# A geometric morphometric relationship predicts stone flake shape and size variability

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## Abstract

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## Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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ORIGINAL PAPER

# A geometric morphometric relationship predicts stone flake shape and size variability

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Marcel Weiss[1] · Tamara Dogandžić[1] · Dawit Desta[1] · Shannon P. McPherron[1]

**Abstract** The archaeological record represents a window on-to the complex relationship between stone artefact variance and hominin behaviour. Differences in the shapes and sizes of stone flakes—the most abundant remains of past behaviours for much of human evolutionary history—may be underpinned by variation in a range of different environmental and behavioural factors. Controlled flake production experiments have drawn inferences between flake platform preparation behaviours, which have thus far been approximated by linear measurements, and different aspects of overall stone flake variability (Dibble and Rezek J Archaeol Sci 36:1945–1954, 2009; Lin et al. Am Antiq 724–745, 2013; Magnani et al. J Archaeol Sci 46:37–49, 2014; Rezek et al. J Archaeol Sci 38:1346–1359, 2011). However, when the results are applied to archaeological assemblages, there remains a substantial amount of unexplained variability. It is unclear whether this disparity between explanatory models and archaeological data is a result of measurement error on certain key variables, whether traditional analyses are somehow a general limiting factor, or whether there are additional flake shape and size drivers that remain unaccounted for. To try and circumvent these issues, here, we describe a shape analysis approach to assessing stone flake variability including a newly developed three-dimensional geometric morphometric method ('3DGM'). We use 3DGM to demonstrate that a relationship between platform and flake body governs flake shape and size variability. Contingently, we show that by using this 3DGM approach, we can use flake platform attributes to both (1) make fairly accurate stone flake size predictions and (2) make relatively detailed predictions of stone flake shape. Whether conscious or instinctive, an understanding of this geometric relationship would have been critical to past knappers effectively controlling the production of desired stone flakes. However, despite being able to holistically and accurately incorporate three-dimensional flake variance into our analyses, the behavioural drivers of this variance remain elusive.

**Keywords** Stone flake shape and size predictions · Three-dimensional geometric morphometrics

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## Introduction and background

Interpreting variation in stone flakes is becoming one of the key focusses in reconstructions of hominin behavioural evolution (Dibble and Rezek 2009; Lin et al. 2013; Magnani et al. 2014; Odell 2000; Rezek et al. 2011; Stout 2011). Despite the fact that unmodified flakes are by far the most abundant artefacts for much of human evolutionary history, exactly how prehistoric flint-knappers controlled stone flake size and shape continues to be a debated question in stone artefact archaeology. Much discussion has focussed on the relative importance of variables which were controlled by the stone artefact knapper, such as core-surface convexity, core scar configuration

prior to flake removal, angle of blow, hammer type and others, the influences of some of which are largely undetectable in the archaeological record today (Bar-Yosef and Kuhn 1999; Boëda 1986; Boëda 1995; Bordes 1961; Débénath and Dibble 1994; Inizan et al. 1995; Tixier et al. 1981). Other research has emphasized the importance of variables which were exclusively associated with platform manipulation, such as platform size and exterior platform angle (EPA), particularly with regard to control of the size and economization of knapped products (Braun et al. 2009; Braun et al. 2006; Dibble and Rezek 2009; Lin et al. 2013; Magnani et al. 2014; Rezek et al. 2011). The development of alternative approaches to evaluating how flake variability can be translated back into human decisions, and actions may help to evaluate some of the current explanations.

Explanations for flake size and shape variation also differ somewhat in associated experimental design. For instance, replicative experiments tend to focus on documenting the processes of stone reduction leading to the formation of specific artefacts. This design often includes tracing the actions associated with different stages in these processes such as, for example, preparing complex core exploitation surfaces. Such approaches have established the complexity of the network of variables which influence flake morphology and have been influential in lithic analysis since the inception of interests in sequences of stone tool production (Buffon and Compte 1778 and see references in Johnson et al. 1978). The application of replicative experimental approaches proliferated in the 1950s–1960s (Bordes 1947; Bordes 1950; Bordes and Crabtree 1969; Crabtree 1966; Crabtree 1967; Crabtree 1968; Crabtree 1970; Crabtree 1972), and they still constitute the predominant way of holistically reconstructing past hominin technological decision making (Ahler 1989; Amick 1989; Amick et al. 1988; Andrefsky 1986; Carr and Bradbury 2001; Eren et al. 2016; Shen and Wang 2000).

Replicative experiments yield substantial information regarding the overall mechanical processes associated with artefact forms recovered from the archaeological record. However, the often lengthy sequences of actions involved complicate matching specific actions with their associated effects on the final morphology of the lithic products. A further drawback is that interpretation within replicative experiments largely relies on the experience and observations of the knapper. However, knappers are often capable of producing stone artefacts while not being fully aware of the influence of different variables on the morphology of those artefacts (Dibble and Rezek 2009). In other words, knappers are unlikely to be fully conscious of the *relative* effects and interactions of variables influencing the flakes produced.

In contrast to replicative experiments, controlled experiments use purpose built machines to create flakes, with the advantage being that individual variables can be controlled and systematically varied to measure their effect on flake size and shape (Cotterell and Kamminga 1987; Dibble 1997; Faulkner 1972; Speth 1972; Speth 1974; Speth 1975). Recently, Dibble and colleagues have used uniform glass cores and a pneumatic hammer to show that many of the important aspects of artefact shape and size can be controlled simply by modifying linear and categorical attributes of flake platforms (Dibble and Rezek 2009; Lin et al. 2013; Magnani et al. 2014; Rezek et al. 2011). This ongoing work largely established the hierarchical importance of platform dimensions and exterior platform angle in driving size variation, relative to the lesser effects of some other variables. However, when these controlled experimental results are applied to actual archaeological assemblages, there remains a significant amount of unexplained variability, particularly when assemblages are considered on a flake by flake basis (Dogandžić et al. 2015; Muller and Clarkson 2014; Muller and Clarkson 2016). While it is possible that this unexplained variability in the archaeological record is a result of measurement error on certain key variables (i.e. true exterior platform angle can often be difficult to measure due to irregular flake dorsal morphology), the fact is that attributes such as platform depth, platform width, and exterior platform angle are likely only very basic 'stick-figure caricatures' of what drives artefact variation (Shott and Trail 2010). For this reason, their power in predicting shape and size on a flake-by-flake basis is unavoidably limited.

A number of studies have shown that the explanatory power of platform variables for predicting flake size variation can be considerably improved by using two as well as three-dimensional measurements (Braun et al. 2008; Clarkson and Hiscock 2011). For instance, using a digital imaging technique to capture platform area, Braun et al. (2008) demonstrated that these digital measures have the potential to explain much more flake size variation than calliper-based measurements. This improvement in explanatory strength may be partly attributed to a lower measurement error associated with these approaches (Braun et al. 2008; Morales et al. 2015; Muller and Clarkson 2014). However, this improvement may also be associated with the ability of digital methods to more holistically capture aspects of platform variability which are important for explaining flake variation, but which are difficult to capture with standard linear measurements. For example, using three-dimensional measurements of platform area acquired via laser scanning, Clarkson and Hiscock (Clarkson and Hiscock 2011) showed that the regressed relationship between platform area and flake size differ in both intercept and slope among platform morphologies (for example, the differing relationships represented by dihedral and focalized morphologies). This finding in itself indicates that certain facets of platform morphology remain unaccounted for within traditional flake measurement systems. These facets need to be captured and incorporated in our analyses if we are to improve the predictive power of platform attributes on stone artefact variation.

The aim of this paper is to build on previous experimental research and to develop proxies of variation in flake shape and size by exploring the predictive power of flake platform regions visible on cores prior to flake initiation. Instead of more traditional linear measurement systems, here, we use the shape analysis tools of three-dimensional geometric morphometrics (3DGM). We use configurations of landmarks on flake platforms to make overall flake shape and size predictions. The goal here is to make flake shape and size predictions based on morphological parameters that the knapper could conceivably control, whether they were conscious of these parameters or not. In this vein, the configuration of platform landmarks we use to predict flake shape and size are all present on the core prior to flake removal.

We show that both size and overall flake shape can be estimated reasonably well relying solely on the predictive power of flake platform regions. The large number of potential influences left to vary randomly in this experiment look to have had only a limited effect on flake formation, indicating that the manipulation of the zone of the core upon which our landmarks fall is critical in determining the flake which is ultimately produced. Flake platform morphology is clearly not the *only* variable that drives flake size and shape variability, but the fact that we are able to achieve good flake shape and size estimations by relying on platform morphology alone suggests that, in terms of the hierarchy of influences on flake formation, platform manipulation is a key factor. This is a step forward in understanding how knappers varied flaking processes in order to vary flake products. It shows that manipulating the relationship between platform and flake shape—either consciously or instinctively—would have allowed prehistoric knappers good control over the shape and size of the flakes they produced.

There are clearly still substantial limitations as to how far the results discussed below can be interpreted. More fully understanding covariation within flake morphologies will entail expanding our samples to more closely resemble the full spectrum of variation in the archaeological record. As the efficiency and availability of new scanning and landmarking techniques continues to rapidly increase in the future, this comprises a challenging forthcoming objective of this work.

## Materials and methods

### Experimental flake production

A single sequence of complete flakes was knapped freehand from a large nodule of high-quality flint (~3000 g) from the Dordogne region of southwest France ('Santonian flint' after (Turq et al. 2008)). A single person (WA) struck 60 flakes from the nodule, and the place of each flake within the removal sequence was recorded. An effort was made to control for

the potential effects of independent variables such as hammer material, applied force and angle of blow by randomizing them in the flake production. For this reason, three hammer types were used: a hard stone hammer made on quartz porphyry, a hammer shaped from antler and another made in copper. The knapper shifted loosely between hierarchical and non-hierarchical core exploitation patterns and allowed core surface morphology to vary between flake removals.

The decision to minimize the effects of external drivers of flake variation by randomizing them may limit the interpretive breadth of this study to some extent. This randomization enabled us to generate a predictive model with wide applicability—which is the central aim of this study—but it also limited our ability to deconstruct the patterns of covariation relative to different flake production strategies.

### Flake data capture

All flakes were scanned with a NextEngine surface scanner using NextEngine High Definition (HD 2011) data capture software. Flakes were manually landmarked in Landmark V3 (2005) with 3 fixed platform landmarks, 4 curves (flake edges and platform outline) and 3 surface patches. All of these are geometrically correspondent across all specimens (Fig. 1).

Curves were initially landmarked with a sufficient number of coordinates to approximate the morphological characteristics of individual flake edges but were then resampled and equidistantly spaced in three-dimensions using functions in the 'geomorph' R package (Adams and Otárola-Castillo 2013). The positions of flake edge landmarks were further adjusted in order to minimize bending energy[1] using functions in the 'Morpho' package (Schlager 2017). Finally, the dorsal, ventral and platform surfaces were landmarked on a single, arbitrarily chosen template specimen.[2] This template configuration of surface landmarks was then deformed onto each of the other specimen meshes in the collection to obtain geometrically correspondent coordinates across the surfaces of all specimens (Fig. 2).

The process resulted in a configuration of 470 geometrically correspondent coordinates, an arbitrary number which nevertheless ensured a close approximation of the size and shape of each of the flakes. Centroid size was calculated from the three-dimensional landmark configurations on the 'body regions' of each flake (see partitioning discussion below) and along with flake mass were thereafter used as proxies for size in the analyses. All configurations were then subjected to Procrustes superimposition, which generally standardizes

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[1] Broadly, the minimum energy required to vertically displace the landmarks from a straight/flat vector onto the curve in question.
[2] Note that the choice of template specimens has no effect on the analyses we perform (Mitteroecker and Gunz 2009).

**Placement of three fixed landmarks [1:3], four curves [(a):(d)] and three surface patches [(i):(iii)]**
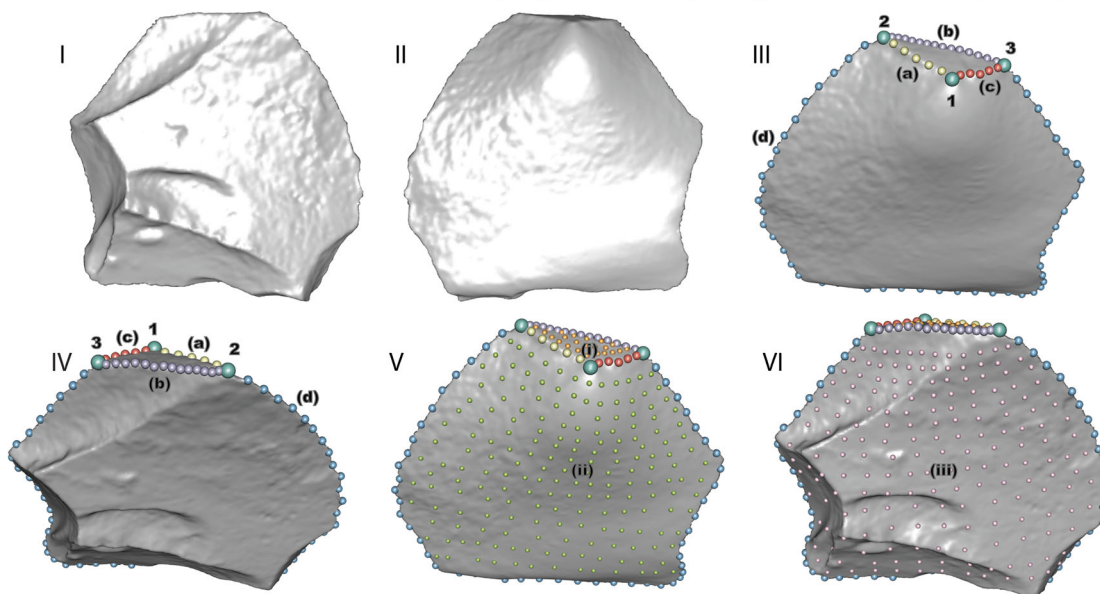


**Fig. 1** Atlas of geometrically correspondent fixed landmarks, curves and surfaces on the template specimen

scale, orientation and location amongst specimens (Rohlf and Slice 1990).

## Analyses

### Landmark partitions: flake platform and flake body

The landmarks were separated into two subsets or 'partitions'. One partition is comprised by the platform surface coordinates and 3 additional lateral landmarks on the very proximal extreme of each of the flake edges (Fig. 3). These 6 edge landmarks are used as an approximation of the connection of the platform to the rest of the flake, and the choice of 3 landmarks

per edge was an arbitrary figure. We refer to this coordinate subset, including the parts of the specimen meshes associated with it, as the 'platform'.

The remaining landmarks, including the entire dorsal and ventral flake surfaces, comprise the other partition and hereafter are referred to as the flake 'body'. Our hypothesis is that there are patterns of shape and size covariance between these two partitions which result from the effect of flake platform attributes on flake size and shape.

Importantly, in discussion of 'predicted flake shape' variation that follows, we are referring exclusively to the flake body partition as predicted by the platform, in other words, the flake with the platform missing.
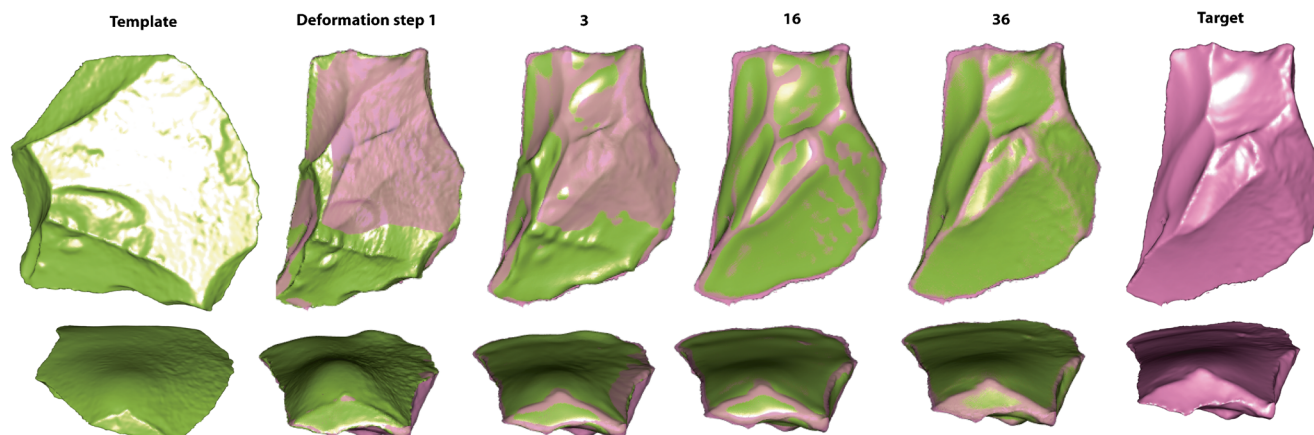


**Fig. 2** Illustration of the deformation process used to warp the surface landmarks from the template specimen onto each of the target specimens in the collection. The *green* and the *purple surfaces* represent the two

different specimens (the template and the target, i.e. the former being warped onto the latter)

**Two-Block landmark partition [(a),(b)]**



**Fig. 3** Two partitions of landmarks used to develop predictive models shown on three different flakes. The *orange points* comprise the platform-associated landmarks, which are used to predict the blue configuration (the flake body-associated landmarks)
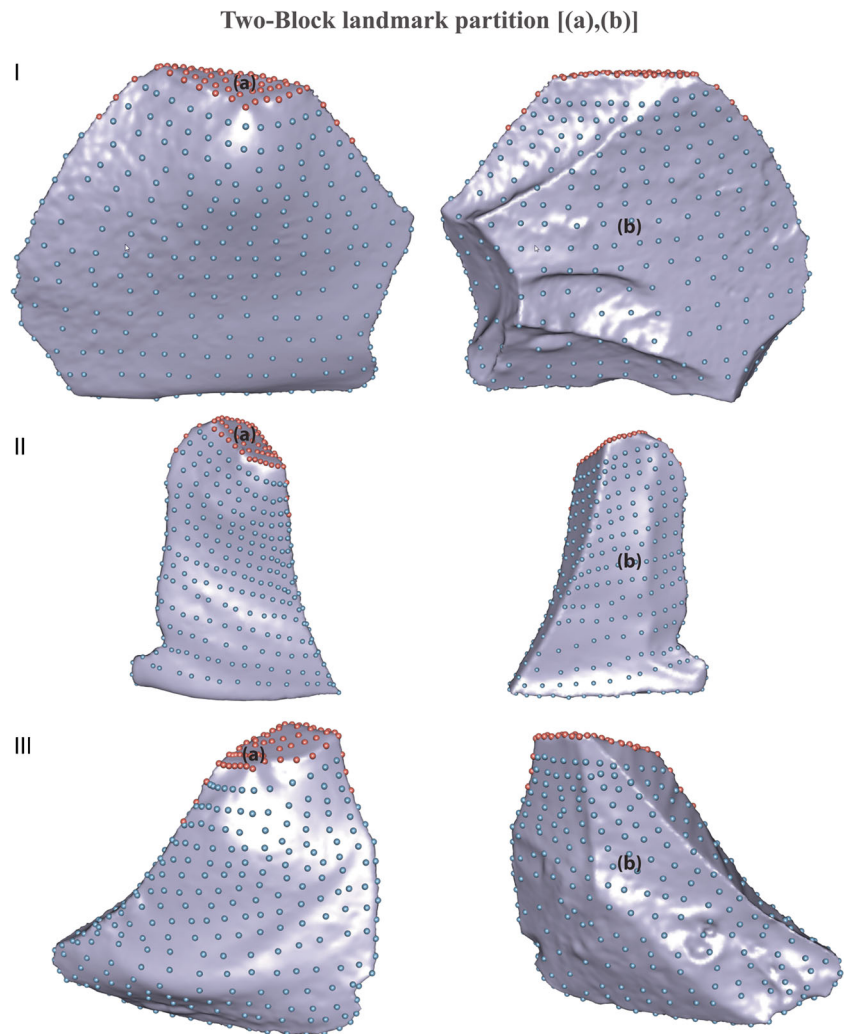
*Individual specimen predictions*

**Two-block partial least-squares method** Two-block partial least-squares (2B–PLS) assesses the covariance between two sets of variables. 2B–PLS differs from multiple regression in that the two sets of variables are treated symmetrically, as opposed to independent variable(s) being used to predict variation in a response (Rohlf and Corti 2000; Sampson et al. 1989). 2B–PLS identifies linear combinations of variables within each of the partitions which maximize the covariance between the partitions. In our analysis, 2B–PLS was used to investigate the covariation in shape between flake platforms and flake bodies. The two sets of variables used here comprise landmark configurations (platform partition and body partition as described above under Landmark partitions: flake platform and flake body).

Shape predictions were also made for individual flakes using the first 7 latent variables of covariation, which here accounted for 94–95% of the covariation between the two partitions. Shape predictions were cross-validated. This means

that a separate 2B–PLS model was developed for each flake ($n = 60$) excluding that particular specimen for which predictions were being sought. In this way, individual specimens could not influence the training sample used to develop the model for flake prediction.

In order to explore and visualize the central patterns of covariation in the dataset, we first plotted the scores of individual flake platforms and bodies against one another on the first dimension of the 2B–PLS, which accounts for 81% of the covariance in the experimental collection. Our objective here was to illustrate how well the aspects of shape represented by this first dimension approximate one another. In addition, since 2B–PLS has no direct test for significance of the approximated covariance between the partitions, we fitted a linear model using the scores of the individual flake bodies as the response and those of the platforms as the predictor. We further calculated the shape extremes for this first dimension of covariation. These shape extremes represent the three-dimensional aspects of the platform and the flake body which account for the most variation with one another. We provide

visualizations of these with two sets of 3D figures (3D Figs. 1, 2 and 3: 3D figure captions are provided in the SOM), which have the associated landmarks on either extreme linked with displacement vectors; in other words, the length and orientation of these vectors represent how much and in what direction the linked landmarks vary across the first dimension of the 2B–PLS.

One issue we foresee with using the 2B–PLS for predicting flake shape is that, due to the fact that landmark configurations are aligned to a single centroid, the distances of *all* landmarks from this centroid vary systematically. This could inflate the accuracy of shape predictions in that the distance of the landmarks from the centroid would be nested in the landmark variation and contingently would be incorporated into flake shape predictions. Any increases in predictive power associated with these distances would be solely associated with the initial alignment of landmarks, rather than any actual covariation in flake morphologies. This potential problem would not influence the nature of the patterns of covariation in the dataset but would artificially inflate the predictive power of the 2B–PLS.

To address this potential issue, two separate 2B–PLS models were fitted to the landmark configurations, which were associated with two different approaches to aligning the landmarks. Firstly, the flake landmark configurations were aligned together (the shape extremes plotted on 3D Fig. 1). Secondly, in an attempt to achieve complete independence of the platform and flake body configurations for shape predictions, separate alignments (to separate centroids) were undertaken on the platforms and flake bodies so that the distance of individual landmarks from the respective centroid could not increase the accuracy of predictions (3D Figs. 2 and 3).

**Shape predictions** Principal components analysis (PCA) was conducted on scaled, translated and rotated landmarks. PCA was conducted on both (a) the actual configurations of body partition landmarks and (b) the configurations of body partition landmarks predicted by the 2B–PLS models. The purpose here was to compare the *actual* covariance matrix of flake body shapes with the covariance matrix of flake body shapes predicted only by flake platform attributes.

To do this, we used simple regression to look at actual flake body shape as a function of flake body shape predicted by flake platforms, for the first three principal components (comprising >72% of the sample variance). MANOVA, conducted with the MANOVA function from the R 'car' package (Fox and Weisberg 2010), was used to further assess the significance of the relationship between the first three principal components of actual and predicted flake body shape.

**Size predictions** Flake centroid size can be considered here as being closely related to 'volume', given the substantial landmark coverage of the flakes. Both flake centroid size and flake

mass predictions were estimated with multiple regression, as detailed below. Importantly, in the alignment of flakes used for size prediction, platform configurations were rotated and translated but not scaled. In this way, important dimensions of overall platform size known to influence aspects of flake body size, such as platform depth, could be retained in the flake body predictions.

Due to the large number of platform landmarks, platform coordinates were decomposed into their principal components. Then the first ten principal components—accounting for 98% of variation in flake platforms—were used to predict flake mass and centroid size. Because mass is a cubic dimension whereas principal component scores are linear, the individual predictors were cubed in the mass prediction model.

### Assemblage level predictions

In addition to a flake-by-flake based assessment, we are interested in how the overall structure of variation differs between actual and predicted flake body shapes at an assemblage level. To visualize these broad differences, we first conducted a cluster analysis on the distances between actual flake body specimens in PC 1 and 2 space. For this, we used the 'pam' cluster analysis function in the cluster package (Maechler et al. 2016).

In order to look for the most appropriate number of clusters (or partition) for this dataset, we iteratively used the cluster analysis function and investigated 1 through 10 different numbers of clusters. We evaluated the appropriateness of each partition by looking at the average dissimilarity of individual cases with the medoids[3] of the groups to which individual cases were allocated in each of the different clustering partitions. The expectation was that the specific number of clusters above which an additional cluster ceased to reduce overall dissimilarity would be the most appropriate partition. However, this exercise demonstrated that dissimilarity decreased across *all* ten partitions. This suggests that there is probably no meaningful clustering in this dataset (Fig. 4).

Therefore, for visualization purposes, we divided the dataset into four arbitrary clusters (or groups of like flakes) based on the similarity and difference between specimens in PCA space. The intention here was to use the clustering factor as a proxy for how the overall structure of the data changed between actual and predicted PCA space. This factor was plotted onto the PCA of actual flake body shapes. This four-level factor, devised on the actual flake body covariation matrix, was then plotted onto PC 1 and 2 of predicted flake shapes.

In other words, the *predicted* flake shapes comprise only what platforms estimate overall flake shape to be. The

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[3] The most representative case of an individual group or cluster (similar to the mean/median, but an actual case rather than a central tendency).

**Fig. 4** Plot showing the decrease in the dissimilarity of individual cases with the medoids of clusters, as one increases the number of clusters in the analysis
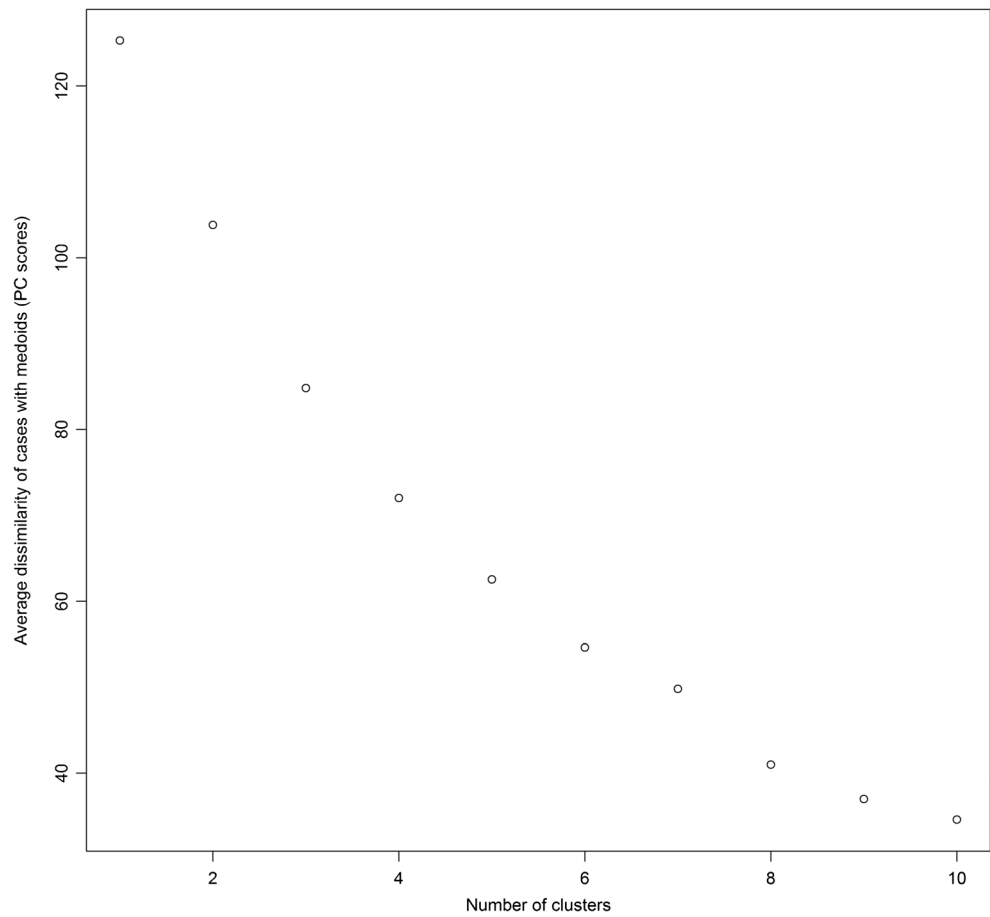


clustering factor provides us with a broader approximation of how well individual flake shapes are predicted by their platforms. In addition, we calculated ellipses for the ranges of points within each cluster of actual flake shapes. We then plotted these ellipses on actual and platform-predicted shape to visualize how the overall structure of each group varied between actual and predicted shapes. To clarify, the clusters were calculated on actual flake shape and these same clusters were then plotted onto the platform-predicted flake shape. With this, we examined how the structure of the four clusters changed between actual and predicted shape distributions, and in particular, whether clusters now overlapped substantially as a consequence of being the results of a prediction.

## Results and preliminary discussion

### Shape predictions

*Flake platform variation*

The partial least square scores of the platform partition were used to predict flake body shape, whereas the principal components of platform variance are considered here for visualization purposes only. 3D Figs. 4, 5, 6 and 7 plot the range of platform shapes in the dataset (PCs 1–4). Readers are referred to these supplementary PLY files to view the nature of these patterns. In addition, a mesh is provided with plots of actual versus reconstructed flake shape for a particular specimen (it is possible to produce such a mesh for any platform fragment of a flake).

*Flake body variation*

The first three principal components of flake body variation account for 72.2% variance in actual flake body shape and 81.1% of flake body shape variance predicted by the 2B–PLS model (Table 1).

Individual regressions of flake body shape predicted by platforms on actual flake body shape for the first three principal components suggest that actual and predicted axes of shape variation are highly correlated (Fig. 5 and Table 2). Further, MANOVA was conducted on PCs 1–3 of actual shape, using predicted PCs 1–3 as predictors. The results of the MANOVA suggest that the first three components of predicted shape are highly significant predictors of actual shape (Pillai = 2.098, approx. F = 42.639, $p < 0.001$).
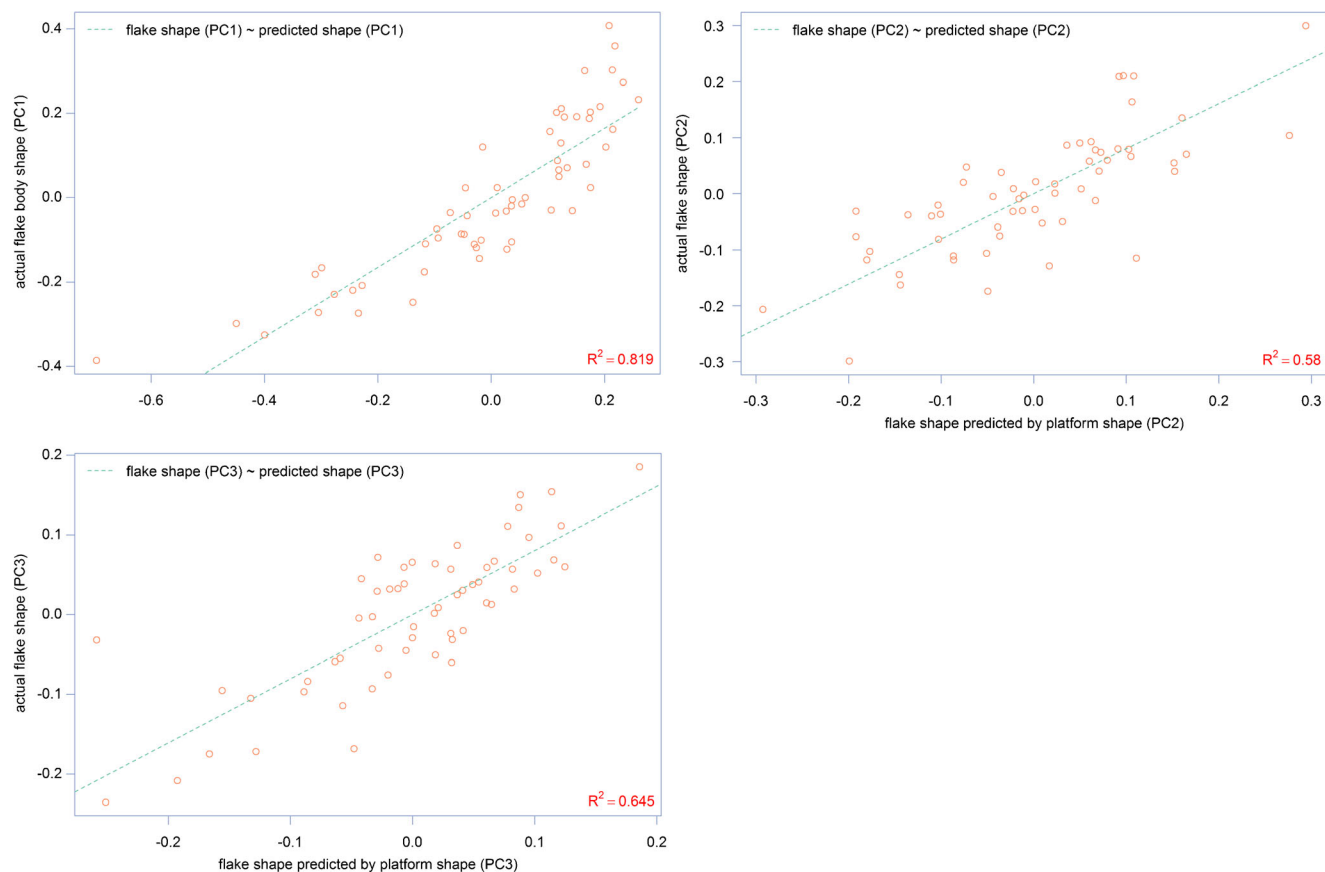
**Fig. 5** Regressions of actual principal components of shape on predicted principal components of shape (PCs 1–3)

## Patterns of platform to body covariation

Plots of the scores of the flakes on the first dimension of the 2B–PLS (accounting for 81% of covariance) suggest that platforms predict flake shape extremely well (Fig. 6). A linear
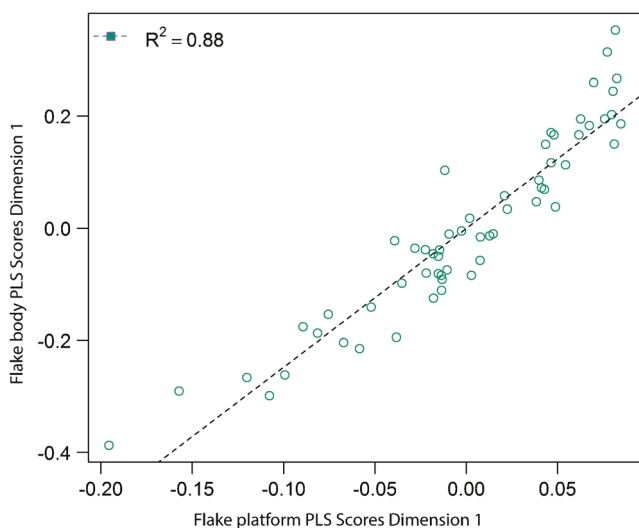


**Fig. 6** Flake body shape on dimension one of the 2B–PLS (81% of all covariation) as a function of flake platform shape on dimension one

model using these scores is significant ($p < 0.001$) and indicates that platforms predict flake bodies quite accurately ($R^2 = 0.88$). This regression is also plotted in Fig. 6.

The shape extremes for the first dimension of covariation for configurations aligned together are plotted in 3D Fig. 1. The shape extremes for separate alignments are plotted in 3D Figs. 2 and 3. Although the capture of this relationship for individual flakes is simple (Fig. 6), the 3D figures show a highly complex pattern of morphological covariance between flake platforms and bodies. Clearly, this relationship is not readily interpretable in terms of independent linear approximations of shape and size. There are clearly complex interactions between platform attributes in terms of how they influence flake variance.

Platform variation driven by platform features which are present on cores prior to the removal of a given flake are the chief drivers of flake variation. Capturing variation in these features is demonstrably important in making flake shape and size predictions. However, the nature of the 3D dimensional shape change along this dimension is complex and, for now at least, is not readily interpretable or explainable in terms of traditional angle and linear platform measurements.

For demonstration purposes, we provide shape reconstructions based on flake platform landmarks for four flakes from the analysed collection. This figure is provided in the
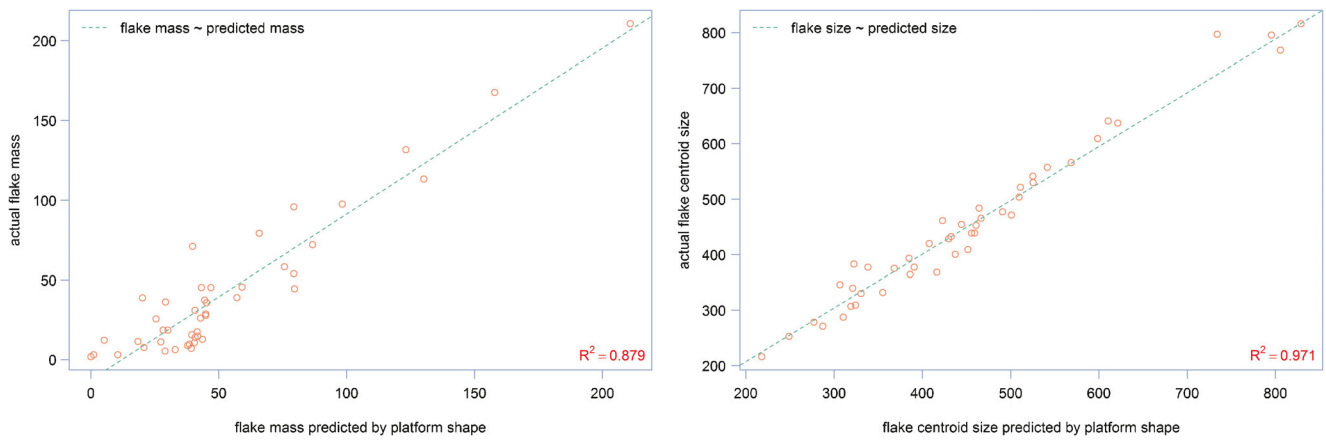
**Fig. 7** Regressions of predicted mass on actual mass and predicted centroid size on actual centroid size

Supplementary Online Information (SOM.Fig.1). This figure provides a qualitative illustration of the error between actual flake shape and flake shape predicted by platform parameters (for these randomly selected flakes).

### Mass and centroid size predictions

The two multiple regression models investigating the relationship between the first ten components of platform variation and overall flake size indicate that both flake mass and centroid size can be reasonably well predicted by platform variation. Regressions of predicted flake mass on actual flake mass and predicted centroid size on actual centroid size both have relatively high $R^2$ values (mass model $R^2 = 0.88$, centroid size $R^2 = 0.97$), attesting to the predictive power of platform variation for predicting flake size in this collection (Fig. 7). In fact, the $R^2$'s achieved in this study are higher than the best previous attempt at predicting mass from platform dimensions across heterogeneous datasets ($R^2 = 0.764$; Muller and Clarkson 2014).

### Assemblage level predictions

The positions of individual flake specimens clearly shifted between actual and predicted PCA plots. However, with regard to flakes shifting across cluster boundaries, the composition of the four clusters did not change substantially (Fig. 8). These plots suggest that although flake shapes which are predicted by platforms deviate from actual shapes on a flake-by-flake basis,

**Table 1** Proportion of variance accounted for by the first three principal components of actual and predicted flake body shape

|  | Actual body shape variance | Predicted body shape variance |
|---|---|---|
| PC1 | 45.19% | 51.37% |
| PC2 | 16.15% | 18.69% |
| PC3 | 10.91% | 11.07% |

the predictions still preserve the overall assemblage level structure of variance of the actual flakes on PCs 1 and 2.

### Discussion and conclusion

The interpretation of variation in stone flakes remains critical to a better understanding of hominin adaptive variability. This variation is likely underpinned by a complex set of interactions among factors such as hominin technological intentions and functional needs, fine-motor skills, cognitive abilities and even technological traditions. But, this variability is also constrained by raw material properties and nodule size, the influences of which are generally difficult to differentiate. At the source of this difficulty is also ambiguity regarding the set of variables which affect stone flake formation at the most fundamental level, their hierarchical effect on flake form and exactly how hominins managed these properties of flake formation in the past.

Much of this disagreement has developed as a consequence of the conceptual and methodological divide between replicative and controlled experiments. As noted above, most of the replicative work has focussed on the impact of core-surface characteristics on flake form, whereas more rigidly controlled approaches have stressed the importance of linear platform variables in flake formation (Bar-Yosef and Kuhn 1999; Boëda 1986; Boëda 1995; Bordes 1961; Debénath and Dibble 1994; Dibble and Rezek 2009; Inizan et al. 1995; Magnani et al. 2014; Rezek et al. 2011; Tixier et al. 1981). Here, we attempted to incorporate methodological tenets of both these sets of approaches but tried to circumvent some of their possible drawbacks by focussing on three-dimensional flake shape variation.

To infer the drivers of variation in stone flake shape and size, we first need to develop proxies for variance while at the same time assess experimentally the effects of independent variables on these indicators. Stone flake platforms constitute zones of the flake which existed on the core surface prior to

**Table 2** Estimates and associated standard errors, t and p values for the models investigating the effect of predicted flake body shape on actual flake body shape

| | Estimate | Std. error | t-value | p value |
|---|---|---|---|---|
| Predicted PC1 (PC1 actual~PC1 predicted) | 0.824 | 0.061 | 13.62 | <0.001 |
| Predicted PC2 (PC2 actual~PC2 predicted) | 0.716 | 0.0795 | 9 | <0.001 |
| Predicted PC3 (PC3 actual~PC3 predicted) | 0.805 | 0.078 | 10.32 | <0.001 |

flake removal. Understanding variation in the relationship of platforms with overall flake shapes therefore provides insight into the key features of the core which likely influenced flake formation, and was at the same time under the control of the knapper. The platform configurations of landmarks used to make flake shape and size predictions in this study were all present on the core surface prior to the removal of the flakes, and our goal was to make these predictions based on a minimum of core surface variables that the knapper could conceivably control. These landmarks therefore constitute proxies for how the zone of the core which they represent influenced the formation of the resultant flakes.

Our findings suggest that three-dimensional platform characteristics are a chief determinant of overall flake shape and size variation. Even without factoring in well-known drivers of variation such as core surface convexity and scar-ridge configuration, we are able to make reasonable size predictions of the flakes in our collection, though we recognize that the range of flake variability represented in our experimental data is limited with respect to archaeological assemblages. Configurations of flake platform coordinates appear to be reasonable predictors of overall flake mass and good predictors of flake centroid size.

The more substantial contribution of this study is the demonstrated ability to predict flake shape. Here, we demonstrated the importance of the relationship between flake platforms and flake shape, and we described a statistical approach which is demonstrably useful in predicting these properties. We developed a generalizable model, the predictive power of which could in potential be applied to any flake which retains a platform. While a number of previous studies have demonstrated the ability of platform attributes to estimate flake size (Braun et al. 2009; Braun et al. 2006; Clarkson and Hiscock 2011; Dibble and Rezek 2009; Lin et al. 2013; Magnani et al. 2014; Rezek et al. 2011), the prediction of flake shape using platform landmark configurations represents a new departure. We were able to predict the three major components of flake shape variation—accounting for >72% shape variance in the sample—reasonably well.

Further, we were interested in how the relative positions of flakes in shape space deviated between actual and platform-predicted flake shapes. One possible way to approach this
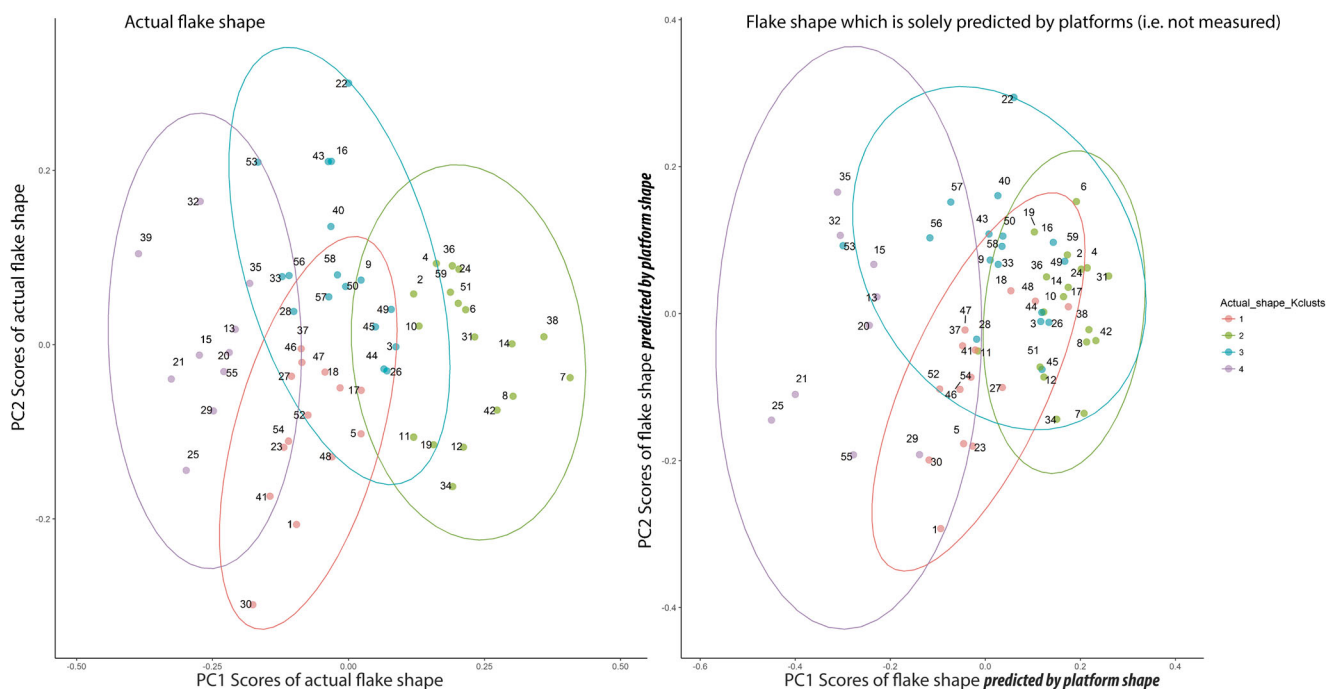


**Fig. 8** Principal components 1 and 2 of actual and predicted flake shape. Importantly, the clustering variable on the plot on the right (i.e. the colours of the points) was devised based on the actual PCA (the plot on the left) and is plotted here to demonstrate the rather minimal deviation in the structure of individual groups between plots

would have been to look at the relative positions of individual flakes on the PCA, between actual and predicted plots. However, we opted for a visually more interpretable outcome. Using cluster analysis, we arbitrarily divided the flakes in PCA space into four groups based on relative similarities and differences in their shapes. We then plotted these groups onto the predicted flake shape PCA to look at how the positions of flakes shifted within the assemblage. Interestingly, although the positions of individual flakes of course shifted between actual and predicted shape space, the relative structure of the four groups of similarly shaped flakes did not change substantially.

The capability of knappers to manipulate platforms effectively is clearly important in the management of core surfaces and the contingent control over the morphology of knapped products. Although preliminary, these findings stimulate further questions about the necessity of invoking technological strategies involving complex core surface preparation or complex force application when interpreting variability in the lithic record. As long as knappers were able to carefully manipulate platform-related parameters, a wide diversity in sizes and shapes of flakes was attainable through the application of relatively simple stone-flaking strategies.

Our study also revealed the extreme complexity of the relationship between platform and flake shape when this relationship is visualized in three-dimensional detail. This level of detail was important in our ability to make predictions for flake shape and size using platforms only, which suggests this approach has future utility in a multitude of archaeological contexts.

These archaeological contexts may include retouched assemblages in which predictions of original unretouched artefact shape and size may be sought (Hiscock and Tabrett, 2010) and, importantly, how complex patterns of allometric change map out in retouched tools produced by different cultural groups in the past. The application of this approach to archaeological collections will enable us to determine which blanks were manufactured and selected for tool production. In addition, it could provide insight into how these maintenance processes were carried out by individuals within different techno-traditional settings and in different ecological frameworks in the past.

More broadly, artefact size and form—and the characterization of changes in size and form—constitute the foundation upon which descriptive and analytical frameworks in lithic studies are based (Shott and Trail 2010). Landmarks on artefacts enhance our ability to characterize differences in shape at higher resolution while 3DGM enables us to retain the geometric relationships between these landmarks in our lithic analyses. Contingently, this detailed documentation of flake shape may enable distinguishing between the behavioural drivers of this variation in finer detail than ever before.

However, the complexity of the relationship between platform and shape documented here also constitutes an interpretive challenge. This complexity makes it difficult to infer the actual behavioural drivers of these patterns by simple visualization of covariation. In other words, we can accurately capture the nature of flake covariation in ways that were not previously possible, but extracting and articulating the behavioural drivers of these patterns remains difficult. Importantly, we can factor this complexity into our predictive models; however, it is not yet clear exactly how human decisions drive different aspects of this complexity. This limitation may be a function of our broader tendency to explain patterns of flake variation through the use of traditional linear or categorical explanatory variables, which are more practical and understandable than 3D landmarks but may be more limited in their capacity to capture important aspects of flake variance.

Linear platform variables also interact in complicated ways in the process of flake production (Magnani et al. 2014; Pop et al., 2017). It is possible that these complex sets of interactions are difficult to reconstruct within our experiments in ways which will enable us to make accurate predictions with the same confidence as we can do with 3DGM. Another possibility is that archaeological flake variance simply does not represent a set of linear responses to the variables which have traditionally been measured. Approximating flake shape and size with landmark configurations is one way of circumventing these potential issues. Admittedly, 3DGM comes with its own set of interpretive complications, some of which are mentioned above. However, here, we were able to incorporate platform variation into the analysis as a single variable, without needing to define how different aspects of platforms are expected to interact with regard to the determination of a particular flake shape.

A related possibility is that this holistic treatment of platform variation more realistically resembles how experienced knappers view and manage their platforms. In theory, platform variance represents a network of linear measures which could be managed by knappers on a variable-by-variable basis. However, it is more likely that knappers managed their platforms instinctively, rather than always being wholly cognisant of how tweaking one linear aspect influenced the effect of another on the flake they intended to produce.

While the approach described here has substantially increased the predictive power of experimental models of flake shape and size variation, and has demonstrated the utility of 3DGM for reconstructing flake variance from platform measurements, there are clearly limitations to how far we can interpret these results. To more clearly understand the covariance between platforms and flake bodies, we need to increase our experimental dataset to one that captures more of the spectrum of shape and size variation that is present in the archaeological record. Follow-up studies will add a wider range of core reduction processes, produced via a wider range

of techniques and on a wider range of raw materials than the collection analysed here. Other drawbacks in applying these results to the archaeological record include the feasibility of scanning and land-marking large archaeological collections at this point in time. However, the efficiency of scanning technologies and the availability of digital methodologies for land-marking stone artefacts have both increased at an exponential rate within just the last 5 to 6 years (Bretzke and Conard 2012; Grosman 2016; Morales et al. 2015). Applying these newly available digital tools to wider ranges of experimental as well as archaeological flake collections and in pursuit of tackling more complex questions about the technological behaviour of past hominins comprise exciting new avenues of this research.

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