú ceramic corpus can be seen for what it is: an ambiguous assemblage of mostly orphaned objects. Almost all Chimú vessels lack a detailed archaeological provenience, and the chain of ownership for most museum pieces can rarely be traced back to Peru. Because most "Chimú" vessels cannot be affiliated to a particular context in coastal Peru, their identification derives from their stylistic attributes, even though some of the earliest Chimú ceramics documented in archaeological excavations appeared at the Inca site of Machu Picchu (Bingham 1915:269) and the coastal creation shrine of Pachacamac, two sites that lie well beyond the political control of the Chimú Empire (Uhle 1902:756).

This contextual ambiguity intersects with a classificatory problem for Andean archaeology. Many treat Chimú pottery as typical of the Late Intermediate Period (c. 900-1476) on the north coast of Peru, a huge and undifferentiated period during which the Chimú polity established its capital and local dominion in the Moche Valley, carried out multiple waves of imperial expansion to the north and south, and fell under the hegemony of Inca imperial rule (1476-1532). Excavators have noted that similar blackwares continued to be produced during the half century of Inca rule, and into the earliest years of the Spanish colonial period. Without knowing when and where a particular museum object comes from, archaeologists have faced difficulties in subdividing Chimú pottery into phases and substyles, which would enable researchers to study changes and variations within the overall assemblage.

1.1. *Early Archaeological Classifications*

From early on, classifications of Chimú ceramics focused on vessel attributes. Beuchat (1918:652-654) noted that coastal tombs had yielded "infinite" formal variations of blackware pots now found in museum collections. He placed these into five principal categories: (1) globular vessels with rectangular fields of low-relief decoration; (2) geometric vessels (cuboid, ellipsoids, ovular); (3) phytomorphic vessels shaped like squash or fruits; (4) zoomorphic vessels representing a broad range of fauna; and (5) anthropomorphic vessels. This classification emphasized aesthetic characteristics of vessel shape, rather than the kinds of formal and functional differences seen in later typologies, and Beuchat acknowledged the diversity found within each of his categories, especially the phytomorphic, zoomorphic, and anthropomorphic vessels. Without any provenience information to guide his analysis, Beuchat did not attempt to seriate Chimú pottery or to distinguish regional variations.

In 1926, Alfred Kroeber made the first concerted effort to describe different phases of Chimú ceramic production, based on a brief visit to the Trujillo area that he made as part of a Field Museum expedition to the central coast. Kroeber noted previous efforts by Uhle (1902) to differentiate between early and late ceramics from Trujillo, which could be tied to the Moche site of Huaca de la Luna/Huaca del Sol and the Chimú capital of Chan Chan. Kroeber used the term *Late Chimú* to refer to Trujillo area blackwares that sometimes were found with Inca ceramics, a designation that encompasses Late Intermediate Period (c. 900-1400s), Inca (1400s-1530s) and some early Colonial pottery. Based on provenance information that recorded the district where some Late Chimú vessels originated, Kroeber (1926:11) identified a broad distribution that stretched from Piura to Casma, with some vessels found as far south as the Nasca drainage. To build a typology and sequence of Late Chimú vessels, he studied the pottery from several collections that he purchased in Trujillo on behalf of the Field Museum.

Kroeber's shape typology for Late Chimú pottery discusses vessels that were common in Moche and Chimú assemblages, and he lists (1926:22) about a dozen Late Chimú shapes, including stirrup-mouth vessels, double jars, double-spout vessels, head-and-spout vessels, figure-and-spout vessels, globular bowls, lipped pots (with and without handles), jars with flaring mouth, flat-handled jars, and jars with tapering spouts. The list of shapes also includes Inca narrow-mouth jars (*aryballus*) and cups (*kero*) in the Late Chimú assemblage. In his decorative analysis of vessels in private collections, Kroeber (27-28) identified the *face vase* and *rotund figure jar* as additional shapes found in the assemblage. The discussion of Late Chimú blackware recorded the relative abundance of the most common shapes found in two private collections that he saw while visiting Trujillo. The Mansiche and Jacoms collections comprised more than 200 vessels, but Kroeber estimated that hundreds of utilitarian pots, plates, and jars had been *rejected* by the collectors when they purchased vessels from the huaqueros who excavated them near Chan Chan.

In his study of collected ceramics from Trujillo, Kroeber established the outline of a shape typology for Chimú blackware vessels, although it was not a comprehensive representation of ceramics in use on the north coast during the periods of Chimú, Inca, and Spanish imperial expansion. Building on the earlier observations of the high degree of diversity seen in Chimú blackwares, Kroeber made some important observations that inform subsequent studies. First, this pottery is widely distributed along the north coast of Peru, although Kroeber (1930:97) argued for strong continuity between regions, which would suggest that regional variations account for little of the overall diversity in the Chimú assemblage. Second, he noted that blackwares were strongly associated with mortuary contexts, and such pottery was not commonly seen on the surface of the urban core of Chan Chan. Such vessels were thus more indicative of Chimú funerary practices than everyday life. Finally, Kroeber described how the private collections that local dealers assembled and sold to museums were already curated in a way that eliminated certain vessel shapes, so that museum collections could be considered representative of the original mortuary assemblage. As Kroeber noted (1930:95) in a later visit to the north coast, one Trujillo collector "refused to purchase from the huaqueros most of the unhandled jars, exceptions being made in favor of effigy pieces, or occasional plain ones when several vessels were bought in a lot in order to acquire one or two attractive ones."

1.2. *Attempts at Seriation*

In the years following Kroeber's work, analysis of Chimú ceramics continued to be oriented around the integration of regional Andean sequences, and the pottery of the Chimú Empire continued to be discussed alongside Moche ceramics that were considered to be Early Chimú (e.g., Bennett 1937; Willey 1945). It was not until the 1960s that a concerted effort was made to move beyond the master sequence, to developed a more fine-grained description of the assemblage associated with the Chimú Empire as it developed, expanded, and fell under Inca and Spanish dominion. In 1966, Harry Scheele and Thomas Patterson published a "preliminary seriation" of Chimú ceramics. They noted (1966:15) that one reason that so little work had been done to classify such material was its abundance: "probably no other pottery style from the Americas is so well represented on the shelves of museums and private collectors throughout the world."

As noted already, this prevalence was remarked on almost 50 years earlier, the result of large-scale collections acquisitions that major museums had engaged in since the late 1800s (e.g., Květinová 2011:65-66). But Chimú pottery continued to flow into established museum collections, and to be sought as new museums were established (see Mowat 1988 for an example of donation and accessioning practices). Collection-building accelerated as new museums were founded after World War II and continued with limited constraints until after 1970, when the UNESCO Convention regarding cultural property established guidelines that gradually altered legal standards and ethical practices surrounding collecting (Gerstenblith 2013). Although some museums continued to send curators to Peru to purchase from antiquities dealers, a cursory review of museum records reveals that many new accessions came as gifts from individual donors, who provided little or no provenance information. For example, the Metropolitan Museum of Art received a feline bottle (64.228.17) from Nathan Cummings in 1964, who had purchased the vessel a decade earlier from a collector in Buenos Aires. The piece was one of more than 1000 artifacts that Cummings is credited with donating to the museum. The Cleveland Museum of Art, founded in 1913, also built its collections through donations, including a blackware jar (1959.333) given by William Ellery Greene in 1959. It was the only Andean artifact given to the museum by the donor.

Building on preliminary work by Pedro Rojas Ponce and Dorothy Menzel, Sheele and Patterson (1966) compared illustrations from the published literature with vessels from Peru's Museo Nacional de Antropología y Arqueología and Harvard University's Peabody Museum of Archaeology and Ethnology. They created a preliminary seriation of Chimú ceramics from the end of the Middle Horizon to the early Colonial Period, distinguishing seven different phases based on the identification of different vessel shapes, decorative elements, and firing characteristics. Although the seriation was developed to build a more fine-grained relative chronology, the small sample sizes of some phases presented interpretive challenges. For example, the fourth phase *Lambayeque*, was based on seven vessels from a single grave in the Lambayeque Valley, located approximately 175 km to the north of Chan Chan, and probably reflects regional ceramic diversity more than a distinct period of Chimú production in the Moche Valley. Other phases were based on small sample sizes and vessels with limited provenance information. One important distinction in the Scheele and Patterson seriation was between Chimú ceramics of the late LIP (Chimu Phase T-1) and those from the time of the Inca occupation (Chimu Phase T-2). The former was defined based on the prevalence of stirrup-spout vessels and the *less carefully made* production of mold-produced vessels that seemed to represent a more restricted set of shapes than the preceding phase (Trujillo Phase T-2). The Chimú-Inca phase maintained elements of existing ceramic production, adding features from Inca vessel shapes. Scheele and Patterson note (1966:24) that this phase seems to be distributed beyond earlier Chimu political boundaries and economic networks—it has been identified on the south and central coast and in the Cuzco region. Overall, Scheele and Patterson's work clarifies how some vessel shapes developed over time, making it possible to assign provenienced gravelots to more specific late prehispanic periods. It also identified some important aspects of production practices and hybridity that have been important for subsequent archaeological fieldwork.

1.3. *Field Archaeology and the Reconstruction of Production Practices*

Although the first attempts at defining Chimú ceramics within a broader north coast sequence utilized museum collections, archaeological excavations have increasingly contributed to the reconstruction of ceramic production practices. In the mid-20th century, excavators turned to cemeteries as a source of well-provenienced vessels that could be used to elaborate the regional sequence (e.g., Collier 1955; Willey 1947). Such work represented only a miniscule proportion of Chimú ceramics that were being dug up at that time, most of which were obtained by huaqueros whose illicit work supplied private collectors and museums around the world. Studies of whole vessels concluded that the use of molds increased in late prehispanic periods on the north coast (Collier 1955), and by the 1960s, some researchers had identified molds and matrices in the pottery collections acquired by some museums (e.g., Grossman 1969-1970; Thompson 1963). Such work constituted an important step toward moving from straightforward aesthetic considerations to questions about the production and consumption of Chimú ceramics, but it remained rooted in mortuary collections that did not focus on evidence of production practices.

At the end of the 1960s, Moseley and Mackey's Chan Chan-Moche Valley Project (1969-1975) began to increase the intensity of professional archaeological research, with regional survey work in the lower Moche Valley and mapping and excavations at Chan Chan and other nearby sites. While not focused on cemetery sites, this project and related studies encountered additional mortuary contexts with well-preserved ceramics (see Donnan and Mackey 1978). It was not until the 1990s, however, that archaeologists began to identify loci of ceramic production based on the presence of overfired sherds, molds and matrices, stamps, tools, kilns, and other evidence (Donnan 1997; Hayashida 1999; Mackey 2003; Mackey and Sapp 2021; Tschauner 2006, 2009). Some of the workshops reflect ceramic production practices during the preceding era of Chimú imperial expansion, whereas others were in use during the Inca occupation of the north coast. Surface collections and excavations in production areas generated multiple lines of material evidence, including large numbers of potsherds that could not easily be assigned to the diverse array of shapes identified in collection-based classifications.

The study of Chimú and Chimú-Inca pottery workshops has focused on two central themes: specialization and cultural (dis)continuity under foreign rule. These issues were nascent in many of the earlier collection-based studies, but the careful excavation and analysis of production contexts added invaluable evidence to the discussion. Molds and matrices encountered at workshops indicate that multiple vessel parts were mass-produced and had to be assembled following a specific sequence, which Tschauner (2006:179) interprets as evidence of specialized production during Chimú times. Tschauner's excavations at the Pampa de Burros workshop in the Lambayeque Valley identified heavy use of vertical half-molds to produce jars, canteens or flasks, bottles, and ollas—virtually all of the shapes that were used by Chimú-era settlements in the surrounding valley (2006:182). He sees the local potters as relatively unskilled producers who relied on more adept makers of ceramic molds, and whose *market-oriented* work could flexibly adapt to consumer preferences (2006:183-185). Levine (2011) builds on this idea, noting that some of the variability seen in the Chimú assemblage could come from ceramic producers *mixing and matching* molds for different vessel parts and adornments to produce new combinations.

For the Inca period, scholars acknowledge a degree of continuity in local potting practices, but also some significant changes. At Tambo Real and La Viña in the Leche Valley, Hayashida (1999) notes the continuity of local practices for shaping vessels (press molds, paddle and anvil) and firing. While local jar shapes persisted in Inca times, she observes the presence of a mold for an Inca flared jar neck (1999:345), which could be added to jars that were shaped using local press molds. Overall, Hayashida sees little evidence of Inca *retraining* of Chimú potters.

Other Inca-Chimú workshops in the Jequetepeque Valley provide evidence that practices varied at different production locations. Donnan's (1997:32-35) surface collections at Cañoncillo encountered dozens of mold fragments, most of which were for shaping the bottom and top hemispheres of ollas. Donnan identified molds for shaping jars along a vertical axis, and for producing bottles, including the distinctive Inca "aryballoid" shape. Although he reports that no molds appeared for shaping handles or rims, there were molds for producing stirrup spouts, as well as for humans, birds, and other animals. The production evidence from this site suggests that while some vessels were largely shaped using molds, some elements were hand-formed and showed variations suggesting the work of multiple potters. At the Inca administrative center of Farfán, Mackey (2004:336-338) excavated a small workshop that produced large jars (tinajas) for brewing or storage, using the paddle-and-anvil technique. Finally, the excavation of three workshop patios at El Algarrobal de Moro, a lower-order Chimú administrative center, encountered 25 mold fragments, including molds for a stirrup spout vessel and a miniature jar (Mackey and Sapp 2021:21-22).

1.4. *Technological Approaches to Chimú Ceramics*

The accumulation of excavation assemblages with Chimú blackwares occurred as archaeologists developed new approaches to the study of ancient pottery. Archaeologists often find it difficult to map the shape-based categorizations developed from whole vessels in museum collections onto the broken fragments they encounter in excavation contexts other than tombs. Middens and house floors typically contain an assemblage that is not fully represented in the corpus of collected vessels, which has been biased toward mortuary offerings and shaped by the aesthetic values of dealers and collectors. Field researchers have used stylistic approaches to assign rough dates from the relative sequence, but the anthropological analysis of excavated pottery has inspired archaeological ceramicists to focus on the social practices underlying the production, distribution, use, and discard of pottery. The shift from style to technology has coincided with the introduction of methods to study the composition of clays, tempers, and pigments used for produce archaeological ceramics.

Given the acknowledged challenges in classifying Chimú vessels, it is not surprising that recent ceramic studies have embraced technological analyses, including petrography (Krzanowski and Pawilowski 1980), neutron activation, X-ray diffraction, X-ray fluorescence, particle-induced X-ray emission (Cunha Lima 2010), and Mössbauer spectroscopy (Tschauner and Wagner 2003). Despite such work, Shimada and Wagner (2019) argue that the reconstruction of the chaîne opératoire for north coast blackwares remains incomplete. It should be noted that many of the techniques used to reconstruct production practices rely on samples of potsherds that can be removed to the laboratory, and potentially altered or destroyed in the process of analysis. More recently, researchers have brought non-destructive techniques such as CT scans (Wauters 2016) and linear morphometric analysis (Květinová 2011) to the study of museum collections. This work emphasizes the variability found in different vessel categories, as well as the reconstruction of productive processes, including the use of molds to manufacture vessel bodies and other elements.

1.5. *3D Scanning and Geometric Morphometrics Analysis of Chimú Pottery*

After a century of classifying Chimú ceramics and reconstructing their production and social uses, archaeologists have yet to bring order to the *infinite* diversity of the museum assemblage, but they have developed important questions for empirical analysis. Rather than attempting to fit Chimú vessels into a neat taxonomy, researchers have drawn attention to the different factors influencing diversity in late prehispanic blackwares. Blackware ceramics were produced over several centuries and across a broad stretch of the north coast, and a significant degree of variation comes from the practices of individual potters at different workshops, who were producing different vessels to meet the changing aesthetic tastes of coastal consumers. There appear to have been differences in the organization of pottery workshops, and some producers relied more on the use of molds and matrices than others. It is not presently clear who designed and produced molds and matrices, or how broadly used and consistently replicated such production templates were. A fine-grained three-dimensional study of vessel bodies and key elements known to have been molded in some instances (e.g., stirrup spouts) could quantify the amount of variation seen in well-preserved vessels, contributing to the discussion of how hierarchical and centralized Chimú ceramic production was beyond the local workshop.

Previous analyses have also noted variable degrees of continuity and change seen in the production of ceramics during the period of Inca hegemony on the north coast. Local potters continued to produce blackwares using many of the same techniques and tools, but they also incorporated new vessel shapes and elements (e.g., flaring jar rims) that were distinctly Inca. Chimú-Inca pottery is often classified qualitatively, but a quantitative analysis of Inca vessel features that appear on such pottery would make it possible to address questions of hybridity, including the degree of foreign influence and the potential resistance of potters working in specific workshops to provide pottery for populations that experienced Inca imperial dominance in different ways.

These two questions can be addressed using three-dimensional data from well-preserved vessels, an approach that presents logistical challenges. To date, Wauters (2016) has used CT scans and X-ray radiography to study 16 stirrup-spout bottles from the Royal Museums of Art and History of Brussels and the Ethnography Museum of Geneva. To produce the scans, the vessels had to be removed from the museums and transferred to hospitals where the necessary equipment could be accessed. While generating high-resolution data, funding constraints and curatorial policies would make it difficult to conduct such research with large sample sizes. As an alternative, portable high-resolution 3D scanning equipment can be brought into museums to scan collections in situ, using the resulting data for geometric morphometric analysis. Between 2018 and 2020, we conducted exploratory research on Chimú ceramics in two collections using this approach.

1.6. *Collections and Research Ethics*

For our broader study, we scanned #### prehispanic ceramic vessels from two collections that reflect the broader history of collecting and curating Chimú ceramics. Our first collection was the Art and Art History Collection (AAHC), a modest sized collection that accumulated haphazardly at the University of Texas at Austin as numerous individuals donors gave the university artifacts that had little or no provenance information. The ancient pottery now in the AAHC was previously curated by the Texas Memorial Museum, which transferred them to the department of Art and Art History in 2004 as the museum implemented new curatorial priorities. In 2018, we scanned 112 Andean vessels from the AAHC collection. The data presented here come from a sample of Chimú bottles (n=23) and jars (n=16) from the UT collection. [Astrid: How many Andean vessels overall in the collection, and how much Chimú? Should we include a table of the samples here, with as much provenance info as we can find?]

As a second collection, we also worked with a large museum sample that was acquired in Peru by a professional archaeologist the early days of museum collecting. The Bandelier Collection at the American Museum of Natural History consists of nearly 8,000 Andean artifacts from Peru and Bolivia. The Swiss-American archaeologist Adolph Bandelier acquired these pieces as part of his 1890s Andean expedition, which was initially funded by Henry Villard. Bandelier visited the Trujillo area in 1893, where he sketched the ruins of Chan Chan and acquired more than 400 Chimú vessels and other artifacts that were accessioned by the museum. Although the records of Bandelier's expedition remain unpublished, the collection offers a large sample size of vessels that were collected at the same time, during a period of archaeological collecting when dealers were less attuned to the targeted collecting that Kroeber observed a generation later. In 2020, we scanned ### Chimú, Inca, and Chimú-Inca ceramic vessels at the AMNH.

The exploratory nature of the work also raised ethical considerations regarding work with museum collections. Archaeologists have intensified their work with museum collections in recent years, and the consideration of whether to conduct such research are as important as the logistical questions of how to accomplish the work. The ethical principles of the Society for American Archaeology highlight the values of stewardship and public responsibility—it is important for archaeologists to care for the material record, and also to share information about it with the public—identifying "public education and outreach" as significant. From this perspective, the non-destructive and museum-based work of 3D scanning presented little risk to the artifacts being analyzed, and our research was designed to be available to the public. When working with the AAHC vessels, we developed an educational component, including a small class of UT undergraduates in the lab-based collection of linear measurements of the vessels being scanned. That supervised research provided a diverse group of undergraduates with artifact analysis, while also teaching them about the loss of heritage and scientific knowledge that accompanies the collection of antiquities.

While the careful study and public reporting of museum collections is consistent with professional ethics in Americanist archaeology, the SAA also identifies a potential ethical concern in doing so: the commercialization of the archaeological record. The SAA clearly states that "Archaeologists should therefore carefully weigh the benefits to scholarship of a project against the costs of potentially enhancing the commercial value of archaeological objects. Whenever possible they should discourage, and should themselves avoid, activities that enhance the commercial value of archaeological objects, especially objects that are not curated in public institutions, or readily available for scientific study, public interpretation, and display." As described above, Chimú blackware pottery is an artifact class that was heavily collected in the past, and it is openly sold today by galleries and internet vendors. As Atwood (2004:22-23) notes, huaqueros, dealers, and collectors are no longer interested in trafficking Andean ceramics, especially mass-produced wares like those of the Chimú Empire. Our work with publicly-held collections poses little risk of increasing the present commercial value of Chimú ceramics, while its public discussion of the losses that accompany undocumented excavations and illicit collection constitutes a benefit that outweighs any associated risks.

2. Methods and Results

Linear shape variables… (Figure 1).

2.1. *Geometric morphometrics*

During the collections research, vessels were scanned with a Creaform GoSCAN 20 at a 0.5mm resolution in VXelements. Scanner calibration was optimized prior to each scan, with positioning targets required for increased accuracy, and shutter speed reconfigured in each scanning instance. Clipping planes were established to reduce the amount of superfluous data collected, and the final mesh was rendered following application of the clean mesh function in VXelements. This process removed isolated patches, self-intersections, spikes, small holes, singular vertices, creased edges, narrow triangles, outcropping triangles, narrow bridges, and non-manifold triangles prior to export as an ASCII stl file. The stl was subsequently imported to R where each mesh was subjected to an automated post-processing routine using the `Rvcg` package to detect and correct any abnormal poly-faces in advance of performing a global remesh to improve mesh quality (Schlager and Rudell 2017). The final meshes were then imported to Geomagic Design X (Dx) for landmarking.

2.1.1. Alignment and reference geometry

Following transfer to Dx, each mesh will be subjected to an additional quality check to eliminate non-manifold poly-vertices, folded poly-faces, dangling poly-faces, small clusters, small poly-faces, non-manifold poly-faces, crossing poly-faces, and small tun-

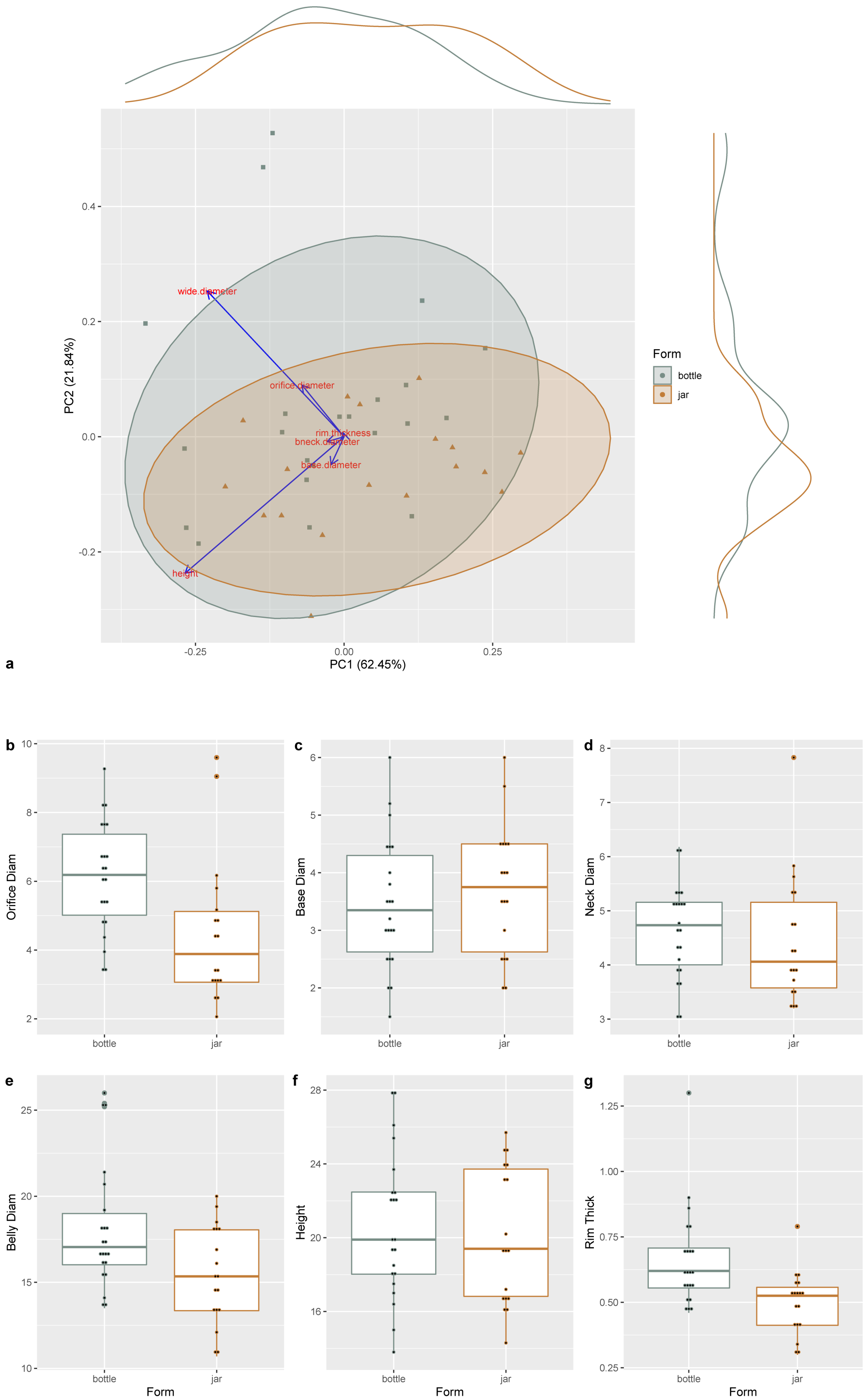

Figure 1. Plots of a, PCA; b, orifice diameter; c, base diameter; d, neck diameter; e, belly diameter; f, height; and g, rim thickness for linear metrics.

nels. Due to the paucity of homologous landmarks on cultural artefacts (Lycett 2009), reference geometry will be constructed around each vessel in a manner that yields a replicable configuration of nine landmarks, and 46 equidistant semilandmarks along the widest vessel profile, with notable similarities to previous landmark configurations (Girrulat 2006; Selden Jr. 2018a,b, 2019, 2021; Topi et al. 2017), which largely follow Birkhoff (1933).

The first component of reference geometry added, and principal assumption, is a reference vector. A sampling ratio of 100 percent was used to apply the reference vector on a revolving axis, after which a reference point was added by projecting it atop the mesh surface at the intersection of the reference vector where it exits the base of the vessel. A reference plane was inserted using the pick multiple points function, by adding a series of 10 points around the circumference of the bottle's base. Each element of reference geometry (vector, point, and plane) was then used in an interactive 3-2-1 alignment where the vessel was aligned to a global origin, orienting it in 3D space where it sits upright atop a planar surface (assumed to be the intent of the maker). Following alignment, the reference plane and point were deleted.

The widest profile is defined as the location on a mesh that lies farthest from the central point where the reference vector exits the vessel base while oriented atop the planar surface. To identify that location, a mesh sketch will be generated with the planar method using the plane at the base of the vessel to identify and sketch the widest vessel circumference. By using the plane located at the base of the vessel for the sketch, the point at which the reference vector exits the mesh remains linked to the remainder of the reference geometry. A circle will then be sketched using the vector as the centre, extending outward until the whole of the vessel fits within. Using the mesh sketch, a cylinder (surface) will be extruded around the vessel. The accuracy analyser in Dx will then be used to identify the point on the vessel with the lowest deviation from the extruded surface, and a plane (MPlane) will be inserted coplanar to the vector and oriented to the widest point, bisecting each vessel at its' widest profile.

Using the MPlane as the basis for a second mesh sketch, a spline with 15 interpolation points will be sketched on one rim. Above that sketch, a horizontal line will be added where both the spline and horizontal line are used to determine the horizontal tangent of the rim. A vertical line was subsequently added that bisected the rim at the location of the tangent. This operation was repeated for the opposing rim. The addition of this added step was necessary because surface scanners are unable to collect data from the interior of the bottles, so the spline needed to be cut in a replicable location. Since some Caddo bottles exhibit slightly inverted-to-vertical rims, the preceding step was extended to include an additional measure. A line was drawn between each rim tangent, then a second from the intersection of the line and reference vector to a point 10 mm down the vector, where a horizontal line (parallel with the rim peaks) was inserted to intersect with both external walls of the bottle. It is at this intersection that the final mesh sketch was cut to discriminate between the neck and rim. While this step admittedly appears odd in the context of a comparison of bottle shapes that all exhibit direct rims, it is of considerable import for inter-type comparisons where other bottle types exhibit differing rim morphologies (i.e., everted, etc.).

Using the MPlane as the basis for a third sketch, a spline will be populated for the entirety of the silhouetted profile. That spline will be split at the location of the horizontal tangents and the remaining sections that continued into the bottle interior were deleted. The second split will be added at the intersection of the spline and reference vector (centre of base). Four additional splits are subsequently added at the juncture of the base/body and body/neck on each side of the vessel at the points of highest curvature. The point of highest curvature used to split the spline is identified using the curvature function in Dx, and does not represent an arbitrary location.

2.1.2. Landmarks and semilandmarks

Seven landmarks and 38 semilandmarks segregate each vessel into two discrete components corresponding with the rim/neck, body/base. Landmarks and semilandmarks were populated along a spline across the vessel profile that included no abstraction/s associated with appliqued sculptural elements. Application of landmarks and semilandmarks began on the side of the vessel profile determined to include the widest vessel profile. Each component was isolated using a series of spline splits, where landmarks were later placed followed by a series of equidistant semilandmarks. Spline splits occur at the horizontal tangent at the rim, the point of highest curvature at the intersection of the neck and body, the point of highest curvature at the intersection of the body and base, and at the only intersection of the reference vector and spline at the center of the base. The constellation of landmarks and equidistant semilandmarks used in this study draws influence from the characteristic points and tangents employed in the study of aesthetic measure by Birkhoff (1933), as well as a selection of studies that followed (Denkowska, Grabska, and Marek 1994; Staudek 1999).

2.1.3. Generalised Procrustes Analysis

Landmarks and equidistant semilandmarks were exported as x, y, and z coordinate data from Dx. Those data were aligned to a global coordinate system (Kendall 1981, 1984; Slice 2001), achieved through generalized Procrustes superimposition (Rohlf and Slice 1990) performed in R 4.1.2 (R Development Core Team 2022) using the geomorph library v.4.0.1 (Adams et al. 2018; Adams and Otárola-Castillo 2013). Procrustes superimposition translates, scales, and rotates the coordinate data to allow for comparisons among objects (Gower 1975; Rohlf and Slice 1990). The geomorph package uses a partial Procrustes superimposition that projects the aligned specimens into tangent space subsequent to alignment in preparation for the use of multivariate methods that assume linear space (Rohlf 1999; Slice 2001). The mean consensus configuration and Procrustes residuals were calculated using a generalized Procrustes analysis (GPA). This initial view of the data demonstrates the degree of variability in the aggregated sample of Caddo bottles. As an exploratory measure, GM methods—to include GPA—aid in clarifying shape differences as well as the production of novel a posteriori hypotheses (Mitteroecker and Gunz 2009).

2.1.4. Principal Components Analysis

Principal components analysis (Jolliffee 2002) was used as an exploratory means of visualizing shape variation among the vessels. The shape changes described by each principal axis are commonly visualized using thin-plate spline warping of a reference 3D mesh (Klingenberg 2013; Sherratt et al. 2014). Principal components analysis (PCA) was conducted on scaled, translated, and rotated landmarks and semilandmarks, and demonstrates that the first two PC's account for 55 (PC1) and 25 (PC2) percent of the variation in bottle shape, with each remaining PC representing eight or fewer percent of the variation. The first two PCs are plotted in Figure XX, where warp grids represent the shape changes that occur in PC1 and PC2.

2.1.5. *Procrustes ANOVAs*

A residual randomization permutation procedure (RRPP; n=10,000 permutations) was used for all Procrustes ANOVAs (Adams and Collyer 2015; Collyer and Adams 2018), which has higher statistical power and a greater ability to identify patterns in the data should they be present (Anderson and Ter Braak 2003). To assess whether shape differs by size (allometry) and site, Procrustes ANOVAs (Goodall 1991) were run that enlist effect-sizes (z-scores) computed as standard deviates of the generated sampling distributions (Collyer et al. 2015). A Procrustes ANOVA was also run to assess whether shape changes with size. The assumption of allometric slope homogeneity was tested with the procD.allometry function using the PredLine option (Adams and Nistri 2010). Should this test not yield a significant result, then allometric slopes are similar–if not identical–across the categories used in the analysis.

A Procrustes ANOVA was used to test for allometry. Results indicate that allometry is significant (RRPP=10,000, Rsq=0.07151, Pr(>F) = 0.0256), meaning that vessel shapes vary significantly with vessel size. Plots of predicted allometric trajectories for bottles and jars are presented in Figure XX. The null hypothesis of parallel slopes is not rejected by the homogeneity of slopes test for group allometries; however, it is apparent that larger bottles and jars differ more than the smaller forms. A second Procrustes ANOVA was used to test for a significant difference in bottle/jar shape, which rose to the level of significance (RRPP=10,000, Rsq=0.0974, Pr(>F) = 0.0035); however, the test for a difference in vessel size did not. The tests of morphological disparity did not yield significant results, indicating that the bottles and jars occupy a similar range of morphospace.

3. Discussion

Linear measurements from the sample of jars and bottles included vessel height, rim thickness, and the diameter of each vessel at its orifice, neck, belly, and base. Of these metrics, vessel height, base diameter, and neck diameter did not differ significantly between the two samples. Overall, the jars and bottles in our pilot sample overlap in some key dimensions, with the bottles showing greater overall size variations, which would be not be consistent with production using a single set of molds. The other three sets of linear measurements showed significant differences between the jars and bottles in our sample, in terms of orifice diameter, belly diameter, and rim thickness. Given the different production scenarios emerging from archaeological field analyses—a combination of hand-shaping and use of whole vessel or elemental molds, the significant differences in orifice and belly diameters might indicate that the kinds of bottles and jars in our sample were produced as distinct shapes, rather than by mixing and matching different molds to cater to changing consumer tastes. The differences in rim thickness suggest that distinct production practices were used when producing bottles and jars. [Zac: Should we discuss the analysis of the figures on the vessels, and then point out that it's inconclusive, or just leave that out?]

The analysis of whole vessel morphology revealed that there was no significant difference in size between the jars and bottles in our sample. There is considerable size difference within both vessel categories, a variation that would argue against widespread use of the same vessel molds. Given the diverse and uncertain provenance of the vessels in the sample, this is not necessarily unexpected, and a broader analysis is still needed. Although our sample of bottles and jars overlaps in size, the analysis of whole vessel morphology demonstrates that they differ significantly in shape. This reinforces the interpretation that these jars and bottles represent distinct vessel shapes, although exploring the significance of that distinction (e.g., different social functions, or production at different places or times) would require a larger vessel sample.

Given the possibility that the selected bottles and jars could have been produced using either whole-vessel or partial molds, we focused the 3D analysis onto neck and basal morphology. PCA results for both revealed significant differences between the two vessel shapes. While bottle and jar necks are of similar diameters where they attach to the vessel body, bottle necks flare outward at their orifice, whereas jars maintain a vertical or slightly narrowing spout. Analysis of basal shape had comparable results: there was no significant difference in the sizes of bottle and jar bases, but the basal shape is significantly different between the two vessel types. Jar bases are significantly more rounded than the flat bottle bases. The analysis of these two vessel elements indicates that the morphological distinctions between bottles and jars derive from more than one vessel element. The results do not answer the question of how molds were used to produce these vessels, although they reinforce the picture that these vessels were produced as distinct shapes. That is, instead of hand-shaping the vessel bodies (or making them from a common press-mold) and adding distinctive mold-made necks and spouts to them, potters produced vessel bodies and necks in ways that kept the distinction between bottles and jars.

4. Conclusions

Our first stage of GM analysis of Chimú blackware pottery confirms that high-resolution scanning and morphological analysis of whole vessels and key vessel elements is feasible for some of the common vessel categories found in the Chimú assemblage. Data collection proved to be logistically straightforward, and our work with publicly-held collections provided opportunities for public education and outreach, enhancing the ethical dimensions of the new research. The morphological analysis of whole vessels presented some challenges for working with some of the more complex shapes that appear in the Chimú assemblage, but we found bottles and jars to be amenable to analysis and abundant enough to build sizeable samples for further analysis.

The morphological comparison of bottles and jars from the AAHC revealed features that were significantly different between the two shape classes. Although of similar sizes, the bottles and jars in our sample were distinguishable as whole vessels, and their basal and neck shapes were significantly different, as were their rim thicknesses. These results do not resolve the broader questions about workshop practices that excavators have posed, but they suggest that the bottles and jars in our sample were produced as distinct vessels, rather than using common press molds to produce some elements (e.g., vessel bodies), or "mixing and matching" molded elements in a way that would make the two shapes harder to distinguish morphologically. By broadening our study to include bottles and jars from the AMNH, we can consider additional characteristics of these vessels, including size differences and the use of modeled adornments (of plants, animals, and humans) on the vessels. Such work will bring us closer to explaining key elements of Chimú ceramic variation over time, and in different parts of the north coast, offering welcome insights into the economic organization of the Chimú Empire.

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4.3. *Data management*

All data and analysis code associated with this project can be accessed through this document or the GitHub repository, which is digitally curated on the Open Science Framework (DOI 10.17605/OSF.IO/VZHJR). The reproducible nature of this undertaking provides a means for others to critically assess and evaluate the various analyses (Gray and Marwick 2019; Peng 2011; Gandrud 2014), which is a necessary requirement for the production of reliable knowledge.

Reproducibility projects in psychology and cancer biology are impacting current research practices across all domains. Examples of reproducible research are becoming more abundant in archaeology (Marwick 2016; Ivanovaite et al. 2020; Selden Jr., Dockall, and Dubied 2020; Selden Jr et al. 2021; Selden Jr. 2022), and the next generation of archaeologists are learning those tools and methods needed to reproduce and/or replicate research results (Marwick et al. 2019). Reproducible and replicable research work flows are often employed at the highest levels of humanities-based inquiries to mitigate concern or doubt regarding proper execution, and is of particular import should the results have—explicitly or implicitly—a major impact on scientific progress (Peels and Bouter 2018).

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