Standardization of ceramic shape: A case studay from the Iron Age pottery from northeastern Taiwan

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The emergence of ceramic specialization in prehistoric societies is often linked to shifts in the complexity of social structures, because standardized ceramic production can reflect craft specialization and the presence of elite control. Previous work on identifying specialization relies on typological or linear metric analysis. Here we demonstrate how to investigate ceramic standardization by analyzing outlines of ceramic vessels. Outline analysis is useful because, unlike more commonly-used landmark analysis methods, it can effectively quantify shape differences for objects that lack distinctive measurement points needed for landmark analysis. We demonstrate this method using pottery from Kiwulan, a large multi-component Iron Age site (AD 1350-1850) in northeastern Taiwan. To measure ceramic specialization, we quantified pottery standardization by analyzing shape variables with reproducible geometric morphometric methods. We computed coefficients of variation (CVs) for shape coefficients obtained by elliptical Fourier analysis to test for shape standardization. We found significant differences in pottery shape and shape standardization that indicate changes in pottery production resulting from contact with mainland Han Chinese groups in northeastern Taiwan. Our case study, which includes an openly available research compendium of R code, represents an innovative application of outline-based methods in geometric morphometry to answer the anthropological questions of craft specialization.

# Introduction

A major historical factor often linked to social change in small-scale societies is the introduction of foreign or exotic trade goods to local Indigenous societies (Mullins, 2011). Monopolization of long-distance trade goods has caused substantial transformations in Indigenous economic, cultural, and socio-political systems (Dietler, 2005, 1997; Junker, 1993; Silliman, 2005). Pericolonial archaeology is the study of these indirect effects of colonialism, investigating areas where direct European colonial rule was limited, their conquests were often short-lived and unsuccessful, but commercial activities yielded economic and political impacts on Indigenous peoples living on the periphery of colonial control (Acabado, 2017; Trabert, 2017). Pericolonial situations were common during the seventeenth to nineteenth centuries in East and Southeast Asia where European trading activity was extensive, but direct European rule less widespread. An emerging priority in archaeological research in Asia is identifying the indirect influences are apparent on Indigenous communities during the colonial period. For example, Acabado (2017)’s study of Ifugao society in the Philippines highland suggests economic and political intensification during the Spanish presence in the lowlands as a strategy of Indigenous peoples to resist Spanish conquests.

Indigenous societies’ responses to colonial contact ranges from passive acceptance to active negotiation with the colonists, and accommodation or resistance of foreign intrusion, which can be identified through their daily cultural practices, such as their consumption patterns of foreign goods (Dietler, 2015; Given, 2004; Mullins, 2011; Scaramelli and Scaramelli, 2005; Silliman, 2001; Torrence and Clarke, 2000). In this paper we investigate the archaeology of a pericolonial situation at Kiwulan (ca. AD 1350-1850), a large multi-component archaeological site in Yilan County, northeastern Taiwan (Chen, 2007), to identify the indirect impacts of colonial settler activity on local Indigenous societies. Yilan is an ideal context to study peripheral colonial influences because the Indigenous communities were isolated by geographical barriers, limiting the frequency of direct contact with the Spanish and the Dutch settlers in northern Taiwan. Kiwulan is situated on a hill near a riverside at the northern margin of Yilan County, which is characterized by a triangular alluvial plain facing east toward the Pacific with high mountains on three other sides.

This research investigates if there was increasing ceramic specialization resulting from Indigenous interaction with Europeans in the 17th century or Chinese in the 19th century, two major foreign influences in early historical Taiwan, which may indicate social changes in local Indigenous societies. We predict that competition within the Indigenous community at Kiwulan for foreign resources and trade partnerships with European or Chinese colonizers may have led to the emergence of craft specialization caused by greater economic and social control of ceramic production by a small group of individuals. Using standardization in ceramic shapes as a proxy for craft specialization, we ask: Did colonial trade impact the shape of locally-produced Indigenous pottery vessels? Did pottery shape become more homogeneous and standardized after foreign contacts with European colonizers or Chinese immigrants?

Several measurements have been used for investigating ceramic standardization that include metric, compositional, and technological variables (Arnold, 2000; Blackman et al., 1993; Boness et al., 2015; Costin, 1991; Rice, 1991; Roux, 2015; Tite, 1999). Among those variables, metric measurements are most widely applied to archaeological assemblages. The coefficient of variation (CV) statistic is regularly used to quantify the degree of standardization in ceramic assemblages (Eerkens and Bettinger, 2001; Junker, 1999; Roux, 2003; Stark, 1995). However, because pottery vessels typically have curved shapes, linear measurements have limited sensitivity to many kinds of shape variations. Thus, to capture subtle shape variations that might also be relevant to standardization, we analyze ceramic shapes using geometric morphometric methods (GMM).

## Geometric Morphometrics

Geometric morphometrics (GMM) differs from traditional linear measurements through its use of Cartesian coordinates of morphological structures to quantify and analyze shape (Adams et al., 2004; Bookstein, 1997; Lawing and Polly, 2010; Slice, 2007). Landmarks, curves or outlines of objects can be represented by coordinates in terms of their unique point locations with respect to numerical values on coordinate axes. There are two common morphometric methods: landmark and outline approaches (Adams et al., 2004). Landmark GMM approaches assign a set of landmarks and/or semilandmarks onto objects as reference points. Generalized Procrustes analysis (GPA) is used to superimpose landmark data on a common coordinate system by translating, rotating, and scaling (Bookstein, 1991). After the procedure of GPA, superimposed landmark coordinates become shape variables that allow further statistical analyses (Slice, 2007). A common procedure is using dimensional reduction techniques, such as Principal Components Analysis or Canonical Variate Analysis, to capture the key features that represent overall shape. Visualization of the reduced data enables the identification of groups, followed by statistical tests to robustly distinguish them. Landmark-based morphometrics have been widely applied to archaeological objects with obvious morphological features that provide unambiguous reference points for landmark placement, such as tips and edges of stone tools or iron weapons (Birch and Martinón-Torres, 2019; Lycett and Cramon-Taubadel, 2013), visually distinctive bone features (Haruda et al., 2019; Meloro et al., 2015), or ceramic assemblages with distinct components (Selden Jr, 2019; Topi et al., 2017). GMM applications can answer research questions related to lithic typological and technological change (Doyon, 2019; Eren et al., 2015; Perez, 2007; Presnyakova et al., 2018; Selden et al., 2018), animal domestication or mobility (Haruda et al., 2019; Owen et al., 2014), or hominid activities through cutmarks and taphonomic traces (Aramendi et al., 2019; Courtenay et al., 2019).

Key questions in archaeological shape analysis normally involve measuring shape standardization over time, or between geographical areas. Standardization is often investigated using multivariate analysis of shape variables computed from landmark data, or coefficients of variation on associated metric data, especially for lithic assemblages. For example, Archer et al. (2015)’s case study of stone points in Southern Africa suggests an increase in shape standardization over time that may relate to increased maintenance of finished points. Buchanan et al. (2018) studied metric data and GMM to identify a more uniform base-shape of Folsom points than Clovis points across the western US (Buchanan et al., 2019). Also using metric data and GMM, Smith and DeWitt (2016) found standardized bases of fluted point in Alaska and northern Yukon that might indicate a risk management strategy to ensure the ease of replacement during long-distance travel. Other factors, such as low levels of cultural innovation in a small group, could also lead to an increase in standardization of point shapes (Okumura and Araujo, 2014).

For ceramics, Topi et al. (2017) identified standardized vessel shapes from the Casas Grandes culture in northwest Mexico using coefficients of variation for the positions of semi-landmarks across shape groups. They suggested standardization might hint the presence of specialized producers, reflecting social complexity. Another way to explore standardization is pairwise testing of variations in morphological disparity among groups of shape variables based on the calculation of distances between groups in morphospace they occupy (Wills, 2001). In this manner, Selden Jr (2018) examined Caddo ceramics using semi-landmark approaches in northeast Texas and found a gradual increase in shape standardization over time that provides a basis for further discussion of craft specialization or group identity (Selden Jr, 2019). Similar applications to lithic assemblages suggests that the Gahagan bifaces from the central Texas exhibit less size standardization than those from the southern Caddo area, indicative of different uses (Selden Jr et al., 2020). Other applications, such as the study of cranial deformation, demonstrate that landmark approaches with multivariate analyses of shape variances are an effective method to evaluate shape standardization (Kuzminsky et al., 2016; Natahi et al., 2019; Perez, 2007).

Despite the wide use of landmark approaches in archaeology, a key limitation is that landmarks may be difficult to reproducibly locate for structures that are mostly or entirely curves if not mathematically-defined. In those cases, outline approaches, such as Elliptic Fourier Analysis (EFA), is better for assessing morphological variations in the whole structure of two-dimensional closed shapes (Cardillo, 2010). EFA uses periodic functions to capture geometric information, where an outline is decomposed into a series of ellipses described by trigonometric functions (Adams et al., 2004; Bonhomme et al., 2014; Claude, 2008). In other words, EFA converts coordinates along a curve into Fourier function coefficients, called harmonic coefficients or harmonics (Kuhl and Giardina, 1982). The number of harmonics determines the quality and precision of the geometric representation of an object. The harmonic power, a cumulative sum of squared harmonic coefficients, provides a robust rule for determining the desired number of harmonics (Bonhomme et al., 2014). The first systematic use of Fourier series to analyze shapes of artifacts in archaeology was Gero and Mazzullo (1984)’s study of lithic flakes in Peru that suggests the changes in shape from a more angular to rounded tool over time. Later, Saragusti et al. (2005) introduced more functions for the further calculation of specific shape attributes, including symmetry, roughness, and deformation, which demonstrates the potential of EFA for analysis of curves. To compare resharpening trajectories in European Middle Paleolithic stone tools, Ioviţă (2009) presented a protocol from outline digitization, EFA procedure, to multivariate linear regression for shape variables. Recent lithic studies desmotrate the wide range of application of EFA to answer questions about typological classification of Late Woodland points (Fox, 2015), the function of flaked obsidian tools in Easter Island (Lipo et al., 2016), shape and symmetry standardization of the British Acheulean (Hoggard et al., 2019), and cultural taxonomies for the European Late Palaeolithic (Ivanovaitė et al., 2020).

Ceramic studies using EFA is rare, however, this approach is promising for answering questions related to ceramic taxonomy and standardization. For example, Wilczek et al. (2014) evaluate the concordance between EFA and Discrete Cosine Transform (DCT), and a traditional typology by studying 154 complete ceramic vessels with varied shapes from the Bibracte oppidum in France. The results show the variation indicated by EFA and DCT matches the traditional ceramic typology, which supports that claim that outline-based approaches can be efficiently used for studying variations in ceramic shapes. Furthermore, Wilczek et al. (2014)’s EFA results help us understand the level of production standardization over time across the region. EFA is suitable for analyzing shapes lacking representative landmarks, or where curves contain the most meaningful variation. In such cases, the focus is the whole shape instead of the different components of a shape. We use EFA to evaluate the level of standardization of ceramics data from Kiwulan, northeastern Taiwan, in relation to the European presence in the 17th century to gain insights into the emergence of ceramic specialization. The reason for using EFA is because there are no sufficient landmarks that could be identified straightforwardly due to the globular body of ceramics. We use a significance test for the equality of coefficients of variation of shape variables to statistically compare the vessel standardization from different periods.

# Archaeological background and materials

Ceramics analyzed in this study come from 40 units (4m by 4m each) sampled from the central, undisturbed area of archaeological excavations at Kiwulan (Figure 1; Figure 2). The chronology of the archaeological deposits consist of two cultural components, the upper and the lower, with a sterile layer in between (Chen, 2007). We focus on the upper component, dated from AD 1350 to 1850, spans the late Iron Age and the historical period, of which the start is defined as the European occupation in Taiwan in the early 17th century. The Dutch first occupied southern Taiwan in 1624, followed by the Spanish in northern Taiwan in 1626 (Andrade, 2007). In 1642, the Spanish was expelled by the Dutch, who then occupied the previous Spanish forts at Helping Dau in Keelung, and in Tamsui. Western Taiwan remained under Dutch colonial rule until 1662 when the Kingdom of Tungning in Taiwan was founded by Koxinga, a loyalist of the Ming dynasty of China (Andrade, 2007).



Figure 1: Map illustrating the location of Kiwulan, and other locations in northern Taiwan that are named in the text. Map data is from naturalearthdata.com



Figure 2: Map showing the largest section of excavation areas at Kiwulan, and the distribution of forty squares sampled in this paper presented in red with square ID number. Small dots represent the location of post-holes. Each square is 4 x 4 m

The archaeological record of Kiwulan’s upper component shows traces of foreign contact, including Europeans in the 17th century, and waves of Chinese immigrants in the 19th century. Imported ceramics from mainland China, stoneware, and ornaments such as beads have been recovered in the upper component, indicating frequent long-distance trade activities with Europeans and Chinese merchants. Archaeological features such as burials, middens, and post-holes with *in-situ* posts are widespread across the 1-2 m thick deposit of the upper component, and demonstrate that Kiwulan was a continuously occupied large settlement site (Chen, 2007). To compare different foreign influences, we classified the upper component into three chronological phases: pre-European, European, and Chinese. We identified these phases based on 32 previously published radiocarbon ages (Chen, 2007), excavation depth measurements, stratigraphic details reported by the excavators (color, texture, disturbance, etc.), and finds of chronologically diagnostic artifacts, such as blue and white porcelains, light grey glazed jars, and large dark brown glazed stoneware jars commonly used in the 17th century, and bricks and tiles employed by the Chinese in the 19th century (Chen, 2007; Hsieh, 2009; Wang, 2011). The deposit exhibited signs of continuous human occupation in each of the three phases with no apparent breaks.

The most abundant artifacts in the upper component are locally manufactured ceramics, which are distributed throughout the temporal sequence, and across the study site. More than 550,000 sherds were excavated, and around 1,200 vessels could be partially reconstructed (i.e. complete rim or base). There are two shapes of locally-manufactured vessels; a cooking pot and a steamer made of two cooking pots stacked together with a clay filter between. Those vessel shapes demonstrate suites of standard morphological components. Each has a globular body with a short neck and wide mouth (Figure 3). The exterior surface below the neck is decorated with a variety of impressed geometric motifs. These vessels were potentially used for cooking indicated by evidence of charred residues and carbon deposits frequently observed on vessel interiors, and soot on vessel exteriors. Firing resulted in orange and brownish color with a fully oxidized core, or a reduced core with oxidized fringes (Chen, 2007). Finger impressions and seams, usually on the interior, indicate that the vessels were shaped by hand, and that the seems between the slabs were pinched. This kind of vessel has been widely found at archaeological sites during the late Iron Age and the historical period throughout the Yilan Plain (National Musuem of Taiwan History, 2005).

Petrographic analysis for 34 thin sections presents a high percentage of inclusions (15-50%), including argillite (15-40%), metasandstone (1-10%), sandstone fragments (1-6%), quartz (1-5%), and trace amounts of feldspar and slate. Particle sizes of range from 500 to 1300 microns. In general, the globular vessel fabric presents a mixture of fine, rounded argillite with a small amounts of rounded metasandstone and rounded to sub-angular monocrystalline quartz. This composition is consistent with the mineralogical composition of local raw materials found in the Yilan Plain (Chen, 2016). There are no substantial changes in the inclusions over time, indicating continuity in pottery fabric composition across the three periods.



Figure 3: A typical pot from Kiwulan (left) and an example of a pottery drawing used for outline analysis (right)

# Methods

The sample consists of 73 reconstructed vessels with rim, body and base parts, and we securely provenanced to pre-contact (n = 32), post-European (n = 27), and Chinese contact contexts (n = 14).

## Digitizing and analyzing by EFA

We used scans of pottery drawings acquired from the Bureau of Cultural Affairs in Yilan (Figure 3). All drawings provide a two-dimensional view of vessel cross-sections, and metric measurements. The scanned drawings were imported into Inkscape (<http://inkscape.org>) for digitization where outlines were manually traced. In those instances where only one side of the cross-section image was available, or some sections were missing, we interpolated the curves and then mirrored and joined to create a closed outline for each vessel. Analyses were conducted in R software (R Core Team, 2019) using functions included in the Momocs package for quantifying and analyzing shapes (Bonhomme et al., 2014). Outlines were converted into a list of successive x, y pixel coordinates for EFA. We analyzed harmonic coefficients by principal component analysis (PCA) for dimensionality reduction to illustrate the diversity of the shape data and identify major patterns of variation.

## Statistical analysis

The principal component (PC) scores were analyzed with a multivariate analysis of variance (MANOVA) test to identify significant differences in shapes between occupation phases. We also computed coefficients of variation values (CVs) for the PCs, treating the PCs as shape variables that are more informative than linear dimensions. The coefficient of variation is a common and widely-used statistical measure of the spread of a set of measurements of a sample. It is defined as the standard deviation divided by the mean:

As a standardized measure of the spread of data, coefficients of variation (CV) allows us to directly compare variation in samples measured with different units or means. This is useful to compare the degree of standardization for archaeological assembles and enables comparison of variation across different sample sizes (Eerkens and Bettinger, 2001, p. 498). Following Eerkens and Bettinger (2001) and Roux (2003), we take this as our measurement of standardization in vessel shape variables: lower CV values reflect higher standardization, and thus increased craft specialization in the community. Given that CV is robust for positive values due to the representation by ratio, we normalized PC scores to a range between 1 and 2 before computation of CV.

To answer the question of whether CV values for vessel samples across our three occupational phases are significantly different or not, we used the Modified signed-likelihood ratio (MSLR) test for equality of CVs (Krishnamoorthy and Lee, 2014). While previous work has used the Feltz and Miller (1996)’s asymptotic test for the equality of coefficients of variation from k populations (Eerkens, 2000; Eerkens and Bettinger, 2001; Hoggard, 2017; Lycett and Gowlett, 2008; Okumura and Araujo, 2014), we prefer the MSLR test for shape variables as a more recent development with lower rates of type I error, better performance with uneven sample numbers, and more power across a range of conditions (Krishnamoorthy and Lee, 2014).

To complement our investigation of craft specialization through shape standardization, we investigated spatial patterns of ceramic vessels at Kiwulan. As craft specialization increases, pottery distribution we expect a shift from a pattern of vessels dispersed across the site to a pattern of clusters that reflects the loci of production (Costin, 2001). We used a Monte Carlo test for randomness in spatial locations of pots to explore whether their distribution is significantly clustered or dispersed.

# Reproducibility and open source materials

To enable re-use of materials and improve reproducibility and transparency (Marwick, 2017), the entire R code (R Core Team, 2019) used for all the analysis and visualizations contained in this paper is openly available online at <https://doi.org/10.17605/OSF.IO/ABVGF>. Also in this version-controlled compendium (Marwick et al., 2018) are the raw data for all the visualizations and tests reported here. All of the figures, tables, and statistical test results presented here can be independently reproduced with the code and data in this repository. The code is released under the MIT license, the data as CC-0, and figures as CC-BY, to enable maximum re-use.

# Results

We found that 13 harmonics captured 99% of the total harmonic power in the elliptic Fourier coefficients of 73 vessels from three phases. Figure 4 illustrates significant differences in vessel shapes described using thin-plate spline warping for paired periods, pre- and post-European periods, and post-European and Chinese periods, with the greatest differences between pre-European and Chinese periods.

The first two principal components (PCs) of the PCA on the elliptic Fourier coefficients explain 74.85% of the total variance, of which 48.32% is explained by the first principal component. With the third component, the first three principal components explain 86.08% of the total variance. PC1 captures the height of the vessels, from tall to short, and the roundness of the body from round to oval-shaped (Figure 4). PC2 relates to the neck and mouth constriction, from narrow to wide. PC3 explains a smaller portion of the variance (11.23%), which relates to the degree of the flare in the neck, from a curved to straight shape. The results reflect a large overlap in shapes from three occupations phases, especially for shapes in the pre-European and post-European periods. However, the spread of shape distribution indicates a wider variation in shapes in the pre-European and post-European periods compared to those in the Chinese period along both PC1 and PC2 axes. In other words, we find a decrease in shape variance in the Chinese period that is evident in the shorter height and narrower mouth of vessels used in that period.

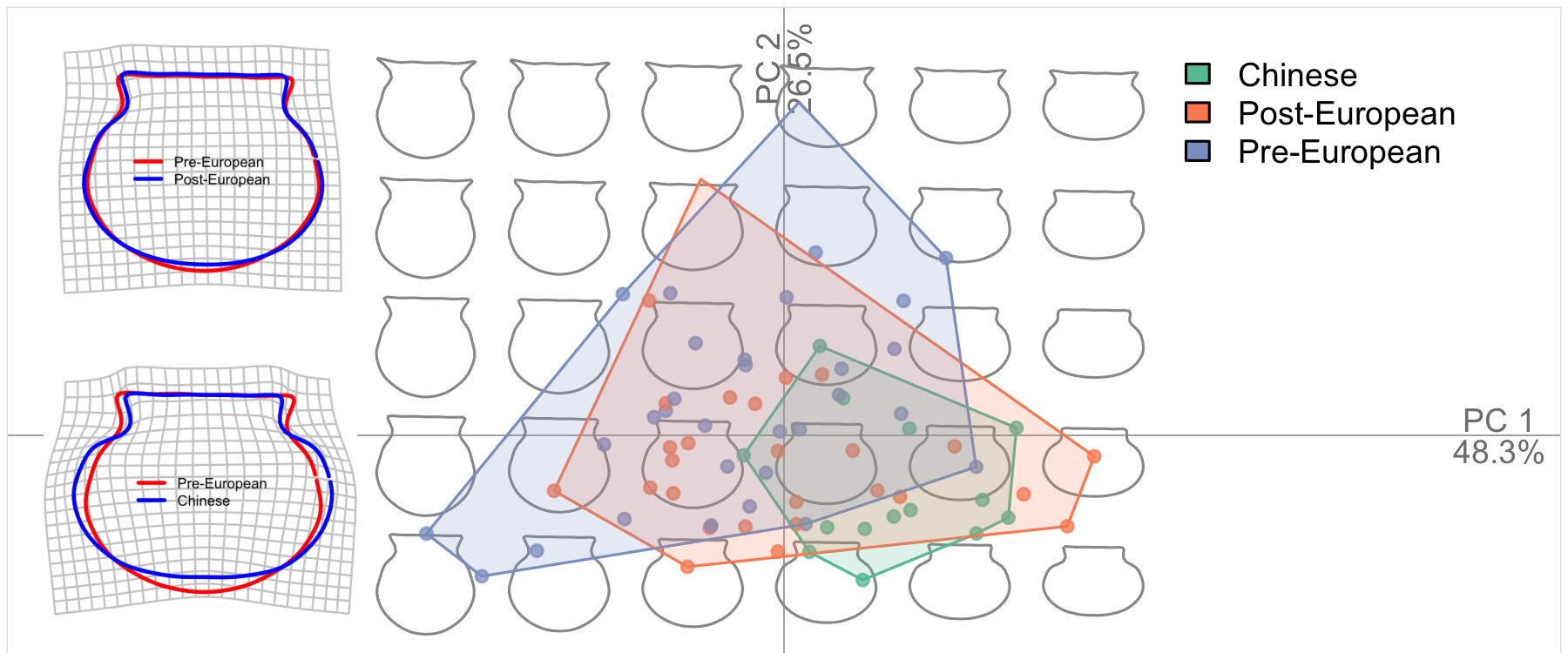


Figure 4: Left: Significant differences in average vessel shapes across phases using thin plate splines (TPS) with outline deformations required to pass from an extreme of one morphospace to another. Right: Pottery shape distribution by each occupation phase according to the first two PCs.

Table 1: Summary statistics for the MANOVA test on the PC scores. Pr(>F) is the p-value associated with the F statistic of the effect and test statistic.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Comparison | Pillai’s trace | Approximate F value | degrees of freedom | Pr(>F) |
| Chinese - Post-European | 0.3806 | 1.6202 | 29 | 0.1452 |
| Chinese - Pre-European | 0.6942 | 7.0177 | 34 | 0.0000 |
| Post-European - Pre-European | 0.3491 | 2.2917 | 47 | 0.0243 |

To test for differences in the distributions of shape variables indicated by the PC scores shown in Figure 4, we used a multivariate analysis of variance (MANOVA) test to compare pairwise combinations across the three occupation phases. Table 1 demonstrated the significant differences in shape between Pre-European and Post-European phases (p = ), and Pre-European and Chinese phases (p = ). These results are consistent with the differences in the visualization of average shapes between the occupations in the thin plate splines (Figure 4, see left). Although there is considerable overlap of shape variables between the Pre-European and Post-European phases, their PC scores differ significantly. There is not a significant difference in vessel shapes between the Post-European and Chinese contact periods.

To compare pottery shape standardization across the three phases we investigate the distributions of the first three PC scores, taking the PC scores as proxy variables for vessel shape (Figure 5). The first PC, capturing vessel height and roundness, shows higher variation in the pre-European period compared to the Chinese period. That indicates that shape standardization was higher in the Chinese period compared to the pre-European period. The second PC also presents a similar pattern of higher shape standardization in the Chinese period compared to the other two phases. The CVs calculated of the three PC also support a general trend toward a more standardized shape over time, especially for first PC.

To see whether the differences in the distribution of PCs between any two phases are substantive or due to chance, we used a modified signed-likelihood ratio test to assess the equality of CVs (Krishnamoorthy and Lee, 2014; Marwick and Krishnamoorthy, n.d.). P-values for this significance test of CVs for PC1 and PC2 show significant differences in the standardization of vessel shapes across periods, especially between Chinese contact with either pre-European or post-European (Figure 5, Table 2). A significant difference was also detected between the pre-European and post-European periods.

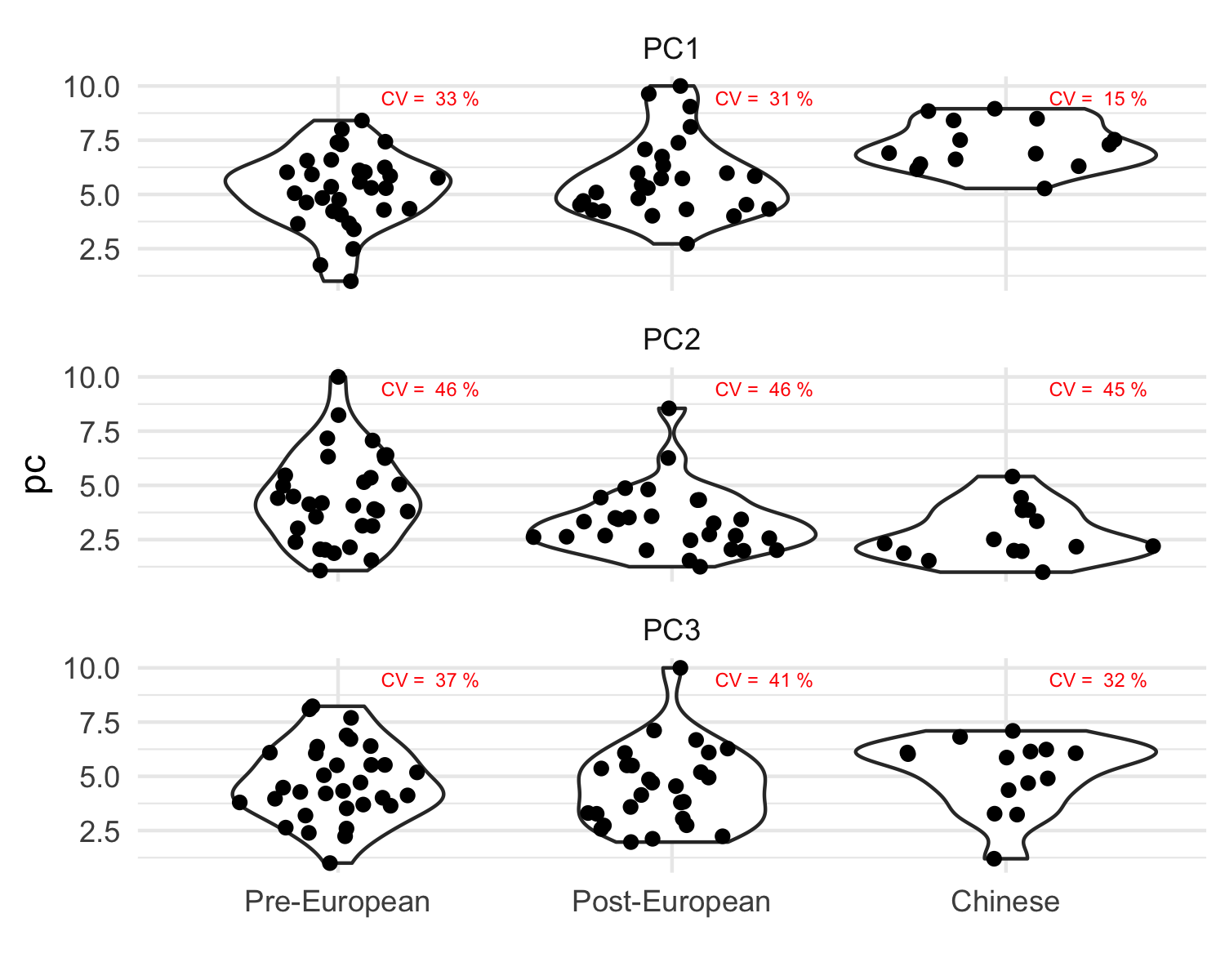


Figure 5: The distribution of mormalized PC scores by phases with CV values (%)

Table 2: P-values of the CV equality test of PC1 and PC2 between phases

|  |  |  |  |
| --- | --- | --- | --- |
| PC | MSLRT | p\_value | phases |
| PC1 | 0.1320 | 0.7164 | Post-European vs Pre-European |
| PC1 | 7.5791 | 0.0059 | Chinese Contact vs Pre-European |
| PC1 | 6.7153 | 0.0096 | Chinese Contact vs Post-European |
| PC2 | 0.0056 | 0.9401 | Post-European vs Pre-European |
| PC2 | -0.0007 | 1.0000 | Chinese Contact vs Pre-European |
| PC2 | 0.0947 | 0.7582 | Chinese Contact vs Post-European |

We also conducted size analysis by examining the body diameter of the vessels to explore any differences in vessel form reflected by size and shape. We measured body diameter directly from each physical vessel in the collection, and we focus on this metric because it is available for more vessels than any other metric. The body diameter of vessels from the Chinese period is larger than those from the two earlier periods, and the vessels before European contact have the smallest body diameter on average (Figure 6: A). Our linear regression models (Figure 6: B) show that shape, captured by PC1 and PC2, changes with size across the three phases, except for PC1 in the Chinese period. That is, the shorter vessels are larger in body diameter according to the significant positive correlation between PC1 and size. However, vessels from the Chinese period does not show this pattern. On the contrary, the negative relationship between PC2 and size suggests that vessels with a narrower neck and mouth tend to have a larger body diameter.

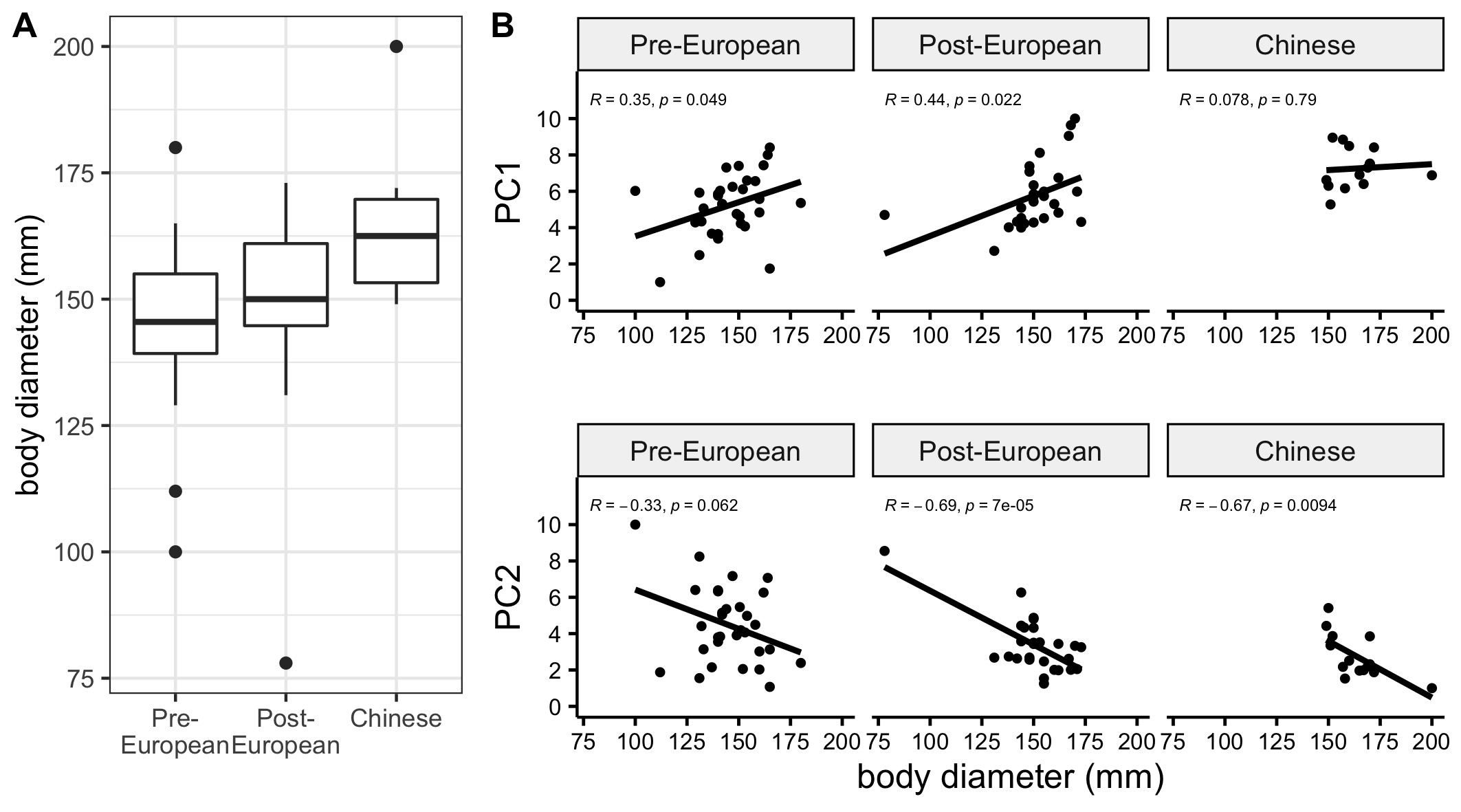


Figure 6: A: Distribution of the body diameter of the vessels across three phases. B: Scatter plots of shape variable, PC1 at the top and PC2 at the bottom, as a function of body diamater

# Discussion

Previous investigations at Kiwulan suggested an unequal distribution of prestige goods, trade ornaments in particular, following the appearance of Europeans (Cheng, 2008; Wang, 2011), which hinted at the emergence of social inequality within the Indigenous community. Ceramic vessel shape standardization was examined to measure craft specialization as a proxy for social differentiation (Costin, 2001; Junker, 1999). The result of our MANOVA demonstrates a significant difference in shapes between the pre-European and Post-European periods, and between the pre-European and the Chinese periods. The average shape presents as a round body with a wide rim and neck before European contact, which shifts to a more oval-shaped body with narrower rim and neck after the European presence. Shape changes are more pronounced during the Chinese contact period. In general, vessels become shorter in height over time, leading to an oval-shaped body. Moreover, size significantly varies with shape for vessels before and after the European presence. Shorter vessels with a narrower opening tended to have a larger body diameter. This correlation between size and shape can be also observed during the Chinese period, but there is no relationship with height.

Our CV tests indicate that there are significant differences in shape standardization between the pre-European period and post-European period, and between the Chinese contact and either pre-European or post-European periods. Pottery shape became more homogeneous and standardized after contact with Europeans and even more so after contact with the Chinese. Compositional analysis shows that the clay pastes are similar, regardless of the increasing standardization of the pottery shape, reflecting continuity in the raw material sources. We can thus rule out changes in clay fabric as a factor in explaining changes in vessel shape. To determine if form changes might be related to changes in the function of pots at Kiwulan, we used geochemical methods to extract and identify lipids trapped in the fabric of potsherds to identify foods that may have contributed residues absorbed into the clay (cf. Kwak and Marwick, 2015). Unfortunately, we did not obtain useful results due to extremely low lipid yields, which is probably due to the very thin, dense, and low porosity fabric of Kiwulan pottery. These physical characteristics of the clay offer limited spaces to trap and protect organic molecules from microbiological degradation (cf. Evershed, 2008, p. 909).

The spatial analysis (Figure 7) for pottery samples presents multiple clusters with high densities of pottery during European presence. Hypothesis testing on spatial randomness indicates a non-randomly dispersed distribution before European contact and more extreme dispersed distribution after European presence. In contrast, the distribution of pottery is more similar to random distributions during the Chinese period. This contradicts our expectation that clustered pattern will be observed with an increase in pottery standardization since the emergence of specialized groups. The absence of clusters in the Chinese period is notable because this was a time of a historically-documented decline of Indigenous population (Chen, 2007; Hsieh, 2009). We might expect reduced numbers of potters to result in pottery production shrinking to a few locations in the settlement during this time. Although the overall number of vessels is smaller during the Chinese contact period, Figure 7 shows that pottery is distributed randomly across the sampling area without any distinctive clusters during this time. This suggests that differences in population across our three occupation phases are probably not driving variation in craft specialization.



Figure 7: A: The spatial distribution of the pottery selected for shape analysis. The quantity is indicated by the color scale. B: Kernel density map visulizes the probability of the density of pottery across space. The maps show a major core area during the pre-European period, multiple core areas during the European period, and a single core during the Chinese period. The bandwidth is based on Silverman (1986)

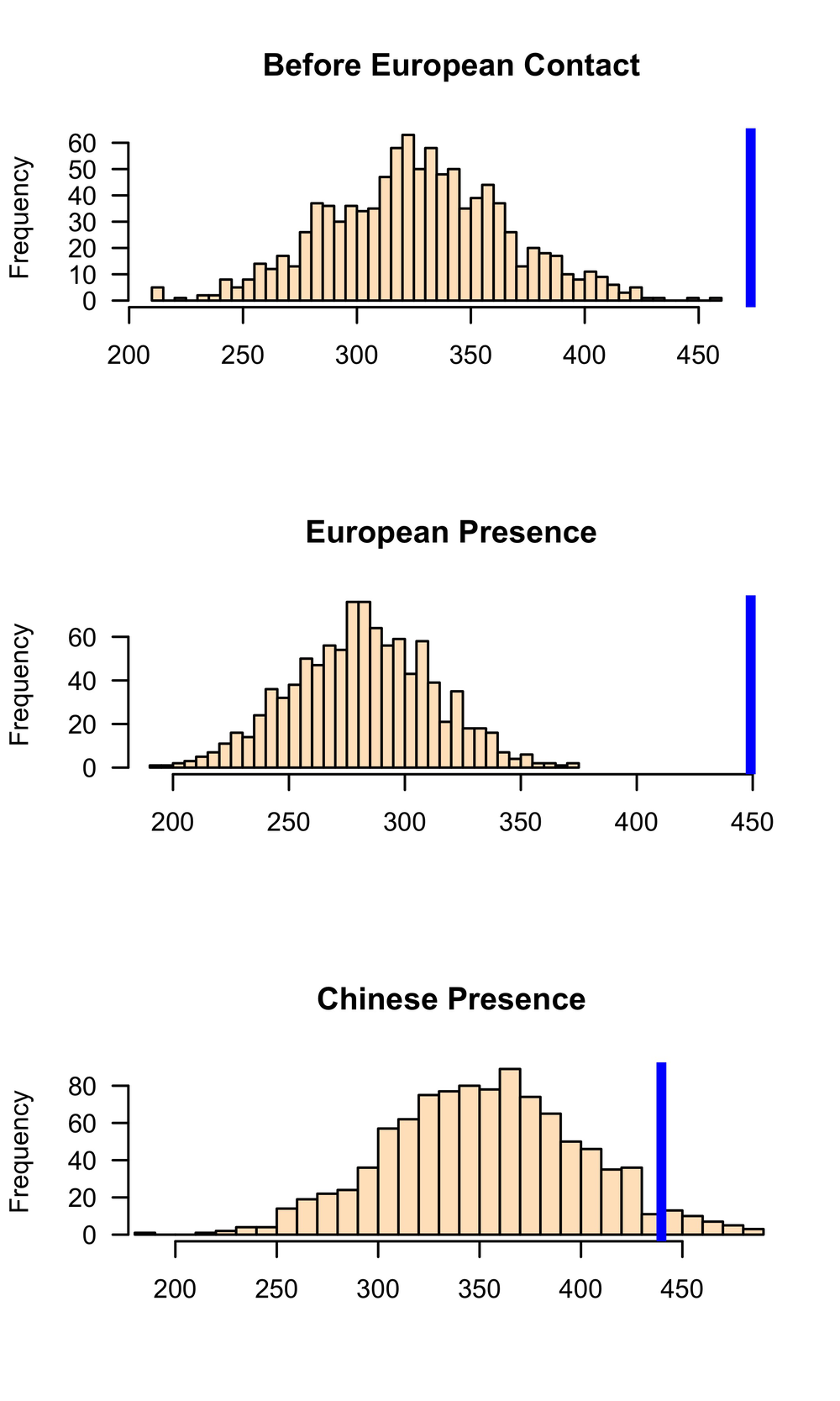


Figure 8: Histograms of simulated average nearest-neighbour distances (ANN) values from 1000 simulations for three phases. X-axis values based on meteres represent ANN expected value. Each sample distribution presents the null hypothesis with the blue line indicating the observed ANN value

Our results offer tentative support for the hypothesis that foreign influences at Kiwulan influenced emergence of social inequality in the local Indigenous society. If increased shape standardization is a reliable indicator of craft specialization, then we may be seeing evidence of a shift from corporate (group-based, distributed, collective, cooperative) to network (individual-based, competitive) organization (Blanton et al., 1996; Feinman, 2010, 2000, 1995; Feinman et al., 2000). However, strong claims for an emergence of social complexity resulting from foreign contact at Kiwulan will need support from multiple and diverse sources of evidence that are beyond the scope of this paper. We find that vessel shapes were more standardized during the Chinese period than the European period.

Compared to other regions in Taiwan, European colonial influence was weak in Yilan due to isolation by the surrounding mountains, and the economic focus of the Spanish and Dutch who preferred northern and northwest Taiwan as their trading base. Indigenous communities in Yilan experienced indirect influence from European trade networks and their colonial activities in a pericolonial context (cf. Acabado, 2017). In contrast to the Indigenous-European interactions at Kiwulan, the interaction between Indigenous people and Chinese immigrants in the 19th century appears to have been more intense and direct. Historical records indicate that Chinese groups settled in Yilan and lived closely with Kiwulan Indigenous societies (Chen, 1963; Ke, 1993). This direct influence is reflected by the archaeological evidence of large amounts of Chinese porcelains and distinctive architectural bricks and tiles used by Chinese (Hsieh, 2009). Similarly, burials at Kiwulan in this later phase show the adoption of coffins in mortuary practices, which Chiu (2004) interprets as the adoption of a symbol of ethnic Chinese.

The shape variation reported here is subtle, and invites consideration of the possibility that the absence of major changes in vessel shape at Kiwulan may have been an act of resistance to foreign influence. Continuities in vessel shape over time draws our attention to the endurance of traditional pottery production practices amid intrusions from Europeans and Chinese. In a culture contact situation, social identity may be expressed through material practices as a means of expressing cultural homogeneity and distinction from other groups (Voss, 2005). It is also important to recognize that social identity might be more complicated in a colonial context, and may be representative of more than a colonized–colonizer or local/foreign dichotomy (Voss, 2008, 2005). Shamaoshan cemetery dating from BC 3 to AD 4 in Southwest China suggests that the process of the incorporation of Southwest China into the Han Empire involved a century of conflicts, resistance, and acceptance among social groups with different identities, especially in the historical context of Han immigrants (Wu et al., 2019). A similar dynamic may have occurred at Kiwulan, with vessel shape indicating both acceptance of foreign influence through increased shape standardization, and resistance through the overall continuity in vessel shape. Vessel shape can be viewed as a symbolic expression the Indigenous identity and social boundaries because shape is a highly visible trait compared with other features of pottery (cf. Roux, 2015). Although there is an increase in number of imported ceramics through time at Kiwulan, production was continuous, and increasingly standardized. This might imply not only the utilitarian function, but a deliberate and increased emphasis on the local ceramic tradition, their cultural custom, as a response to intensified foreign contact (cf. Acabado, 2017).

# Conclusion

This study demonstrated an application of EFA on ceramic shapes to explore the emergence of ceramic specialization as indicative of foreign influences. Here, EFA is combined with a significance test for the equality of CVs of shape variables to provide a robust method of identifying and statistically assessing differences in shape standardization. The direct relationship between foreign influences and standardization of ceramic shape was tested on ceramics from Kiwulan, a large Iron Age Indigenous settlement in northeastern Taiwan. Lower variation in ceramic shape was identified after European presence began, and even lower variation during the period of Chinese presence. Our findings help to expand upon those factors that may lead to the standardization of ceramic production in a pericolonial interaction context. More homogeneous shapes during the contact periods, without any changes in clay paste composition or production technique, suggest that shape standardization was intentional. The results further suggest that expressions of social identity or cultural boundaries in Indigenous societies through highly visible vessel qualities, such as shape, may be heightened during periods of foreign contact in pericolonial contexts. Current GMM studies are mostly used for lithic topology, variations in bone shape in the filed of bioarchaeology or zooarchaeology, and some new applications for understanding cutmarks and tophomic processes. We demonstrated how we can use EFA-based GMM to identify the differences in ceramics to tackle the issue of specialized production. Our analysis, with its openly available methods and data, is readily extensible to other pottery assemblages in the region to further explore related questions about craft specialization and standardization in Iron Age ceramic technologies.

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### Colophon

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#> processx 3.4.3 2020-07-05 [1] CRAN (R 4.0.1)  
#> ps 1.3.3 2020-05-08 [1] CRAN (R 4.0.0)  
#> purrr \* 0.3.4 2020-04-17 [1] CRAN (R 4.0.0)  
#> R6 2.4.1 2019-11-12 [1] CRAN (R 4.0.0)  
#> raster 3.3-13 2020-07-17 [1] CRAN (R 4.0.2)  
#> RColorBrewer 1.1-2 2014-12-07 [1] CRAN (R 4.0.0)  
#> Rcpp 1.0.5 2020-07-06 [1] CRAN (R 4.0.2)  
#> readr \* 1.3.1 2018-12-21 [1] CRAN (R 4.0.0)  
#> readxl 1.3.1 2019-03-13 [1] CRAN (R 4.0.0)  
#> remotes 2.2.0 2020-07-21 [1] CRAN (R 4.0.2)  
#> reprex 0.3.0 2019-05-16 [1] CRAN (R 4.0.0)  
#> rio 0.5.16 2018-11-26 [1] CRAN (R 4.0.0)  
#> rlang 0.4.7 2020-07-09 [1] CRAN (R 4.0.0)  
#> rmarkdown 2.3 2020-06-18 [1] CRAN (R 4.0.0)  
#> rprojroot 1.3-2 2018-01-03 [1] CRAN (R 4.0.0)  
#> rrtools 0.1.0 2020-07-11 [1] local   
#> rstatix 0.6.0 2020-06-18 [1] CRAN (R 4.0.1)  
#> rstudioapi 0.11 2020-02-07 [1] CRAN (R 4.0.0)  
#> rvest 0.3.6 2020-07-25 [1] CRAN (R 4.0.2)  
#> scales 1.1.1 2020-05-11 [1] CRAN (R 4.0.0)  
#> sessioninfo 1.1.1 2018-11-05 [1] CRAN (R 4.0.0)  
#> sf \* 0.9-5 2020-07-14 [1] CRAN (R 4.0.2)  
#> sp 1.4-2 2020-05-20 [1] CRAN (R 4.0.0)  
#> stringi 1.4.6 2020-02-17 [1] CRAN (R 4.0.0)  
#> stringr \* 1.4.0 2019-02-10 [1] CRAN (R 4.0.0)  
#> testthat 2.3.2 2020-03-02 [1] CRAN (R 4.0.0)  
#> tibble \* 3.0.3 2020-07-10 [1] CRAN (R 4.0.0)  
#> tidyr \* 1.1.0 2020-05-20 [1] CRAN (R 4.0.0)  
#> tidyselect 1.1.0 2020-05-11 [1] CRAN (R 4.0.0)  
#> tidyverse \* 1.3.0 2019-11-21 [1] CRAN (R 4.0.2)  
#> tweenr 1.0.1 2018-12-14 [1] CRAN (R 4.0.0)  
#> units 0.6-7 2020-06-13 [1] CRAN (R 4.0.1)  
#> usethis 1.6.1 2020-04-29 [1] CRAN (R 4.0.2)  
#> vctrs 0.3.2 2020-07-15 [1] CRAN (R 4.0.2)  
#> viridis \* 0.5.1 2018-03-29 [1] CRAN (R 4.0.0)  
#> viridisLite \* 0.3.0 2018-02-01 [1] CRAN (R 4.0.0)  
#> withr 2.2.0 2020-04-20 [1] CRAN (R 4.0.0)  
#> xfun 0.16 2020-07-24 [1] CRAN (R 4.0.2)  
#> xml2 1.3.2 2020-04-23 [1] CRAN (R 4.0.0)  
#> yaml 2.2.1 2020-02-01 [1] CRAN (R 4.0.0)  
#> zip 2.0.4 2019-09-01 [1] CRAN (R 4.0.0)  
#>   
#> [1] /Library/Frameworks/R.framework/Versions/4.0/Resources/library

The current Git commit details are:

#> Local: master /Users/bmarwick/Desktop/kwl.pottery  
#> Remote: master @ origin (https://github.com/LiYingWang/kwl.pottery)  
#> Head: [15aa648] 2020-07-29: resolve merge conflict

Word count: 5220