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The Potential of Geometric Morphometrics for Danish Archaeology: Two Case Studies

This article is designed to provide an introduction into the application and potential of geometric morphometric methodologies for Danish archaeologists, researchers and enthusiasts. The article first introduces the reader to the mathematical underpinnings of statistical shape and form (shape *plus* size) before detailing the fundamentals of geometric morphometrics, emphasising its statistical power and coverage in comparison to traditional morphometrics. Throughout this article, and in two archaeological case studies, we detail the complete workflow, from data acquisition and landmark placement, through to subsequent analysis. We emphasise open-source software packages which can be used in conducting shape analysis and highlight the wealth of information available on this subject. While a high degree of technical knowledge is necessary, an incredible amount of analytical possibility can be harnessed through the adoption of two- and three-dimensional geometric morphometric methodologies.

Introductory Remarks

Shape is fundamental to our everyday lives. From the cars we drive, to the kitchen accessories we buy, from the sofa we sit on, to the bed we lie in, the concept of shape is central to our material life. It plays a role in how items can function, how they are perceived and considered, and can hint at their possible origins or makers. It is therefore unsurprising that shape has been paramount to how archaeologists comprehend and understand past societies, from our earliest ancestors to historical and contemporary societies (Archer et al. 2015; Bigoni et al. 2013; Birch and Martinón-Torres 2019; Bosman et al. 2017; Charlin et al. 2014; Hoggard et al. 2019; Iovita and McPherron 2011; Roe 1968; Serwatka 2015; White 1998; Wymer 1999). In every such exercise there is, usually, a necessity to quantify and describe different geometrical shapes, and through the data collected, infer archaeological meaning through visual summaries of data, exploratory and analytical exercises, and the testing of suitable hypotheses or models. Recently, archaeologists have changed how they record and understand the shape of different archaeological finds, utilising techniques grounded in the discipline of geometric morphometrics (GMM henceforth). In using GMM archaeologists can record a higher resolution of artefact shape and, when utilised through a multivariate statistical framework observe minute, but significant, differences in artefacts and groups of artefacts. With this in mind, we provide an introductory guide to GMM for Danish archaeologists, museum-sector staff and researchers, and enthusiasts. This article first provides some central definitions and concepts, detailing the theoretical fundamentals, and the methodological and analytical workflow. With specific reference to open-source non-propriety software, this article will, through two Danish case studies (from both prehistoric and historic periods) exemplify the potential of GMM to the Danish archaeological record. While primarily aimed at Danish archaeologists, given its noted lack of uptake in Danish research, in acting as an introductory guide to GMM this article is also of interest to a much broader audience of interested individuals.

Defining Shape, Morphometrics and GMM

Everybody knows what shape is, but perhaps it can be difficult for us to define. We talk about different shapes everyday, describing the make-up of different objects, through an almost universal vocabulary: square, round, wiggly, pointy. However, while we prescribe different objects to different shapes, it is perhaps more difficult to define what shape *actually* is. The best definition of shape, that is to say the most concise and agreed upon, is perhaps that by the statistician Prof. Christopher Small, who defines shape as “the total of all information that is invariant under translation, rotations, and isotropic rescalings” (Small 1996: preface). Six equilateral triangles will therefore have the same shape, as too will six circles, six spheres or six cubes. But, as also emphasised by Small (1996), two objects rarely contain the same information (within a degree of measurement error), with the archaeological record best exemplifying this statement; thus, the ability to quantify and assess different shapes is paramount to any analysis of artefact morphology. In using the above definition, it is important to note that two objects can have the same *shape* but be of differing *size*. Size, similarly to shape, is often a vague term. Size can be quantified and perceived in different forms. Which is 'bigger' for example: a snake, a hippopotamus or a giraffe? Size can be defined in numerous ways, through: 1) a lineal measurement (such as length), 2) a calculated mass or weight, or 3) its centroid size (see below). For archaeologists the notion of size may also be of interest (e.g. miniaturisation of lithics over time), furthermore there will be occasions where archaeologists may be interested in the combination of both size and shape i.e. the *form*.

All three variables (*form*, *shape* and *size*) can be quantified, analysed and understood through the discipline of morphometrics. First coined by Professor of Zoology (University College Dublin) Robert Blackith in 1957 (Blackith 1957), morphometrics is the quantitative study of size, shape and their variance and/or covariance. For morphometricians, there are commonly two different branches of morphometric study: traditional morphometrics and GMM. Traditional morphometrics focus on the study of lineal measurements (lengths, widths, angles, ratios and indices), in isolation and in conjunction, through the analysis of scattergraphs or perhaps more complicated frameworks e.g. Euclidean Distance Matrix Analysis (EDMA). Traditional morphometrics are deeply rooted in the history of archaeology, providing the basis of artefact classification for over half a century (e.g. Bordes 1961; Hodson et al. 1966; Roe 1969). Traditional morphometrics are however more subjective and erroneous in precision: measurement error can be introduced from a variety of different variables including the measuring equipment, the observer, the orientation of the object or the protocol. GMM on the other hand is underpinned by the study of pre-determined Cartesian landmarks (*x,y* in two dimensions or *x,y,z* in three dimensions), semilandmarks (equidistant points placed using an algorithm, between one or two end-points), and their spatial configuration. Archaeologists can use GMM approaches to explicitly:

1. Determine whether two or more artefacts and assemblages are different in terms of their shape and form;
2. Determine how shape in artefacts are related to size and development (allometry) or to a number of other factors;
3. Determine whether differences in the shape of assemblages or artefacts correspond to a particular model or hypothesis;
4. Determine network-based models of artefact production centres (through cluster analyses of shape);
5. Determine on an assemblage level the mean and median shapes, and the distribution of shape variance.

As noted above, central to the application of GMM are landmarks, and it is generally accepted by the morphometric community that there are three different landmark types *sensu* Bookstein (1991). Type I landmarks are localised mathematical points, defined by an obvious biologically homologous structure; they are easy to identify repetitively, such as the intersection of specific bones. These would be considered the 'best' landmark type to use where possible. Type II landmarks are mathematical points defined in geometry; these are not biological in nature and can reflect points including maximum curvature. Type III landmarks, on the other hand, are mathematical points defined with reference to another point, and here it is important to note that semilandmarks are defined as a special type of Type III landmark *sensu* Bookstein (1991). There is no rule as to how many landmarks or semilandmarks are required, or where they should be placed; however, guidance is available (Bookstein 1991; MacLeod 2008, 1999; Slice 2007). It is agreed that landmarks should be repeatable and feature on all examples, although methods can be employed to resolve missing landmarks (Arbour and Brown 2014). In every instance, these landmarks should be placed in the same order (for correspondence between landmarks to work) and should cover as much of the shape as possible, as to resolve issues with subsequent transformation (see Zelditch et al. 2004). A sufficient number of landmarks should be used to sample the artefact shape, however oversampling should be avoided as each landmarks adds weight to the statistical analysis. For bioarchaeologists there is greater landmark choice available as there are a greater number of points of morphological correspondence (and the existence of Type I landmarks). It is also arguably

Geometric Morphometric (GMM) open-source software
Examples include…

For **data acquisition**…

- The TPS suite (see Rohlf 2017a, 2017b)
- R Environment Packages including…
    - geomorph (Adams and Otárola-Castillo, 2013)
    - Momocs (Bonhomme et al. 2014)
    - morpho (https://github.com/zarquon42b/Morpho)
    - StereoMorph (https://github.com/aaronolsen/StereoMorph)
- PhyloNimbus (https://www.phylonimbus.com/)
- ImageJ: Fiji (https://fiji.sc/)

For **data transformation and/or visualisation**…

- All above packages (with the exception of ImageJ)
- Palaeontological Statistics (Hammer et al. 2001)
- MorphoJ (Klingenberg 2011)

Text Box 1. Examples of open-source software used in the acquisition, transformation and visualisation of two- and/or three-dimensional data.

easier to study biological three-dimensional shapes as issues including orientation are less of an issue. For non-biological examples, greater creativity is needed to study an artefact shape, particularly as these shapes will feature a greater number of atypical examples, and fewer points of morphological correspondence (homologous points). The use of sliding semilandmarks are also of note here; see Okumura and Araujo (2018) for an overview on the concept of homology.

The morphological data can be collected from a variety of formats (photographs, illustrations, microscribe data, three-dimensional scans, etc.), and there exist a wealth of programs available for the placement and subsequent analysis of landmark and semilandmark data. See Text Box 1 for an overview or Morphometrics at SUNY Stone Brook for a more full list of resources.

In addition to the number of ways with which shapes can be described in two- and three-dimensions, so too are there a number of different analytical procedures. These can be broadly categorised as either landmark-based or outline-based methodologies (see Figure 1). To demonstrate these categories, we present two Danish case studies: the first, a novel study on Danish medieval brooches (using a landmark-based approach), the second, a study on Bronze Age palstaves (using an outline-based approach). These studies are brief, and do not represent the exhaustive amount of analyses, methods and tests which can be performed on artefact shape. However, when combined, these case studies demonstrate the analytical and interpretive potential of morphological studies as through GMM.

For more information on geometric morphometrics, and morphometrics more generally, readers are encouraged to pursue other more in-depth reviews on this subject including Adams et al. (2000), Bookstein (1991), MacLeod (1998, 2008) and Slice (2007), and references herein. For more information on the history of morphometrics and GMM please refer to Reyment (2010).

A note on the case studies

In encouraging readers to interact with GMM, and encouraging data transparency and open science (Marwick 2017), all data used in these two case studies are available on the Open Science Framework. The R script is extensively annotated to guide the user through the GMM analytical process, and we encourage readers to contact the authors for any further guidance. In both case studies the TPS Suite was used for the collection and processing of data, while all

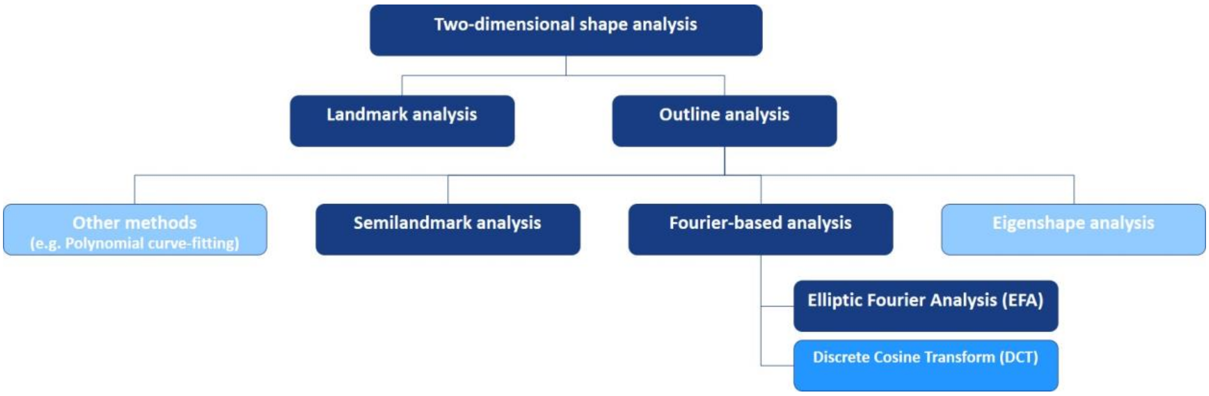

Figure 1. An overview of the different methods used in two-dimensional shape analysis (dark blue: more common in archaeology).

analyses were conducted in the R Environment (R Development Core Team 2011), using the Momocs (Bonhomme et al. 2014), geomorph (Adams and Otárola-Castillo 2013), and tidyverse (Wickham 2016) packages (and their associated dependencies).

Case Study 1: Examining Danish Medieval Brooch Typologies

Ring brooches represent a very common form of jewellery throughout the Danish medieval period, with a variety of different designs and styles recovered. With such morphological variability, the ability to categorise these brooches appropriately, and to a high resolution, is of the upmost importance. However, with the majority of brooches found out of context, often recovered through metal-detecting, categorisation is reliant on the creation of typologies based on single finds. One recent example, attempting to catalogue this variability, is the Jensen/Søvsø typology (2005, 2009). While such is of great merit to the study of brooch types it is unknown how the true variation in brooch shape can be catalogued into the Jensen/Søvsø typology. A two-dimensional geometric morphometric approach is here adopted to document brooch shape variation, without *a priori* classification, explore the main trends in shape change, and ultimately test the robustness of the Jensen/Søvsø (2005, 2009) typology. In testing this typology, the methodology is explicitly investigating the eight main groupings (1-7 and a 'special' grouping), all of which are focused on two-dimensional morphology (Table 1).

Type	Description *sensu* Søvsø (2009)	Dataset (N_{brooches})
1	*Cirkulære spænder med brede, flade rammer* (Circular brooches with wide, flat frames)	76
2	*Cirkulære spænder med smalle, trinde rammer* (Circular brooches with narrow, thick frames)	35
3	*Cirkulære spænder med håndslagsmotiv* (Circular brooches with a hand-shake motif)	10
4	*Skjold-og hjerteformede spænder* (Shield- and heart-shaped brooches)	10
5	Stjerneformede spænder (Star-shaped brooches)	4
6	*Kantede spænde* (Angular brooches)	9
7	*Pasformede spænder/buklet ramme* (Curved brooch/curved frame)	4
S	*Særtyper* (Special types)	6

Table 1. The eight categories of Medieval brooch sensu Søvsø (2009) and the number of each category analysed in this case study.

Unlike biological structures, brooches do not feature homologous points, repeatable on every specimen. Brooches do, however possess a shape which can be captured through geometric principles: every brooch has a centroid (a centre) and an internal cavity, and thus points can be captured from both the inner and outer most part of the brooch. While this is not ideal, it represents the best method for capturing the overall shape of all ring brooches. The following procedure was therefore adopted. Images of complete brooches were processed from Jensen (2005), the thesis which provided the typological framework in Søvsø (2009). These images were edited to remove pixel-noise, cropped appropriately, and rotated so that the pin (*torn*) and hinge (*tornfæste*) were horizontal. Using the Integrated Morphometrics Package (IMP8) MakeFan open-source software, a fan of 24 equally-spaced lines was added onto each image, rooted from the shape centroid. This allowed the positioning of 48 landmarks, 24 landmarks on the outer-part of the brooch, in clockwise order, and a second set of 24 landmarks on the inner-part of the brooch. All images were then synthesised in tpsUtil v. 1.69 (Rohlf 2017a), with land-marks placed in TpsDig2 v. 2.27 (Rohlf 2017b). While the pin and hinge may obscure the process, estimations through spline transformations were made in TpsDig2. For an illustration of the landmark positioning refer to Figure 2.

While there are now landmarks, cataloguing the shape of the ring brooch, size is still present. To extract shape, all landmark data was subject to a Generalized Procrustes Analysis (Adams et al. 2004; Bookstein 1991; Gower 1975; Rohlf and Slice 1990). This procedure translates all landmark data to a common origin (0,0), scales to a common size (through the unit-centroid), and through a least-squares criterion optimally rotates all coordinates. Through this three-fold approach (and the necessary amount of iterations necessary for the most optimal fitting of ring brooches), the resulting aligned Procrustes coordinates represent solely the shape of each artefact, which in turn permits an exploratory and statistical analysis of shape. For a visual representation of the Procrustes variables please refer to Figure 3.

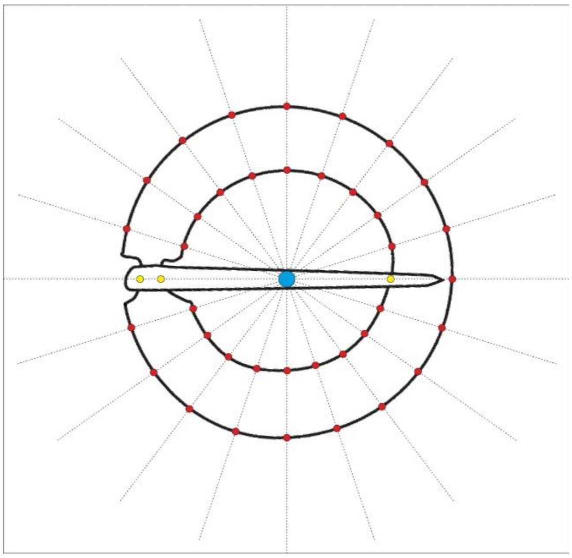

Figure 2. Example of a Danish medieval brooch and the landmark configuration (yellow: calculated through spline transformations; blue: the brooch centroid).

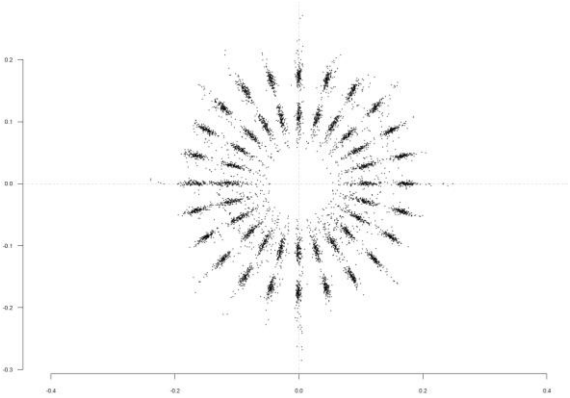

Figure 3. The Procrustes coordinates for all medieval brooches examined in this case study.

First, shape can be investigated through a principal components analysis (PCA). In this, artefact shape can be plotted within a two- (or three-) dimensional morphospace, with the main sources of shape variation representing the most major axes or components (Figure 5. The PCA graph displays the variation of each typological group, and how each artefact (each represented by a single node) relates to the main sources of variation (here representing 68.8% of all shape variance in the first two components). In Figure 4, this graph represents changes in brooch thickness and distal exaggeration, as determined through an examination of the XY transformations (not displayed here). This PCA is of interesting reading. First, many of the categories overlap and do not appear to be distinct. Groups 3, 5 and 6 demonstrate the greatest variation from the centre of the graph (representing the mean centroid), appearing most different, however all other groups converge on the graph centroid (0,0). Second, a

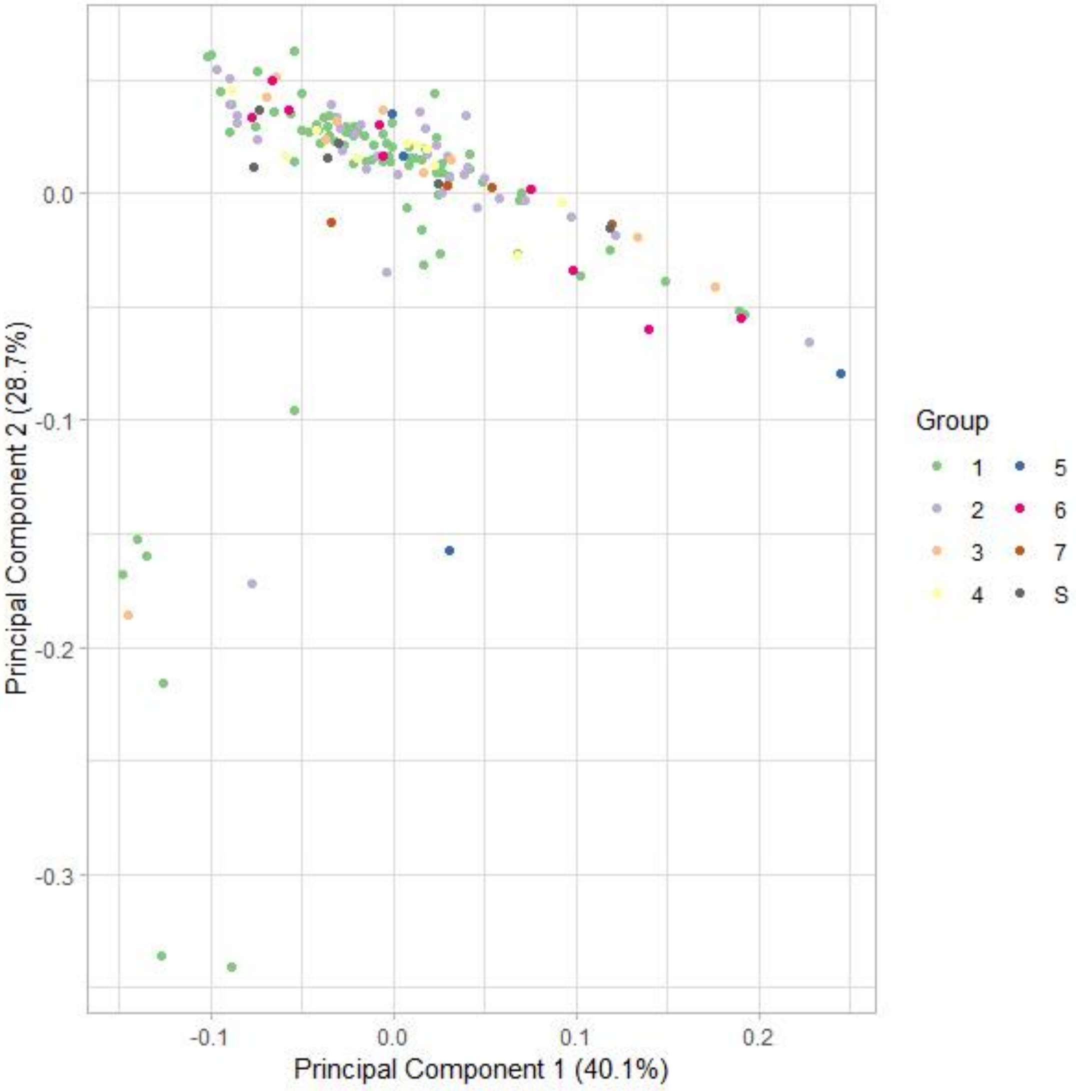

Figure 4. A principal components analysis (PCA) exemplifying variation in brooch shape (through the principal components). See the R Script for the specific XY shape transformations.

from the centre of the graph (representing the mean centroid), appearing most different, however all other groups converge on the graph centroid (0,0). Second, a number of brooches do appear to not follow this pattern, as exemplified by points in the bottom left of the graph. Closer inspection reveals that these attributes are represented by the third principal component (representing morphological changes from circle- to star-shaped brooches), an axis not represented in this graph. Finally, the distribution of points, indicate a diagonal trend, perhaps representing a gradual change in shape between the first two components.

This shape variance can be explored further, through a statistical, rather than exploratory, framework. Through the Procrustes coordinates, a Procrustes ANOVA (Goodall 1991) can be performed to test for difference in shape and artefact grouping, utilising the principal component scores (i.e. the continuous measures of shape). The Procrustes ANOVA (with 1000 permutations) demonstrate that there is no statistical difference between shape and typology (*F*: 1.1029, *Z*:0.4696, *p*: 0.3210), exemplifying issues with this typology, when examined through a GMM approach.

A number of other possible procedures can be examined through GMM. If the eight dataset groups were larger, a discriminant analysis could be conducted, which in turn would assess the degree to which random shapes can be assigned to each of the groups created by Søvsø (2009). In this example, the majority of groups do not meet the recommended sample size (n = 40), as suggested by Kovarovic et al. (2011) and so a discriminant analysis would be problematic. Hierarchical clustering could be investigated which would in turn reveal possible clusters in specific shapes and provide a new method for categorising ring brooch shapes. Mean shapes could also be investigated (see the second case study), in addition to visualisations exemplifying the difference from one shape to another shape. Other externally-calculated variables including size, region, or, with specific reference to this study, the notion of decoration could also be examined. However, with only the grouping data and illustrations, this brief GMM exercise has, demonstrated how a novel landmark-based strategy can be of benefit to understanding and testing the typology of brooches, and exemplified the benefit of GMM in comparison to lineal morphometrics. The groupings, as provided by the above typology, are insufficient as to categorise two-dimensional brooch shape, with the variety of archaeological examples failing to be correctly classified. Lineal measurements would have been difficult to propose and measure, with very few distances (other than length and width) possible to extract. Through further study (as proposed above), a new system for the categorisation of brooch shape can be developed, and through interactive web-based applications designed in R, as coded using shiny tools can be developed for archaeologists on-site to aid brooch categorisation and shape management.

Case Study 2:
Exploring Bronze Age Palstaves

Palstaves, similarly to ring brooches, are a common form of artefact recovered throughout the Danish archaeological record and represent the imposition of an explicit shape template onto an object. Here, two relatively straight forward questions are proposed, based on the existence of decorated and undecorated palstave examples:

1. Do decorated palstaves have a different shape to undecorated palstaves?
2. Is there a relationship between palstave shape change and size?

Similarly to medieval ring brooches, typologies on palstave shape are longstanding, with groupings having implications for their distribution and production (Forel et al. 2009; Monna et al. 2013). A number of different questions can be proposed including the existence of regional Danish differences in palstave shape, aspects of function and use, or the degree of potential copy error in certain production centres. However, as a case study designed to exemplify the utility of GMM, we chose these two relatively straight-forward questions.

In this example, and similarly to the previous study, only a number of lineal distances could be recorded (length, width, thickness or incremental measurements), and so a significant amount of potentially important shape information could be lost. However, unlike the previous exercise there are few points of morphological correspondence. Palstaves lack specific morphological features which can be observed on all examples or feature far fewer distinct morphological signatures in comparison to biological examples, and so landmark-based methodologies may be inappropriate. All examples, however, possess an outline which can be easily extracted and analysed.

The following procedure was therefore adopted. Illustrations of palstaves were first processed (at 300 dpi) from a series of Bronze Age catalogues by Ekkehard Aner and Karl Kersten (Aner et al. 2008; Aner and Kersten 2014, 1995, 1990), detailing palstaves from Vejle, Skanderborg, Viborg, Ringkøbing and Aarhus. A greater number of examples from other catalogues could be collected, however this study represents a small study demonstrating the potential of this dataset (and a larger analytical exercise is here actively encouraged). In total, 87 palstaves were analysed, of which 71 are undecorated and 16 decorated (for a breakdown see Table 2). All examples were complete, with minimal damage, and were thus deemed suitable for analysis.

Region	$N_{palstaves}$
Aarhus	5
Vejle	8
Ringkøbing	23
Viborg	25
Skanderborg	26

Table 2. The distribution of palstaves examined in this case study (total: 87)

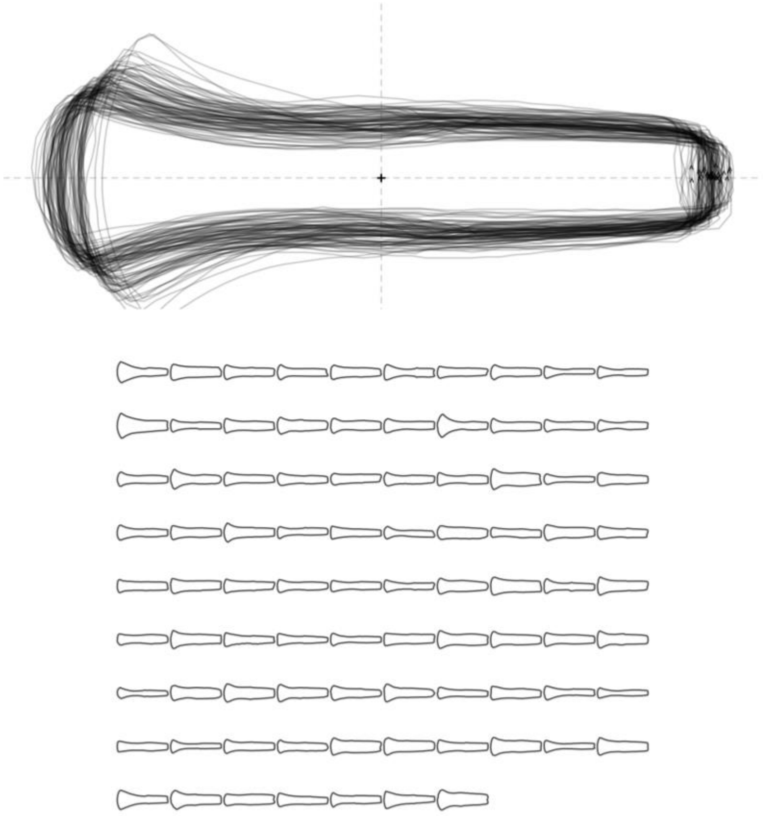

Figure 5. The different palstave shapes examined in this case study (centred, adjusted for rotation and rescaled). Top: a ‘stack’ of all examples (centred and rescaled). Bottom: a panel of all examples in this case study.

All images (in .png format) were first ‘cleaned’ as to eliminate pixel noise. In tpsUtil v 1.69 (Rohlf 2017a), all images were then converted into one file. in TpsDig2 v.2.27 (Rohlf 2017b), with outlines of each palstave. All images (in .png format) were first ‘cleaned’ as to eliminate pixel noise. In tpsUtil v 1.69 (Rohlf 2017a), all images were then converted into one file. in TpsDig2 v.2.27 (Rohlf 2017b), with outlines of each palstave extracted using the “Outline object” function. Following this, each shape transformed into 100 semilandmarks, here deemed a suitable number of points as to categorise palstave shape. The file was then screened for issues in Notepad. For an overview of the different palstave shapes analysed in this case study, see Figure 5.

In this analysis, elliptic Fourier analysis (EFA henceforth) was utilised. Unlike the above case study, which examines differences in shape through individual points of correspondence (landmarks), EFA, a method of closed-outline analysis (extended on from the Fourier series first derived by Jean Baptiste Joseph Fourier), converts semilandmarks into an infinite series of repeating trigonometric functions (harmonics) or curves. In practice, we use a set of parametric equations to fit a curve (Fourier harmonic amplitudes) using the x and y Cartesian semilandmarks. These harmonics/curves estimate the shape, and through the Giardina and Kuhl (1977) and Kuhl and Giardina (1982) formulae, varying detail of shape can be explored. With a greater number of harmonics, a greater level of detail for each shape can be obtained, however too much detail can lead to greater statistical noise, and an over-importance on shape minutiae can occur during the statistical workflow. Luckily, functions in Momocs (Bonhomme et al. 2014) can calculate the optimal level of shape; here, 17 were necessary for 99.9% total shape (harmonic power). Unlike the above procedure, size and position are already considered in the EFA parametric equations, however normalisation through centring and scaling is recommended prior EFA for the best elliptic fitting. It is, perhaps, for reasons of ease and function why outline analysis has been viewed as the commonly-accepted method for the analysis of Palstave shapes outside of Denmark (Forel et al. 2009; Wilczek et al. 2015). For a more extensive review of EFA, please refer to Caple et al. (2017).

Figure 6. A principal component analysis (PCA) exemplifying the main sources of variation, and the configuration of decorated (purple) and undecorated (light blue) examples within this variation.

Differences in palstave shape through an exploratory PCA (just as performed in the previous case study). In this, 92.4% of all shape variance is explained by two principal components, with the first principal component extending from thin palstaves with a small palstave head, to wider examples with larger palstave heads. The second principal component, in comparison, represents differences in the palstave body. These are exemplified in Figure 6, where all decorated and undecorated examples are plotted within a two-dimensional morphospace. The PCA plot demonstrates that decorated examples (in purple) cluster towards the right-hand side of the graph (with more positive principal component scores), with a smaller number of decorated palstaves in the general distribution of non-decorated examples. This difference is attestable too through a statistical framework, and specifically a MANOVA of the first ten principal components (representing 99% of all shape data). The MANOVA demonstrates what can be viewed in Figure 7, specifically that this difference in shape (through the presence and absence of decoration) is apparent (*Hotelling-Lawley*: 0.3815, *F*: 2.8999, *p*: 0.0040). Mean shapes for each group are here detailed, to exemplify the change from decorated to undecorated shapes (Figure 7).

To examine how size relates to shape, the sources of shape variation (represented by the principal components) can be examined and investigated against a length measurement (here in mm). A multiple regression of the first ten principal components against length, demonstrates a positive relationship which, while weak, is of statistical significance (*Multiple R-squared:* 0.0681, *F*: 6.214, p = 0.0146). The shape of the palstave therefore does correlate with changes in size, indicating an overall form-based change. See the R script for visualisations of the residuals, leverage and respective fitting (for all palstaves and their respective groupings).

Similarly to the first case study, and as per guidance (Kovarovic et al. 2011), the decorated group are of insufficient size as for a discriminant analysis to be deemed robust, however this and all procedures listed in the first case study can also be applied here.

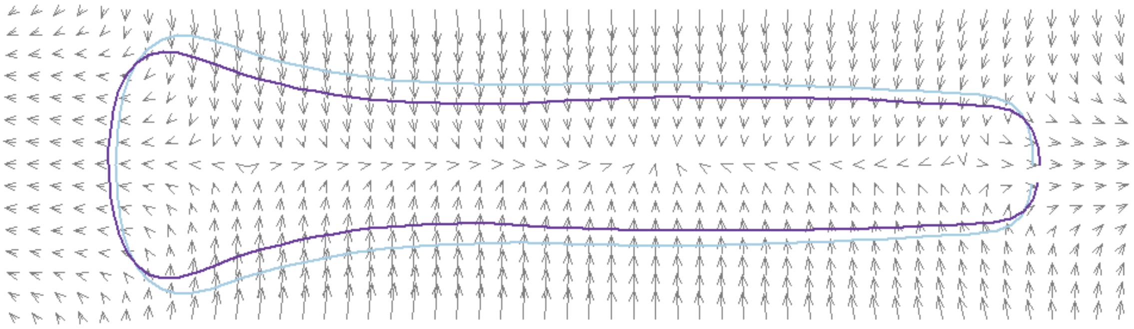

Figure 7. Mean shapes for both undecorated (light blue) and decorated (purple) examples. Arrows demonstrate the morphological change from undecorated to decorated examples.

In this second case study GMM exemplifies differences in the shape of undecorated and decorated palstaves. Further testing, through other archaeological and experimental analyses, could now be adopted to investigate whether differences in morphology relate to the utility of the palstave, with larger, broader analyses investigating whether this level of variation, and the observations noted here, apply to the rest of Denmark and Scandinavia.

Concluding Remarks: The Interpretive Potential and Future of GMM

In the two case studies this article aimed to detail the interpretive potential of GMM to the Danish archaeological record. Both examples represent perhaps atypical artefact types, artefacts which are not usually examined through conventional GMM, and a creative approach was necessary to categorise their shape. In performing such, both studies demonstrate how GMM can be vehicle for understanding artefact morphology to a higher resolution than that of lineal measurements; many of the above shape-based changes are minute and may not be recognised through more traditional approaches. While squares and circles are different to the eye, the classifications constructed by archaeologists rarely categorise the true degree of shape variation present within an artefact class. The value of lineal morphometrics should, however, not be taken for granted and this article does not wish to demean their value; after all, it is the research question proposed by the individual which will warrant a specific type of morphometric analysis. Traditional morphometrics are able to observe differences, similarly to the above shape-based approaches, and remain the easiest shape data to collect. But with open-source GMM software as above, and an understanding of GMM, benefits in the analytical and interpretive potential can be observed.

The majority of references used in this paper represent the accumulation of GMM over roughly the last two decades. A number of recent developments will change and further strengthen the potential of GMM methodologies to analysis of artefact shape. These include the adoption of machine learning techniques (MacLeod 2017, 2018; MacLeod et al. 2010), which will in-turn deliver more consistent, accurate and stable results without forcing any *a priori* decisions in landmark placement or data collection. There is also the development and use of more probabilistic methods of grouping, through Bayesian approaches which will also aid our understanding of grouping and group identification – this too is beginning to emerge in archaeological GMM studies (Otárola-Castillo et al. 2018). Only with a move beyond conventional biological and non-biological approaches to GMM shape analysis will archaeologists truly appreciate the merit and value of such techniques. These methodologies can be adapted and can be conceivably be applied to a variety of different artefact types, from other Scandinavian stone tool typologies and medieval period jewellery to prehistoric longhouse shapes (as through the remaining postholes), historic metalwork, and even rock art. With all this potential it is unsurprising, that GMM is driving many archaeological debates forward, and will continue to shape the future of archaeological analyses.

Links

Morphometrics at SUNY Stone Brook
https://life.bio.sunysb.edu/morph/

Open Science Framework
https://osf.io/en5d2/

Integrated Morphometrics Package (IMP8) MakeFan open-source software
http://www.canisius.edu/~sheets/morphsoft.html

Categorisation of brooch shape designed in R
https://shiny.rstudio.com/

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