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Evaluating the effects of parallax in archaeological geometric morphometric analyses

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Abstract

Geometric morphometrics is a powerful set of techniques that can be used to visualize and analyze the shape of artifacts. With the growing use of geometric morphometrics in archaeology, it is important to understand and identify limitations in the method. One such limitation is the accumulation of measurement error. Here, we investigate the impact of parallax or the effect of the position of an object in relation to the camera. We designed an experiment to assess the effect of parallax on measurements of artifact morphology by photographing a sample of artifacts at close range (50 cm) and systematically shifting the fixed angle of the camera relative to the artifact in five steps: 90°, 95°, 100°, 105°, and 110°. We took digital images of geometric microliths from three Jordanian Epipalaeolithic sites at each of the camera angles. We then digitized the outline of each artifact using 24 sliding landmarks. Our subsequent analyses of microlith shapes grouped by camera angle show that they are statistically indistinguishable from each other, which suggests that within these parameters, parallax has little effect on geometric morphometric measurements. While taking digital images directly above artifacts is ideal, the angle at which previously published photographs of artifacts is sometimes unknown. Our findings suggest that small deviations of the camera angle (up to 20° from horizontal) will not significantly impact geometric morphometric analyses.

Keywords Geometric morphometrics · Parallax · Camera angle · Microliths · Canonical variate analysis

Introduction

Geometric morphometrics (GM) is a powerful set of techniques that can be used to visualize and analyze the shape of organisms, objects, or artifacts. GM methods were developed in biology and physical anthropology over the last two decades (Adams et al. 2004, 2013; Bookstein 1991; Dryden and Mardia 1998; Marcus et al. 1996; Rohlf and Marcus 1993; Slice 2007; Zelditch et al. 2012) and have recently

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become more widely used in archaeology (e.g., Courtenay et al. 2019; Owen et al. 2014; Ros et al. 2014; Selden et al. 2014; Wallace et al. 2019) and in particular, in the study stone tools (Archer and Braun 2010; Buchanan et al. 2018; Buchanan and Collard 2010; Buchanan et al. 2011; Buchanan et al. 2015; Cardillo 2010; Charlin and González-José 2012; Charlin and González-José 2018; Costa 2010; Lycett and von Cramon-Taubadel 2013; Lycett et al. 2010; Petřík et al. 2018; Ragan and Buchanan 2018; Selden et al. 2018; Serwatka and Riede 2016; Suárez and Cardillo 2019; Thulman 2012; Thulman 2019; Wang et al. 2012). As the use of GM increases in archeological research, it is important to recognize and evaluate potential sources of measurement error that might impact the results of these studies.

Fruciano (2016) describes measurement error as the introduction of unexplained variance into analyses which reduces statistical power and in some cases can overwhelm the explained variance and obscure the statistical signal. Although the term measurement error suggests that it is the accumulation of errors solely through measurement, Fruciano (2016) points out that this type of error can also arise during specimen preparation and observation. Fruciano's (2016)

work reviews biological studies of GM measurement error and provides examples of measurement error that arise during specimen preparation and observation. In particular, one study found that differences in the preparation technique of biological specimens can influence the results of GM studies (Arnqvist and Martensson 1998). Similarly, Cardini's (2014) study explored the impact of two-dimensional digitizing of three-dimensional objects. Another commonly assessed source of measurement error is inter- and intra-observer error in digitizing. With observer error, measurement error can be introduced in several ways, including having multiple people digitize artifacts, the digitizing done at different times by the same person or several people, or by multiple people with different levels of knowledge or skill (Ayala et al. 2011; Breuker et al. 2006; Debat et al. 2003; Kitthawee and Dujardin 2009; Klingenberg et al. 2010; Osis et al. 2015; Takahashi 2013; Takahashi et al. 2010; von Cramon-Taubadel et al. 2007).

While the aforementioned sources of measurement error are important to recognize, measure, and minimize, here we are concerned with the influence of parallax as a source of measurement error. Parallax is the effect of the position of an object in relation to the camera. For many GM studies, digital cameras are used to capture images of the objects (e.g., stone tools) and these images are subsequently digitized for GM analysis. Measurement error due to parallax can be introduced into an analysis when the position of the camera relative to the focal object is too close or not parallel with the object. Mullin and Taylor (2002) investigated the effects of the camera being too close to the object of study. Using a standardized camera set-up and varying the distance of the camera to the focal object (a paper grid), they found that digitized images taken from a shorter distance warped the grid; however, they show that the resulting error was small and consistent. Therefore, they argued that GM analyses done with this type of parallax could still be used.

In this study, we also focus on parallax as a source of measurement error, but here our focus is on potential error introduced by varying the angle of the camera lens. Archeologists often rely on digitizing published photographs of artifacts for GM analysis; thus, the camera angle and set-up are often not known, potentially introducing error into GM measurements. To investigate this source of error, we took digital photographs of a sample of geometric microliths (stone tools) from three Epipalaeolithic sites in Jordan. We kept the distance from the camera to the artifacts consistent (measured from the center of the camera), varied the angle of the camera in five-degree increments—from 90°, 95°, 100°, 105°, to 110°—and statistically compared the resulting digitized shapes. Our expectation is that if parallax is a significant source of measurement error, then increasing the angle of the camera lens will result in increasingly warped shapes that differ from the shapes digitized without parallax.

Materials

For this study, we analyzed 92 geometric microliths from three Jordanian Epipalaeolithic sites: 30 from Kharaneh IV and Uyun al-Hammam (WZ148) and 32 microliths from Wadi Judayid (J2) (Fig. 1) (Henry 1995; Macdonald et al. 2018; Maher 2005; Maher and Macdonald 2013). Our microlith samples were randomly drawn from the larger assemblages of geometric microliths recovered from these three sites (Kharaneh IV analysis ongoing; WZ148 $n = 4973$; J2 $n = 219$). The Epipalaeolithic of the Near East precedes the Neolithic and is divided into three phases: Early, Middle, and Late. These phases are further subdivided into a series of culture groups or industries based on microlith form and other cultural patterns (i.e., Bar-Yosef 1970; Goring-Morris and Belfer-Cohen 1998). The former two phases are characterized by mobile hunter-gatherers, while the latter is typified by the Natufian culture, seen as the precursor to the origins of agriculture (although see Maher et al. 2012b for critique). Epipalaeolithic tools kits are composed of microlithic stone tools that were used as projectile inserts and cutting tools (Macdonald 2013; Richter 2007), along with larger tools such as scrapers, burins, and denticulates. Diagnostic microliths dating to the Middle and Late Epipalaeolithic period are geometric in shape, formed into triangles, rectangles, trapezoids, and lunates (crescent-moon shapes). Epipalaeolithic sites were chosen for this analysis because of the regular and geometric shape of the tools, making them easy to digitize for GM analysis and thereby minimizing user error in digitization.

Kharaneh IV (KHIV) is located in eastern Jordan and was occupied 19,830–18,600 years ago. This site dates to the Early-Middle Epipalaeolithic periods and was a hunter-gatherer aggregation locale at the time of occupation (Macdonald et al. 2018; Maher et al. 2012a). Microliths from the Middle Epipalaeolithic occupation of the site were chosen for analysis, specifically trapeze-rectangle-shaped microliths. Uyun al-Hamman (WZ148) is located in northern Jordan and dates to the Middle Epipalaeolithic. Radiocarbon dates place the occupation between 17,250 and 14,500 year BP (Maher et al. 2011a). This site functioned as a habitation site and later as an Epipalaeolithic cemetery, where numerous individuals were interred (Maher 2011; Maher et al. 2011b). The lithic assemblage is characterized by trapeze-rectangles, and a sample of these lithics was chosen for GM analysis. Both Kharaneh IV and Uyun al-Hammam are unusual for Early/Middle Epipalaeolithic sites in their large size and density of cultural material. Finally, the site Wadi Judayid (J2) is located in southern Jordan. This site dates to the Late Epipalaeolithic (Early Natufian), with radiocarbon dates placing the occupation between 12,090 and 12,784 BP. The site is smaller than Kharaneh IV and Uyun al-Hamman, however, is medium-sized for Early Natufian occupations. The lithic assemblage is dominated by lunates, and a selection of these lunates was used in this GM study.

Fig. 1 Examples of geometric microliths from Kharaneh IV, Uyun al-Hammam, and Wadi Judayid

Kharaneh IV (KHIV)

Uyun al-Hammam (WZ148)

Wadi Judayid (J2)   1 cm
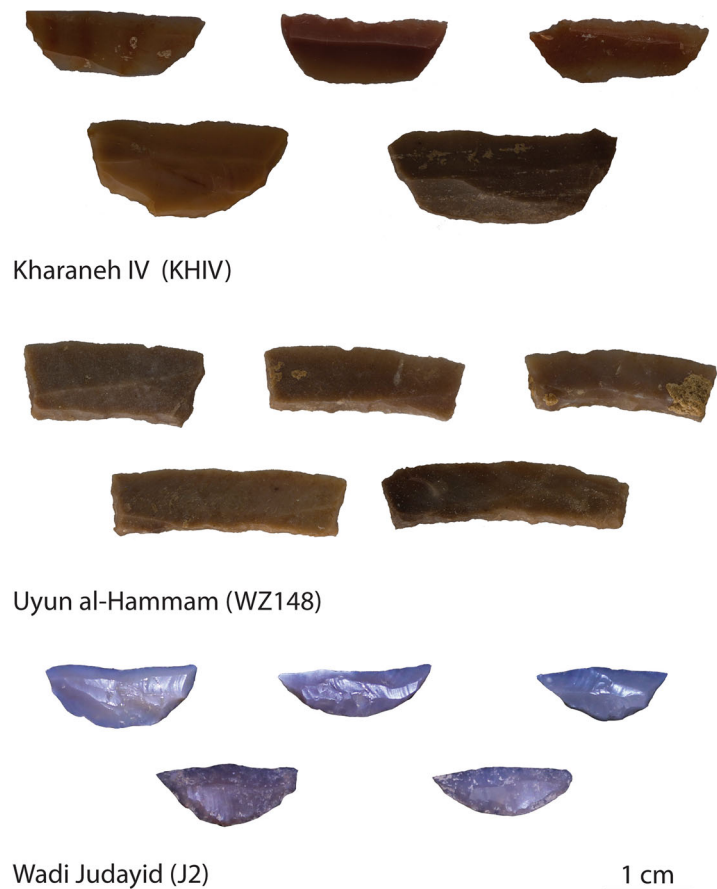
Methods

A Canon EOS Rebel SL1 camera with a macro (0.25 m/0.8 ft) EFS 18-55-mm lens was used to take digital images of the microliths. The camera was fixed on a tripod and a camera remote was used to take the images. To position the camera at different angles, we used a bubble level affixed to the top of the camera and secured the camera in the tripod stand at different angles. We took digital photographs of each of the 92 microliths in our sample with the camera initially fixed at 90° or directly above and parallel with the horizontal plane of the artifact, and 50 cm vertically above the artifact. The microliths were generally rectangular, trapezoidal, or crescent in shape and can have one or two converging ends. For the image capture, we positioned the long axis of the microlith horizontal to the bottom of the frame, with the retouched edge placed on the bottom, and maintained the same artifact orientation for each of the camera positions (see Fig. 2 for example of artifact position). After taking photos of the 92 artifacts with the camera at 90°, we then repositioned the camera at a 5° tilt from 90° or horizontal (85° or 95°) and retook photographs of the same 92 microliths. We repeated the same procedure with the camera tilted at 10° from horizontal (80° or 100°), 15° from horizontal (75° or 105°), and 20° from horizontal (70° or 110°) (Fig. 3).

The 460 resulting images were then used for two-dimensional landmark digitization and subsequent geometric morphometric analyses. To accomplish this, we imported the 460 photos into tpsDIG2 software (Rohlf 2017) and one of us (KR) placed 24 landmarks along the edges of each specimen. Digitization of the landmarks began with the placement of the first landmark on the upper left edge (or left point if the edges converged) of each microlith and continued by equally spacing 23 subsequent semilandmarks along the perimeter of each microlith in a clockwise direction (Fig. 2). For rectangular and trapezoidal tools, two landmarks were placed on both of the short ends of the microlith (see Fig. 2 as an example). This procedure was carried out for each artifact in the sample. We
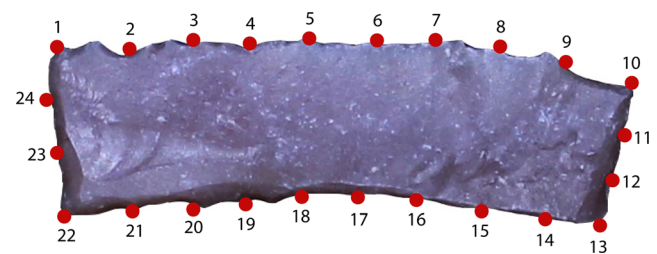
Fig. 2 Example of semilandmark placement along the perimeter of a geometric microlith (artifact from Uyun al-Hammam). Placement of the microliths for photographs maintained the retouched edge along the bottom

Overall Consensus

Fig. 3 Consensus configurations for all the imaged microliths with the corresponding camera angles

allowed each of the 23 landmarks to slide between adjacent landmarks prior to analysis. Sliding semilandmarks were chosen because the microliths do not have clear homologous features to place fixed landmarks (excepting the two "corners"). Thus, the use of sliding semilandmarks allows for the positioning of landmarks along an undifferentiated edge, minimizing intra-observer error when digitizing each specimen. In an earlier pilot study, we superimposed digital combs with equally spaced lines on each photo and placed the landmarks using this procedure and found that the results were qualitatively similar to the sliding procedure, and thus chose the sliding semilandmark method in keeping with other GM studies on Epipalaeolithic microliths (Macdonald 2013).

After digitizing the specimens, we followed standard GM procedures for extracting shape variables from landmark data (see Buchanan et al. 2014). First, we carried out the superimposition procedure to control for size differences among the specimens (Rohlf and Slice 1990; Rohlf 2003). Landmark superimposition entails three steps: (1) landmark coordinates are centered at their origin or "centroid," and all configurations are scaled to unit centroid size; (2) the consensus configuration is computed; and (3) each landmark configuration is rotated to minimize the sum-of-squared residuals from the consensus configuration. We carried out the superimposition procedure using the tpsSuper program (Rohlf 2015b). Next, the landmarks were projected to tangent Euclidean space (Kendall 1984; Rohlf 1998; Slice 2001). We conducted a regression of the distances in tangent space against the Procrustes distances to determine the fit between the specimens in shape space and linear tangent space. This test was carried out using the tpsSmall program (Rohlf 2015a). The correlation between the two distances was strong (slope =

0.9937; correlation = 0.9999; root MS error = 0.000078), indicating that the projection was adequate. Following the superimposition and projection procedures, we computed the weight matrix. The weight matrix is the partial warp scores and the uniform component describing the shape variation in our dataset, where the partial warps are the eigenvectors of the bending-energy matrix that describe local deformation along a coordinate axis and the uniform components are vectors that express global information on deformation. The first uniform component accounts for variation along the X-axis of a configuration, and the second uniform component accounts for variation along the Y-axis. Partial warps and the uniform components together represent all information about the shape of the specimens (Rohlf et al. 1996; Slice 2005). Partial warps and uniform components were computed using the tpsRelw program (Rohlf 2016).

Following the superimposition of the landmark configurations, we carried out canonical variate analysis (CVA) on the weight matrix to determine if differences in camera position result in statistically important shape differences among the microliths. In the CVA, we used camera angle as the grouping variable. This procedure calculates the Mahalanobis distance from the pooled within-group covariance matrix and uses this as a linear discriminant classifier. We used a leave-one-out (jackknifing) procedure to cross-validate group assignments (Kovarovic et al. 2011). Following the CVA, we used a MANOVA procedure to test for statistical differences among the groups (the different camera angles) of microliths. The statistical analyses were carried out in PAST 3.23 (Hammer et al. 2001). Images and data from this experiment are available on Zenodo (DOI: https://doi.org/10.5281/zenodo.3866638).
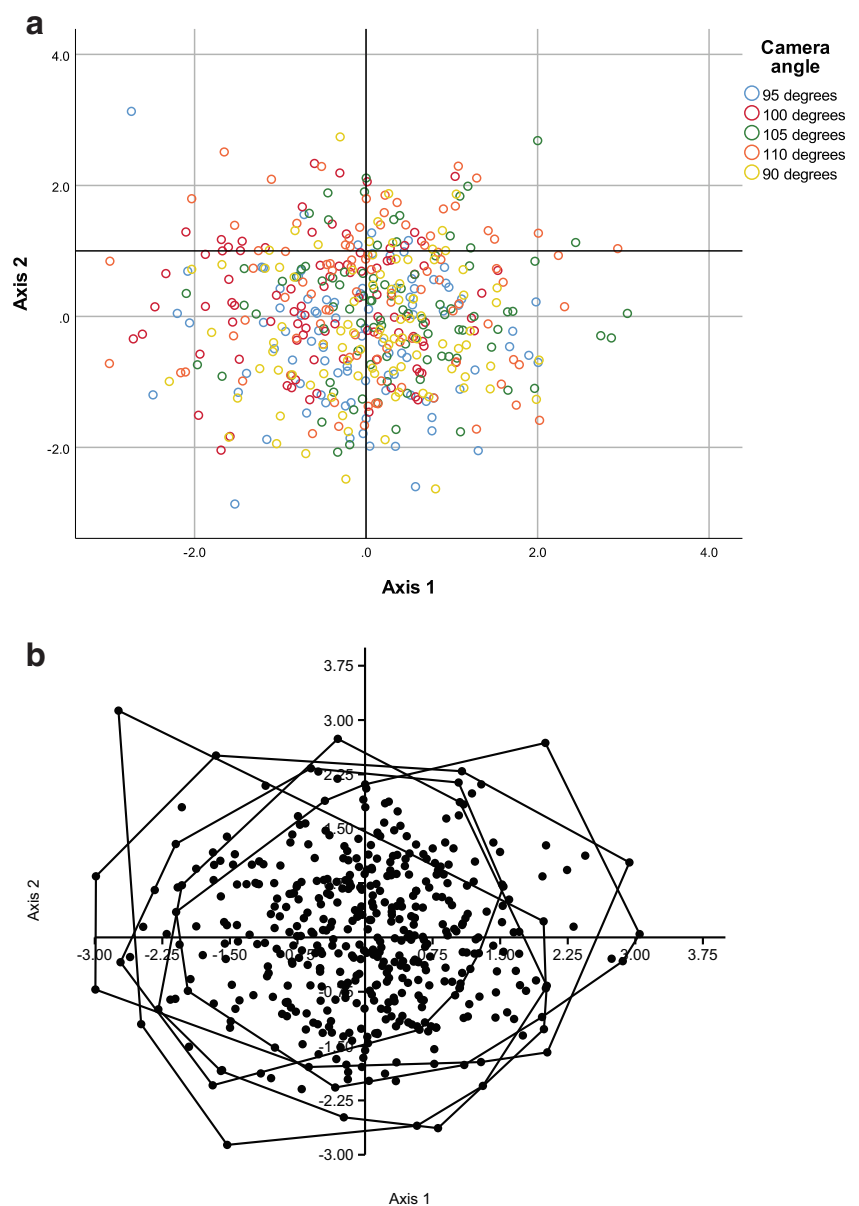
Results

The consensus configurations associated with each of the camera angles derived from the superimposition procedure are shown in Fig. 3. These average shapes appear similar. The first two axes of the CVA of the weight matrix represent nearly 60% of the overall variation in the dataset and visual inspection of the microlith shape distribution by camera angle shows a substantial degree of overlap (Fig. 4). The cross-validated classification matrix associated with the group (camera angle) membership assignments made by the CVA procedure had a low overall correct classification rate of 10.87%. We might expect that the highest correct classification rates should be associated with the most different camera angles—90° and 110°—however, these angles show similar levels of

Table 1 Cross-validated confusion matrix of group membership. Group classifications to camera angles are read by column, where correct classification should result in each of the 92 per group occurring along the diagonal

Camera angle	90	95	100	105	110
90	9	28	20	20	15
95	19	14	21	17	21
100	24	20	11	19	18
105	24	19	18	6	25
110	13	19	22	28	10
Total	89	100	92	90	89

misclassification to each other and to the other camera angles (Table 1). The results of the MANOVA testing for statistical

Fig. 4 **a** Bivariate distribution of canonical variate scores representing 32.44% of the overall variation on the X-axis and 27.55% of the overall variation on the Y-axis. **b** The limits of the variation represented by the groups of 92 microliths digitized for each of the five different camera angles are defined by convex hulls

differences in the weight matrix variables by camera angle show no significant difference (Wilks' lambda = 0.8153, df = 176, 1646, $F = 0.4913$, $p = 1$; Pillai trace = 0.1988, df = 176, 1660, $F = 0.4932$, $p = 1$). These results indicate that for this study, the camera angle, and thus parallax, did not make a significant difference in the GM analysis of artifact shape.

In an additional set of analyses (see Supplementary Materials), we first reduced the variation within the group of microliths by removing the most variable assemblage (KHIV) and conducted CVA and MANOVA by camera angle, we then removed two of the most variable assemblages (KHIV and WZ148) and again conducted CVA and MANOVA by camera angle. We did this to examine the impact of within group variation on the tests of parallax. The results of both sets of analyses are consistent with the results presented above, and increasing the camera angle does not produce groups that are distinguishable by camera angle suggesting that parallax has little effect.

Discussion

Archeologists increasingly use GM to analyze artifact shape and from these shapes, analyses make inferences about cultural transmission, cultural differences, production techniques, and function, among other things. Thus, recognizing and assessing sources of measurement error in this process are ever more critical. Here we investigated one such potential source, parallax; specifically, parallax related to varying camera angles. Parallax is of particular relevance to archaeology because it is common for archeologists to digitize published photographs or photographs provided by museums for GM analysis (in cases of missing or stolen artifacts, old photos might be the only source of new measurements) and in many cases, the position of the camera is not recorded and unknown.

Our results indicate that digitizing photos of artifacts from varying camera angles up to 110°, or 20° from horizontal, has no significant impact on the statistical analysis of digitized shapes. The results of the CVA demonstrated that classification rates among the five different camera angles show little difference overall and no patterned difference by camera angle. The MANOVA test confirms this by showing that the shape variables of the same artifacts derived from the five different camera angles are statistically indistinguishable. These findings suggest that within the parameters of our experiment—the camera fixed at 50 cm above the artifact and varying in angle between 90 and 110°—parallax has little effect.

Our results are in agreement with the experimental study on parallax conducted by Mullin and Taylor (2002). To reiterate, Mullin and Taylor (2002) investigated the effects of varying the distance of the camera above the object of study and did not vary the angle of their camera. They used a paper grid as their focal object and after digitizing the grids, they found that digitized images taken from a shorter distance warped the grid, but that the resulting error was small and consistent. Therefore, they argued that GM analyses done with this type of parallax could still be used. Our results indicate that there is little effect in varying the angle of the camera, also suggesting that parallax was not an issue for GM analysis in this study. Thus, these results suggest that it is possible to use published photos of artifacts for GM analysis, even though the camera angle is unknown. However, it is important to note that the Epipalaeolithic geometric microliths used for this study are small and sit flat on the table surface. Future research will test whether parallax affects GM analysis in larger, more "three-dimensional" artifacts, such as handaxes. Other areas of future study include using a wide-angle camera lens, rather than a macro-lens, to test whether the lens type impacts the effect of parallax on GM measurements.

While parallax due to camera angles varying between 90 and 110° appears to have little effect on the resulting GM shape analysis, clearly taking digital images with the camera set precisely at 90° and parallel with the artifact or object is ideal. However, using photographs taken by other researchers is common in archaeology, whether they are published or archived, and it is rare for the details of the camera set-up to be published. Our findings suggest using photos of artifacts with unknown set-ups is not entirely problematic, as variation in camera angle does not significantly alter images for use in geometric morphometric analyses. Of course, we urge researchers publishing photos to record and describe their camera set-ups so that future researchers can better utilize the photos with GM.

References

Adams DC, Rohlf FJ, Slice DE (2004) Geometric morphometrics: ten years of progress following the 'revolution'. Ital J Zool 71:5–16

Adams DC, Rohlf FJ, Slice DE (2013) A field comes of age: geometric morphometrics in the 21st century. Hystrix 27:7–14

Archer W, Braun D (2010) Variability in bifacial technology at Elandsfontein, Western cape, South Africa: a geometric morphometric approach. J Archaeol Sci 37:201–209

Arnqvist G, Martensson T (1998) Measurement error in geometric morphometrics: empirical strategies to assess and reduce its impact on measures of shape. Acta Zool Acad Sci Hung 44:73–96

Ayala D, Caro-Riaño H, Dujardin J-P, Rahola N, Simard F, Fontinelle D (2011) Chromosomal and environmental determinants of morphometric variation in natural populations of the malaria vector Anopheles funestus in Cameroon infection. Genet Evol 11:940–947

Bar-Yosef O (1970) Epipalaeolithic cultures of Palestine. Unpublished PhD Thesis, Hebrew University of Jerusalem

Bookstein FL (1991) Morphometric tools for landmark data: geometry and biology. Cambridge University Press, Cambridge

Breuker C, Patterson J, Klingenberg C (2006) A single basis for developmental buffering of Drosophila wing shape. PLOS ONE 1. https://doi.org/10.1371/journal.pone.0000007

Buchanan B, Collard M (2010) An assessment of the impact of resharpening on Paleoindian projectile point blade shape using geometric morphometric techniques. In: Lycett S, Chauhan PR (eds) New perspectives on old stones: analytical approaches to Paleolithic technologies. Springer, New York, pp 255–274

Buchanan B, Collard M, Hamilton M, O'Brien M (2011) Points and prey: an evaluation of the hypothesis that prey size predicts early Paleoindian projectile point form. J Archaeol Sci 38:852–864

Buchanan B, O'Brien M, Collard M (2014) Continent-wide or region-specific? A geometric morphometrics-based assessment of variation in Clovis point shape. Archaeol Anthropol Sci 6:145–162

Buchanan B, Eren MI, Boulanger MT, O'Brien M (2015) Size, shape, scars, and spatial patterning: a quantitative assessment of Late Pleistocene (Clovis) point resharpening. J Archaeol Sci Reports 3: 11–21

Buchanan B, Andrews B, O'Brien M, Eren MI (2018) An assessment of stone weapon tip standardization during the Clovis–Folsom transition in the Western United States. America Antiq 83:721–734

Cardillo M (2010) Some applications of geometric morphometrics to archaeology. In: Elewa AMT (ed) Morphometrics to nonmorphometricians. Lecture Notes in Earth Sciences. Springer, pp 325–341

Cardini A (2014) Missing the third dimension in geometric morphometrics: how to assess if 2D images really are a good proxy for 3D structures? Hystrix 25:1–10

Charlin J, González-José R (2012) Size and shape variation in Late Holocene projectile points of southern Patagonia: a geometric morphometric study. Amer Antiq 77:221–242

Charlin J, González-José R (2018) Testing an ethnographic analogy through geometric morphometrics: a comparison between ethnographic arrows and archaeological projectile points from Late Holocene Fuego-Patagonia. J Anthrop Archaeol 51:159–172

Costa A (2010) A geometric morphometric assessment of plan shape in bone and stone Acheulean Bifaces from the middle Pleistocene site of Castel di Guido, Latium, Italy. In: Lycett S, Chauhan PR (eds) New perspectives on old stones: analytical approaches to Paleolithic technologies. Springer, New York, pp 23–42

Courtenay L, Yrayedra J, Mate-González MÁ, Aramendi J, González-Aguilera D (2019) 3D analysis of cut marks using a new geometric morphometric methodological approach. Archaeol Anthropol Sci 11:651–665

Debat V, Béagin M, Legout H, David J (2003) Allometric and nonallometric components of Drosophila wing shape respond differently to developmental temperature. Evolution 57:2773–2784

Dryden I, Mardia K (1998) Statistical shape analysis vol 4. Wiley, Chichester

Fruciano C (2016) Measurement error in geometric morphometrics. Dev Genes Evol 226:139–158

Goring-Morris AN, Belfer-Cohen A (1998) The articulation of cultural processes and Late Quaternary environmental changes in Cisjordan. Paléorient 23:71–93

Hammer Ø, Harper DAT, Ryan PD (2001) PAST: paleontological statistics software package for education and data analysis vol 4(1), 3.17 edn., Palaeontologia Electronica

Henry DO (1995) Prehistoric cultural ecology and evolution: insights from southern Jordan. Plenum Press, New York

Kendall DG (1984) Shape manifolds, procrustean metrics and complex projective spaces. Bull Lond Math Soc 16:81–121

Kitthawee S, Dujardin J-P (2009) The Diachasmimorpha longicaudata complex: reproductive isolation and geometric patterns of the wing. Biol Control 51:191–197

Klingenberg C, Wetherill L, Rogers J, Moore E, Ward R, Autti-Rämö I, Fagerlund A, Jacobson SW, Robinson LK, Hoyme HE, Mattson SN, Li TK, Riley EP, Foroud T, CIFASD Consortium (2010) Prenatal alcohol exposure alters the patterns of facial asymmetry. Alcohol 44:649–657

Kovarovic K, Aiello LC, Cardini A, Lockwood CA (2011) Discriminant function analyses in archaeology: are classification rates too good to be true? J Archaeol Sci 38:3006–3018

Lycett SJ, von Cramon-Taubadel N (2013) A 3D morphometric analysis of surface geometry in Levallois cores: patterns of stability and variability across regions and their implications. J Archaeol Sci 40: 1508–1517. https://doi.org/10.1016/j.jas.2012.11.005

Lycett SJ, von Cramon-Taubadel N, Gowlett JAJ (2010) A comparative 3D geometric morphometric analysis of Victoria west cores: implications for the origins of Levallois technology. J Archaeol Sci 37: 1110–1117

Macdonald DA (2013) Interpreting variability through multiple methodologies: the integration of form and function in Epipalaeolithic Microliths. University of Toronto

Macdonald DA, Allentuck A, Maher LA (2018) Technological change and economy in the Epipalaeolithic: assessing the shift from Early to Middle Epipalaeolithic at Kharaneh IV. J Field Archaeol 43:437–456. https://doi.org/10.1080/00934690.2018.1504542

Maher L (2005) The Epipalaeolithic in context: palaeolandscapes and prehistoric occupation of Wadi Ziqlab, Northern Jordan. Unpublished PhD dissertation, Department of Anthropology, University of Toronto

Maher LA (2011) Reconstructing paleolandscapes and prehistoric occupation of Wadi Ziqlab, Northern Jordan. Geoarchaeology 26:649–692

Maher LA, Macdonald DA (2013) Assessing typo-technological variability in Epipalaeolithic assemblages: preliminary results from two case studies from the Southern Levant. In: Borrell F, Molist M, Ibanez-Estevez JJ (eds) Stone tools in transition: from hunter-gatherers to farming societies in the Near East. 7th Conference on PPN Chipped and Ground Stone Inductries of the Fertile Crescent. Universitat Autònoma de Barcelona. Servei de Publicacions, Barcelona, pp 29-44

Maher LA, Banning EB, Chazan M (2011a) Oasis or mirage? Assessing the role of abrupt climate change in the prehistory of the Southern Levant Camb. Archaeol J 21:1–29

Maher LA, Stock JT, Finney S, Heywood JJN, Miracle PT, Banning EB (2011b) A unique human-fox burial from a pre-Natufian cemetery in the Levant (Jordan). PLOS ONE 6:e15815

Maher LA, Richter T, Macdonald D, Jones MD, Martin L, Stock JT (2012a) Twenty thousand-year-old huts at a hunter-gatherer settlement in Eastern Jordan. PLOS ONE 7:e31447. https://doi.org/10.1371/journal.pone.0031447

Maher LA, Richter T, Stock JT (2012b) The pre-Natufian Epipalaeolithic: long term behavioural trends in the Levant Evolutionary. Anthropology 21:69–81

Marcus L, Corti M, Loy A, Naylor G, DE Slice (eds) (1996) Advances in morphometrics. Springer Science & Business Media

Mullin S, Taylor P (2002) The effects of parallax on geometric morphometric data. Comput Biol Med 32:455–464

Osis S, Hettinga B, Macdonald S, Ferber R (2015) A novel method to evaluate error in anatomical marker placement using a modified generalized Procrustes analysis. Comput Methods Biomech Biomed Eng 18:1108–1116

Owen J, Dobney K, Evin A, Cucchi T, Larson G, Vidarsdottir U (2014) The zooarchaeological application of quantifying cranial shape differences in wild boar and domestic pigs (Sus scrofa) using 3D geometric morphometrics. J Archaeol Sci 43:159–167

Petřík J, Sosna D, Prokeš L, Štefanisko D, Galeta P (2018) Shape matters: assessing regional variation of Bell Beaker projectile points in Central Europe using geometric morphometrics. Archaeol Anthropol Sci 10:893–904

Ragan K, Buchanan B (2018) Assessing collector bias: a geometric morphometric analysis of a collection of isolated Clovis points from the midcontinent. Midcont. J Archaeol 43:91–111

Richter T (2007) A comparative use-wear analysis of late Epipalaeolithic (Natufian) chipped stone artefacts from the Southern Levant. Levant 39:97–122

Rohlf FJ (1998) On applications of geometric morphometrics to studies of ontogeny and phylogeny. Syst Biol 47:147–158

Rohlf FJ (2003) Bias and error in estimates of mean shape in geometric morphometrics. J Hum Evol 44:665–683

Rohlf FJ (2015a) tpsSmall, 1.33 edn. Department of Ecology and Evolution, State University of New York, Stony Brook

Rohlf FJ (2015b) tpsSuper, 2.02 edn. Department of Ecology and Evolution, State University of New York, Stony Brook

Rohlf FJ (2016) Relative warps version 1.62 shareware program. Department of Ecology and Evolution. State University of New York, Stony Brook

Rohlf FJ (2017) tpsDig2 version 2.31 shareware program. Department of Ecology and Evolution. State University of New York, Stony Brook

Rohlf FJ, Marcus LF (1993) A revolution in morphometrics. Trends Ecol Evol 8:129–132

Rohlf F, Slice D (1990) Extensions of the Procrustes method for the optimal superimposition of landmarks. Syst Zool:39. https://doi.org/10.2307/2992207

Rohlf FJ, Loy A, Corti M (1996) Morphometric analysis of Old World Talpidae (Mammalia, Insectivora) using partial-warp scores. Syst Biol 45:344–362

Ros J, Evin A, Bouby L, Ruas M (2014) Geometric morphometric analysis of grain shape and the identification of two-rowed barley (*Hordeum vulgare subsp. distichum* L.) in southern France. J Archaeol Sci 41:568–575

Selden R, Perttula TK, O'Brien M (2014) Advances in documentation, digital curation, virtual exhibition, and a test of 3D geometric morphometrics: a case study of the Vanderpool vessels from the ancestral Caddo territory. Adv Archaeol Pract 2:64–79

Selden R, Dockall J, Shafer H (2018) Lithic morphological organisation: Gahagan bifaces from the Southern Caddo Area. Digital Applications in Archaeology and Cultural Heritage 10:e00080

Serwatka K, Riede F (2016) 2D geometric morphometric analysis casts doubt on the validity of large tanged points as cultural markers in the European Final Palaeolithic. J Archaeol Sci Rep 9:150–159

Slice DE (2001) Landmark coordinates aligned by Procrustes analysis do not lie in Kendall's shape space. Systematic Biology 50:141–149

Slice DE (ed) (2005) Modern morphometrics in physical anthropology. Kluwer, New York

Slice DE (2007) Geometric morphometrics. Annu Rev Anthropol 36:261–281

Suárez R, Cardillo M (2019) Life history or stylistic variation? A geometric morphometric method for evaluation of Fishtail point variability. J Archaeol Sci Rep 27

Takahashi K (2013) Multiple capacitors for natural genetic variation in Drosophila melanogaster. Mol Ecol 22:1356–1365

Takahashi K, Rako L, Takano-Shimizu T, Hoffmann A, Lee S (2010) Effects of small Hsp genes on developmental stability and microenvironmental canalization. BMC Evol Biol 10:284

Thulman D (2012) Discriminating Paleoindian point types from Florida using landmark geometric morphometrics. J Archaeol Sci 39:1599–1607

Thulman D (2019) A typology of Florida fluted points using landmark-based geometric morphometrics. PaleoAmerica 5:181–190

von Cramon-Taubadel N, Frazier B, Lahr M (2007) The problem of assessing landmark error in geometric morphometrics: theory, methods, and modifications. Am J Phys Anthropol 134:24–35

Wallace M et al (2019) Searching for the origins of bere barley: a geometric morphometric approach to cereal landrace recognition in archaeology. J Archaeol Method Theory 26

Wang W, Lycett S, von Cramon-Taubadel N, Jin J, Bae C (2012) Comparison of handaxes from Bose Basin (China) and the western Acheulean indicates convergence of form, not cognitive differences. PLOS ONE 7:e35804

Zelditch ML, Swiderski DL, Sheets HD (2012) Geometric morphometrics for biologists: a primer. Academic Press, London