Journal of Archaeological Science 41 (2014) 297–307

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Identifying design and reduction effects on lithic projectile point shapes

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ARTICLE INFO

Article history:
Received 29 May 2013
Received in revised form
16 August 2013
Accepted 18 August 2013

Keywords:
Lithic projectile points
Shape variation
Geometric morphometrics
Factor model

ABSTRACT

Since lithic tools are intended to accomplish certain functions as a response to environmental demands, their original design changes considerably during use. Thus, exploring variability on the original designs can be informative of cultural adaptive processes on past populations. However, the complex life-cycle of a stone tool includes loops of damage due to use followed by breakage and resharpening that dramatically blur the size and shape attributes defining the original design. Here we use the Factor Model, a statistical approach recently modified to be used in landmark data, to evaluate original design attributes versus changes attributed to maintenance activities on a sample of Southern Patagonia lithic stemmed points, including arrows and spears. The model enables the separation of shape aspects that tend to covary because of common factors affecting simultaneously the two fundamental modules of a classical stemmed weapon (blade/stem), from those shape features explained only by local factors affecting modules independently. Our results show that original design differences explain most of the total shape variation, and also indicate that maintenance patterns differ among point types considered as different weapon systems (arrows and spears). Whereas arrow reduction is focused on tip modifications, spears present a broader array of shape changes including the tip and the shoulders. These results demonstrate that disentangling the sophisticated interaction among original design and maintenance activities of lithic projectile points enables a proper and independent exploration of adaptation to functional demands and cognitive models of past populations.

1. Introduction

Even though stone tools can be seen as simple artefacts, lithic technology was a complex system of central importance to cultural adaptation during long periods of human evolution. Technological behaviours are subject to selective pressure and evolutionary change, and therefore stone tools were essential to humans to cope with changing conditions around them during long time spans (Dunnell, 1978; Torrence, 1989; Bousman, 1993; Bleed, 1997).

As similar to other cultural traits, lithic points can be seen as the actual end products of behaviours that are inherently human (technology), but also they are shaped by the sum of the processes that produce these outcomes, that is, the cognitive underpinnings (Foley and Lahr, 2003). The design of projectile points, including size and shape attributes, raw materials used, etc. is a very informative trait because it reflects the demands of the environment and the responses of populations to those demands within the constraints of raw-material availability, mobility patterns and hunting strategies, among others (Foley and Lahr, 2003). In this context, the roles that different factors play in stone tool design have been largely discussed by archaeologists. In addition, how to assess their relative importance as determinants of the final point's morphology is a complex task (Dunnell, 1978; Torrence, 1983; Kuhn, 1994; Bleed, 1986; Shott, 1986; Nelson, 1991; Ahler and Geib, 2000). It is widely accepted that a design must be effective, meaning that it should execute the job it is designed for regardless of the "simplicity" or "complexity" of the technological tasks involved (Bleed, 1986; Nelson, 1991). Thus, reaching the best compromise between costs and benefits maximizes the system utility, but this achievement heavily depends on each particular environmental constraint (predictability of game resources, lithic raw materials and wood availability, time stress, etc.).

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http://dx.doi.org/10.1016/j.jas.2013.08.013

In this sense, a lithic point's original complexity and design are informative about both behaviour and cognitive models of human populations in particular geographical and chronological contexts. However, the archaeological record rarely provides "original" designs, mainly because projectile points experience a life-cycle involving several maintenance activities such as resharpening and reworking that largely affects their original form (Andrefsky, 2006; Bradbury and Carr, 2003; Buchanan, 2006; Castiñeira et al., 2011; Flenniken and Raymond, 1986; Shott, 2005; Shott et al., 2007; Shott and Ballenger, 2007, among others). Consequently, the resulting shapes recovered at archaeological sites present a palimpsest of morphological traits that result from a superimposed combination of shape-generating processes departing from the original design and going throughout several cycles of use, damage and resharpening events that add on shape variation until the tool achieves its final form at discard. In a recent paper we have suggested that shape covariance patterns, rather than shape itself, can be informative of such life-cycle changes (González-José and Charlin, 2012). Following the above reasoning, maintenance activities can be seen, in addition to the original design, as part of the cognitive model involved during the life-cycle of a stone projectile point. Thus, the dissection of the shape aspects parsing the original design from those indicating maintenance activities is of key importance to appraise the validity of stone tools as a window to understand past technological adaptation and cognitive views.

Previous research has attempted to identify reduction effects throughout several methods. For instance, experimentation with replicated projectile points simulating different weapon systems has assessed dimension changes due to use, breakage and rejuvenation (Flenniken and Raymond, 1986; Odell and Cowan, 1986; Towner and Warburton, 1990; Shea et al., 2001; Andrefsky Jr., 2006; Shott and Ballenger, 2007; Hunzicker, 2008). Several allometric studies have measured morphometric variations on archaeological points and have proposed different reduction or resharpening models and indexes to measure it (Ahler and Geib, 2000; Ballenger, 2001; Clarkson, 2002; Bradbury and Carr, 2003; Buchanan, 2006; Shott et al., 2007). Geometric morphometrics analyses have also been applied in order to control the effect of potential noisy factors as size, resharpening, differences in lithic raw materials and hafting, geographical origin or distance among samples, among others (Buchanan and Collard, 2010; Castiñeira et al., 2011, 2012; Buchanan et al., 2012). Some of these works used elliptic Fourier analysis performed on the point's contour (Iovita, 2009, 2011), multivariate regression correction of landmark coordinate data (Charlin and González-José, 2012) and composite corrections involving proportions, shape, asymmetry, and size parameters (González-José and Charlin, 2012).

Here we expand these previous efforts by applying a Factor Model explicitly aimed to separate the effects of common factors generating global patterns of covariation, from local factors influencing localized (within-module) shape covariation and not contributing to variation in the counterpart module. The using of a statistical method specifically developed to segregate portions of covariation due to global versus local factors is of straightforward utility to the case of a blade–stem artefact, where total covariation among parts can be coherently separated into the covariation among blade and stem from the covariation occurring within the parts of each single module (the blade *or* the stem). Mitteroecker and Bookstein (2007, 2008) postulated a formal model aimed to explore the integrated/modular nature of the genotype–phenotype map (sensu Wagner and Altenberg, 1996) of complex biological structures. The Factor Model (Mitteroecker and Bookstein, 2007, 2008) is aimed to decompose the effects of common versus local developmental factors that differently affect groups of characters. Even though this approach arises from an Evolutionary Development (Evo-Devo) perspective, we suggest here that it can be of help to understand factors affecting the whole projectile point versus those impacting on the blade or the stem independently.

In the Factor Model approach, morphometric modules can be defined as sets of variables with non-zero within-module covariances, even when the covariances due to common factors have been removed, so that the residual between-module covariances are all near zero (Mitteroecker and Bookstein, 2007). Thus, "local factors" tend to contribute to morphological variation within one module only and, hence, generate modularization of the structure under study. Conversely, "common factors" affect traits across different modules, thus promoting integration among parts. It should be remarked that the Factor Model is not a "module-seeker" procedure, but a statistical method aimed to separate the effects of integration versus modularity on a set of modules defined a-priori. Also, this is not the same as analyzing variation separately on the blade and the stem (as in González-José and Charlin, 2012), since in such approaches, some portions of the variation in one module will be due to covariation with its counterpart, regardless if the analyses is made on both parts in a separate way. Our extrapolation to the lithic projectile points case assumes that the original design of the point considers a preconceived idea of two tightly integrated parts, the blade and the stem, which must accomplish a given function. In our approach, it is assumed that the original design is the main source of common factors accounting for covariation between the blade and the stem. Concomitantly, maintenance activities tend to be focused on the blade, since it is the module most exposed to damage during the impact and renewal of the point. Hence, resharpening can be viewed as a local factor promoting a blade/stem modularity pattern through differential reduction of the blade versus the stem during the point's life-cycle.

In other words, we intend to use the Factor Model under the following reasoning: the design of a point operates as a general source of shape attributes that involve highly coordinated (integrated) sub-aspects of shape in the blade and the stem. We assume here that the shape attributes of both modules are necessarily integrated since they are conceived to accomplish a given, specific function and hence design particularities are focused on the blade as well as on the stem. Alternatively, maintenance activities, especially those aimed to reactivate a broken blade will be, by definition, a source of shape variation focused exclusively in one of the modules of the point, not affecting the remaining one. We claim that, as a general outcome, design and maintenance activities are mutually exclusive sources of shape variation and covariation in the general context of the Factor Model. This is so because the former only generates integrated blade/stem variation, operating as a common factor in the Factor Model jargon, and the later only originates pure modular shape variation (e.g. not mutually accompanied by shape changes in the counterpart module, intended here as a local factor). This conceptualization is represented in the scheme on Fig. 1.

From the geometric morphometric point of view, the Factor Model separates the full shape space into an integrated space, defined by the common factors (the dimensions of shape variation that are integrated between the blade and the stem), and into the modular space, the space defined by local factors, reflecting those shape changes that remain after removing the effect of the common factors (Mitteroecker and Bookstein, 2007, 2008). It is important to note the conceptual difference among the three morphospaces. In the full morphospace, it is impossible to differentiate the covariation aspects among the shape and the blade from the covariation patterns occurring within the blade or the stem. It can be seen as a composite morphospace, where it is impossible to differentiate among design attributes mutually covarying among

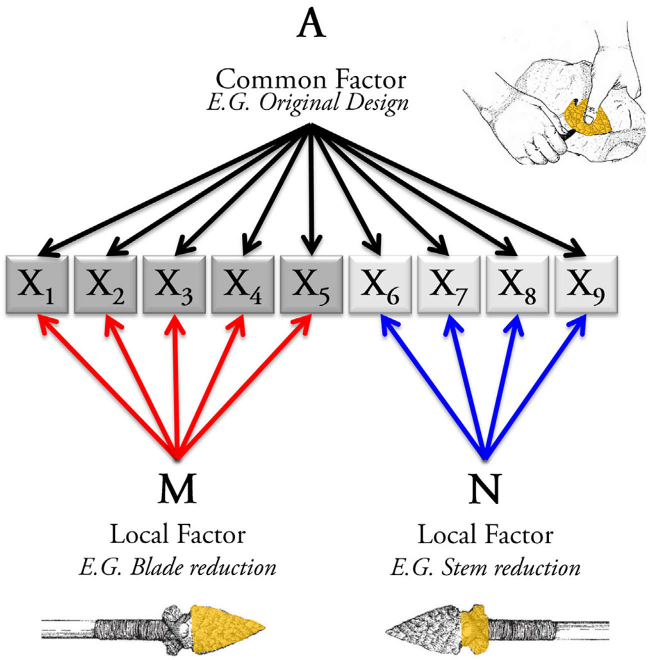

Fig. 1. A scheme of the Factor Model extrapolation to stemmed lithic points with one common factor A (e.g. original design) affecting all nine shape variables X1,…,X9 corresponding to the whole projectile, and two more local factors M (e.g. blade maintenance/damage) and N (e.g. stem maintenance/damage) influencing five and four variables in the blade and the stem, respectively. The full shape-space is determined by the influences of all the effects represented in the scheme (e.g. black, red and blue arrows). The integrated shape-space depicts shape changes due to influence of common factors (black arrows). The modular shape-space is determined by the influence of the local factors affecting exclusively the blade attributes (red arrows) or the stem traits (blue arrows). Note that in the integrated shape space, the influence of local factors is not taken into account, and vice versa. Modified from Mitteroecker and Bookstein (2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the blade and the stem, from this shape attributes acting on the blade/stem, without any effect on the stem/blade. In the integrated morphospace, the Factor Model depicts only the covarying aspects among the blade and the stem, and any shape covariation occurring exclusively within the blade or the stem are removed from this shape space. Finally, the modular shape space only depicts the covariation landmark displacements occurring within the blade or the stem that are completely independent from the shape covariation occurring in the integrated space (Fig. 1).

The general hypothesis tested here is that the between-group magnitude and pattern of shape changes will differ in the different morphospaces (full, integrated and modular) since they reflect different sources of variation (e.g. a combination of design plus maintenance, pure design, and pure maintenance activities).

2. Materials and methods

2.1. Samples

Our attempt to take advantage of the Factor Model on archaeological data is tested on a sample of 185 lithic projectile points from Southern Patagonia, which expands a sample used previously by us (Charlin and González-José, 2012; González-José and Charlin, 2012) and consists of Late Holocene lithic stemmed points from southern Patagonia (southern Santa Cruz Province, Argentina and Magallanes, Chile). Further information regarding Southern Patagonian population dynamics, inferred gene-flow patterns, and biological affinities on a regional and continental context can be find in González-José et al. (2002). Lithic points were assigned to two different typological categories according to Bird's (Bird, 1938, 1946, 1988) pioneering classification (see a detailed review of the classification system in Charlin and González-José, 2012). Bird considered that points belonging to Period V (covering the last 700 years BP) in the regional cultural sequence, named Bird-, Fell- or Magallanes V type or "Ona" points (hereafter referred to as Bird V), were arrow points because of their smaller size in comparison with older ones, and based on their "similarity" to Ona arrows observed on ethnographic contexts (Bird, 1988). In contrast, he proposed that points corresponding to Period IV (from 3500 years BP until historic period), named Bird-, Fell- or Magallanes IV or "Patagónicas" points (hereafter referred to as Bird IV), were spear points or hafted knives (Bird, 1988). Although subsequent analyses questioned many aspects of these assumptions (Gómez Otero, 1986–1987, 1987; Massone, 1979, 1981, 1989–1990; Nami, 1984; Prieto, 1989–1990), a detailed functional study of Bird IV and Bird V points considering several design variables and the physical properties of lithic raw materials, has pointed out the use of Bird V points as arrows and Bird IV types as throwing and thrusting spears (Ratto, 1991, 1993, 1994, 2003). Our previous analyses based on geometric morphometric methods have also distinguished three technical systems with different shape, size, asymmetry, and modularity patterns in southernmost Patagonia during Late Holocene (Gónzalez-José and Charlin, 2012).

In the case of pieces belonging to museum collections or those whose images were taken from published works on the regional literature, we adopted the classification used by the referenced authors. Only complete points were included in this study. Small damage (<3 mm) was tolerated, and the shape was estimated from the adjacent planes of the piece. Further qualitative and quantitative data of each point is presented on Table S1 (see online Supplementary Table 1).

The size and shape of each point was defined by 24 two-dimensional landmarks and semilandmarks placed around the points' contour. Landmark configurations were superimposed using a Generalized Procrustes Analysis (GPA, Rohlf and Slice, 1990; Goodall, 1991), and sliding semilandmarks were relaxed following the minimum bending energy criterion (Bookstein, 1996). The minimization of the bending energy is equivalent to seeking the smoothest possible deformation of one curve into the other, using a generally accepted mathematical definition of smoothness (Perez et al., 2006). Subsequent analyses were done with the complete 24-landmark configuration, or with partial configurations consisting of blade-alone landmarks (1–9 and 17 to 24 in Fig. 2), or stem-alone landmarks (10–16 in Fig. 2).

On each space (full, integrated and modular, see below) we will compare shape differentiation among Bird IV and V points. Specifically, we will measure among group differentiation using Hotelling's T^2, which is the multivariate analogue of the two sample t-test in univariate statistics (Hotelling, 1931). Finally, the within-group amount of variation was estimated using the volume of the convex hull (de Berg et al., 2000) enclosing the data points of each group, which quantifies the portion of shape space occupied by the group. Shape changes were visualized using the TPS function (Bookstein, 1991) applied to the first two Principal Components (PC) of the Procrustes superimposed coordinates (full shape space), the common factors extracted using the Factor Model (integrated shape space), and the local factors obtained after the multiple regression of blade/stem shape on the common factors (modular shape space).

Projectile points were classified as Bird IV or Bird V types by their original discoverers, excepting 76 pieces corresponding to sites studied by one of us (JC, Cóndor 1 cave, Laguna Azul, Laguna Cóndor, Frailes 2, Alero Norte 2, Las Buitreras 1, see references in online Supplementary Table 1) or belonging to collections that were photographed and reanalyzed to recover geometric-

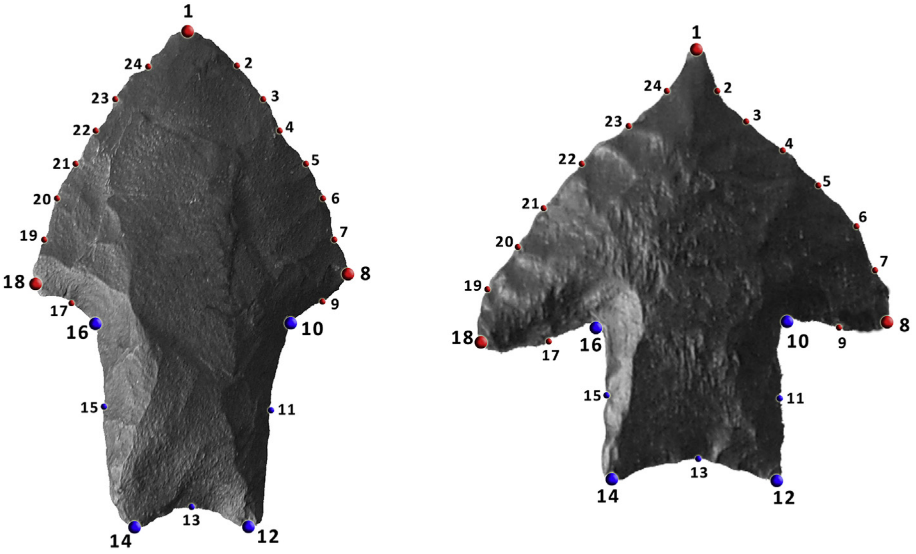

Fig. 2. Landmark configuration. Landmarks (large dots) and semilandmarks (small dots) used in this study. Red and blue points correspond to the blade and stem sub-configurations, respectively. Illustrated points from the "Abrigo de los Pescadores" site, Middle Gallegos Basin (right, Type IV) and from "Laguna Condor" site, Superior Gallegos Basin (left, Type V), both from the CENPAT-CONICET collection (courtesy of Dr. Julieta Gómez-Otero). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

morphometrics data (Thierauf collection from Museo Regional Provincial "Padre Manuel Jesús Molina", Río Gallegos, Argentina; Ronald Black collection from Museo Regional de Magallanes, Punta Arenas, Chile; Menghin collection from Instituto de Antropología, Facultad de Filosofía y Letras, Universidad de Buenos Aires; Peggy Bird and Punta Dungeness 2 collections from Instituto de la Patagonia, Punta Arenas, Chile; Potrok Aike and Pescadores' shelter collection from Centro Nacional Patagónico-CONICET, Puerto Madryn, Argentina, Supp. Table 1).

2.2. Geometric morphometrics

A total of seven landmark and 17 semilandmark coordinates were digitized on the contour of the points in order to achieve a good representation of its size and shape (see Fig. 2). GPA removes the effects of translation, rotation, and scaling (Rohlf and Slice, 1990; Goodall, 1991). After superimposition, pure shape information is preserved in the specimens' aligned landmarks. The superimposed landmark coordinates were separated into two modules: the blade, represented by landmarks 1 to 9 and 17 to 24, and the stem consisting of landmarks 10 to 16 (Fig. 2).

2.3. The Factor Model

To account for common and local factors affecting projectile design plus maintenance activities we followed Mitteroecker and Bookstein (2007, 2008). The common factors were estimated as the dimensions of shape variation that are integrated among the blade and the stem. To estimate common factors, Mitteroecker and Bookstein (2007) employ the two-block partial least squares (PLS) approach, also called singular warp (SW) analysis when applied to Procrustes coordinates (Bookstein et al., 1996, 2003; Rohlf and Corti, 2000). For each extracted dimension, the analysis yields two singular vectors, one for the blade and one for the stem, which can be construed as the two shape changes that most highly covary in the sample (Mitteroecker and Bookstein, 2008). Mitteroecker and Bookstein (2007) demonstrated that the two PLS loading vectors serve together as a common factor estimate when the vectors are scaled appropriately (see Mitteroecker and Bookstein, 2007 for a discussion of several scaling methods). The successive common factors statistical significance was obtained after a permutation test aimed to detect dimensions that differ significantly from a random distribution (Mitteroecker and Bookstein, 2008). The local factors defining the modular blade and stem shape spaces were obtained using the residual scores of the multivariate regression of each block on the common factors.

To sum up, different shape variables are obtained in four different morphospaces: full, integrated, blade-modular and stem-modular. Between and within-group differences in these different morphospaces were then estimated. Analyses made on the full shape space represent the overlapped effects of integrated and modularized traits on the shape variables. Differences observed in the integrated shape space defined by the common factors reflect the attributes that emerge from the integration between the blade and the stem. The modular shape spaces for the blade and the stem complement the dimensions of the integrated shape space and explain covariation patterns in the blade independent from changes occurring in the stem, and vice-versa. The corresponding analysis was run in R Development Core Team (R Development Core Team, 2011) using the routine implemented by Sydney et al. (2012).

Between group differences were estimated using a T^2 Hotelling test, whose significance is obtained after a permutation test (Klingenberg, 2011). Bird IV and V types' internal variation was assessed using the Procrustes variance of observations in each group, which is the mean squared Procrustes distance of each specimen from the mean shape of the respective group or, equivalently, the sum of the sample variances of all Procrustes coordinates (Klingenberg and McIntyre, 1998); and the area of the convex hull (de Berg et al., 2000) enclosing the data points of each group, which quantifies the portion of shape space occupied by the group. Procrustes variance quantifies the average dispersion of data points around the mean shape, whereas the area of the convex hull is a measure of the degree of difference among opposite extremes in each group, and therefore it does not consider observations located near the centre of the scatter of data points. Following Drake and Klingenberg (2010) Procrustes variances and convex hulls were computed from the first two PCs of the full and modular morphospaces, and from the first two Common Factors, because they explained most of the variation in the sample and because computation of higher-dimensional volumes presented computational difficulties (dimensions with small amounts of variation produce volumes near 0 for all samples, which led to problems with numerical precision).

Finally, we use Principal Component Analyses and scatterplots of the Common Factors to simultaneously evaluate between and within group variation, along with a visualization of shape changes occurring along each axis on the different morphospaces. Shape changes were visualized as wireframe deformations from the consensus shape. All the geometric morphometric analyses and graphics were done using MorphoJ (Klingenberg, 2011).

3. Results

The scatterplot exhibiting the first two Principal Components obtained on the full shape space defined by the Procrustes superimposed coordinates is presented in Fig. 3. Collectively, these first two PCs explain 88.1% of the total variation. Variation along the first PC correspond to elongated blades with narrow stems and small tip angles on the negative scores, versus shorter blades, broad stems and large tip angles on the positive values. Bird V or “Ona” points are placed on the negative scores, whereas Bird IV or “Patagónicas” points occupy the positive values across the first PC. The second PC describes variations focused on the lateral expansions of the shoulders, with less projected ones on the positive values. The Hotelling’s T^2 test revealed significant differences in shape among Bird-IV and Bird-V points (Hotelling’s $T^2 = 196.83$, $p < 0.0001$), and the Procrustes variances and the area of the convex hull delimited on the morphospace of the first two PCs revealed slightly greater diversification into the Bird-V group (Fig. 4).

When the Factor Model is applied to our database, four significant common factors are obtained (Table 1). The first two common factors (CF) explain 95.5% of covariation among the blade and the stem, indicating a clear spectrum of the integrated variation among

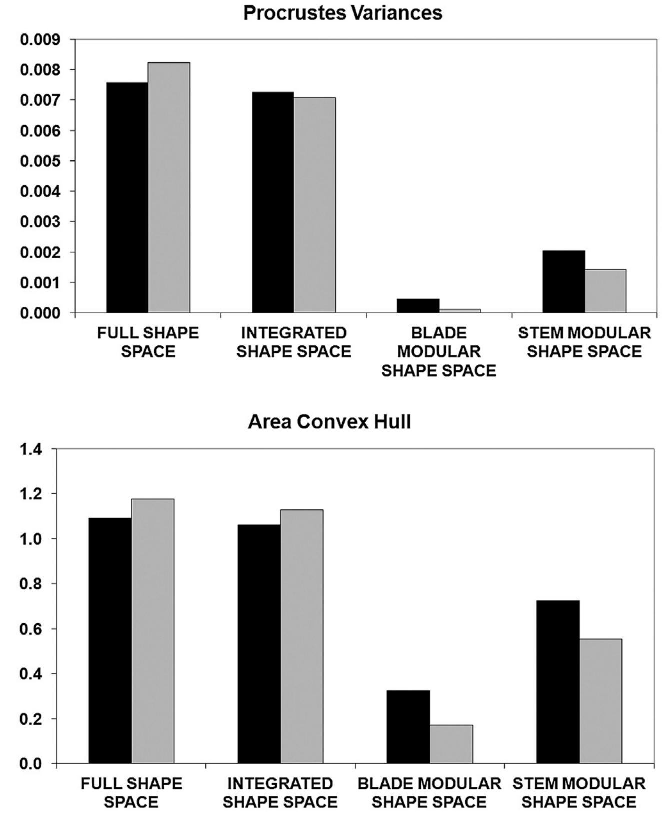

Fig. 4. Point shape disparity (within-group variance) in the different samples and morphospaces, quantified by the Procrustes variances (top) and the areas of the convex hulls (bottom) for the first two dimensions (PCs or CFs). Black bars: Bird IV; grey bars: Bird V.

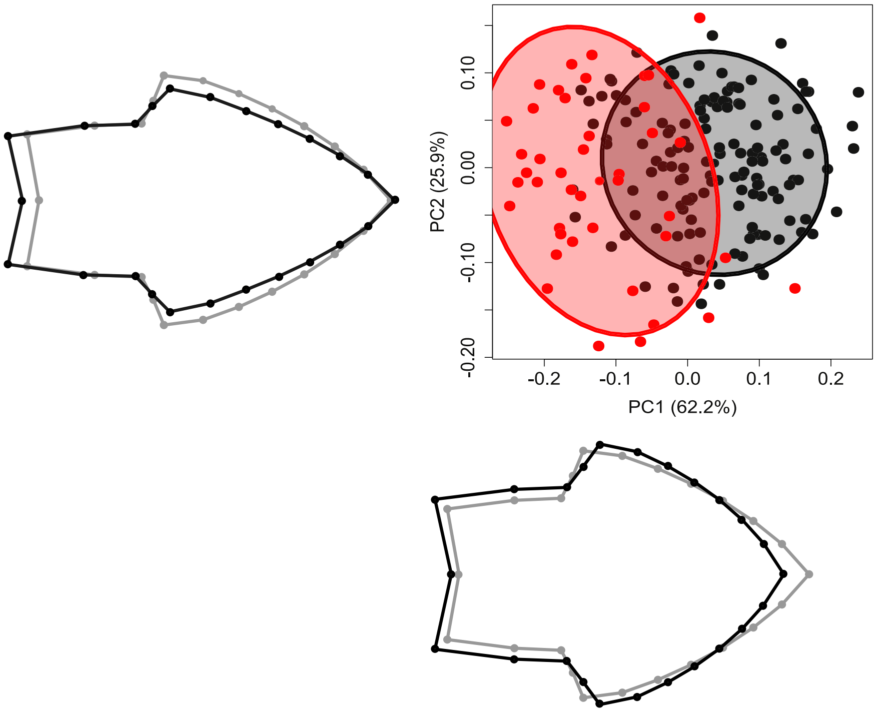

Fig. 3. Plot of the two first Principal Components extracted from the full shape space. Shapes corresponding to the positive (black wireframe) and negative (grey wireframes) scores of each PC are shown. 80% equal probability ellipses are shown for the Bird IV (black) and Bird V (red) points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
First four significant (p) common factors extracted from the dimensions of the PLS analysis. This table provides the covariance (Covar) in units of squared Procrustes distance × 1000, correlation among the PLS scores of the two blocks (Corr), the percentage of the within-type variance explained by the common factors or scaled PLS loading vectors (Exp. Var.), and the percentage of the within-types covariance explained by the common factors (Ex Covar).

	Covar.	Corr.	Exp.Var.	Exp.Covar.	p
1	5.09	0.911	59.8	68.42	0.001
2	2.02	0.842	25.71	27.1	0.001
3	0.19	0.592	2.85	2.53	0.001
4	0.11	0.336	2.73	1.46	0.001

both parts composing the projectile point. Interestingly, shape variations along the first CF (Fig. 5) greatly differ from variations observed on the full shape space and entails long and narrow blades, sharp tip angle, narrow shoulders integrated to relatively small stems for the Bird V types, and short, more robust blades, larger tip angles and wider shoulders combined with broad, relatively larger stems for the Bird IV points. In terms of internal variability of types in the integrated space (Fig. 4), results indicate a slightly greater variation on the Bird-V group (convex hull) or equal, very slight smaller variation among the Bird-IV points (Procrustes variances).

The blade and stem modular shape spaces are presented in Figs. 6 and 7, respectively. The two first PCs describing variation along the blade modular shape space (Fig. 6) explain 65.9% of the total variation and, in comparison to the pattern observed on the full and integrated morphospaces, the patterning of inter and within-group variation is altered in this morphospace. Thus, shape changes along the first two PCs seem to be indicative of different patterns of reduction. For instance, shoulder reduction is clearly sorted along the first PC, whereas tip resharpening is depicted as variations across the second PC (Fig. 6). Interestingly, types are less differentiated on the blade modular shape space (Hotelling's $T^2 = 30.63$; $p = 0.0240$), and even though both Bird IV and V show reduced within-group variation in the blades (see Procrustes variances and area of the convex hull, Fig. 4), the Bird V points' reduced within-group variation is mainly distributed along the second PC (Fig. 6). In other words, Bird IV points exhibit damage and reduction in both shoulder and tip, whereas Bird V mainly varies along the tip-reduction, second PC axis (Fig. 6).

Variation on the stem modular morphospace is presented in Fig. 7, and the first two PCs explained a 71.2% of the total variation. The scatterplot depicts a scenario sharing some similarities with the blade modular-shape space: Bird IV points vary broadly across the first two PCs, in particular achieving the most positive values across the first PC, characterized by wide stems presenting a basal notch. In contrast, Bird V points present only limited variation along the first PC and this general reduction of internal variability is corroborated quantitatively in the Procrustes variances and area of the convex hull presented in Fig. 4. In general, Bird V stems are straight or slightly convergent toward the base. Noticeably, local factors affecting the stem are not enough to differentiate Bird IV from Bird V points (Hotelling's $T^2 = 6.57$, $p = 0.255$).

4. Discussion

Lithic technology, an essential skill that humans developed to cope with changing conditions around them, was a complex system of central importance to cultural adaptation during long periods of human evolution. When attempting to explore variation in lithic projectile points in order to obtain information about cultural adaptive processes on past populations, assessing the role that different factors played in stone tool design and their relative importance as determinants of the final point's morphology becomes a complex task. In response to this challenge here we propose to take advantage of a formal theoretical model originally aimed to explore the integrated/modular nature of the genotype–phenotype map (sensu Wagner and Altenberg, 1996) of complex biological structures. Therefore we extrapolate the Factor Model (Mitteroecker and Bookstein, 2007, 2008) which allows separating the effects of common versus local developmental factors that

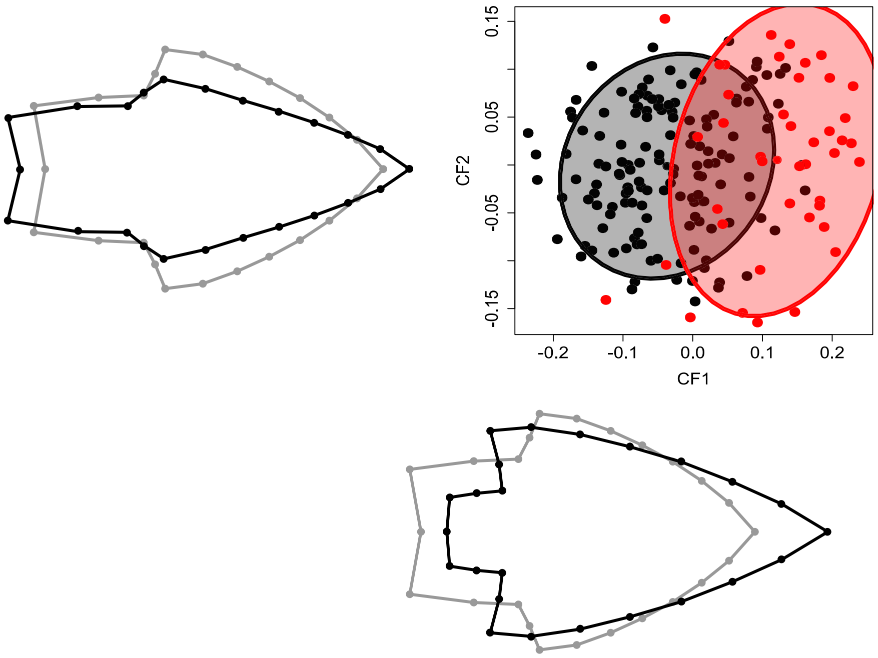

Fig. 5. Plot of the two first Common Factors depicting the integrated shape space (variation that affects both the blade and the stem). The shape changes corresponding to the positive (black wireframe) and negative (grey wireframes) scores of each CF are shown. 80% equal probability ellipses are shown for the Bird IV (black) and Bird V (red) points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

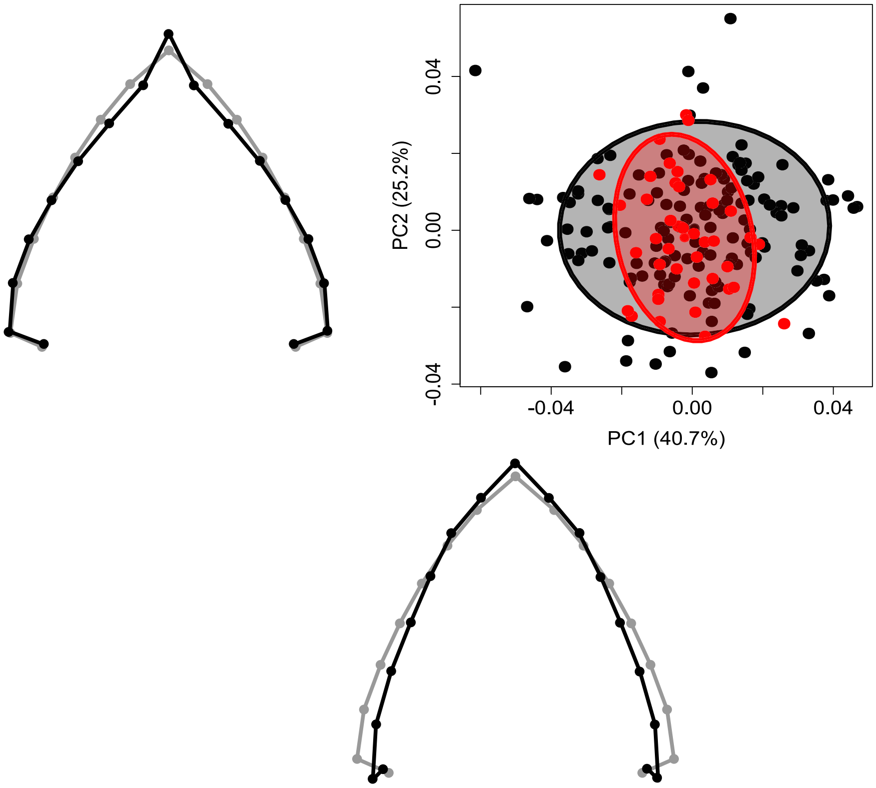

Fig. 6. The modular shape space of the blade landmarks reflects shape variation due to local factors in the blade. The figure shows the first two PC scores of this space. The shape changes corresponding to the positive (black wireframe) and negative (grey wireframes) scores of each PC are shown. 80% equal probability ellipses are shown for the Bird IV (black) and Bird V (red) points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

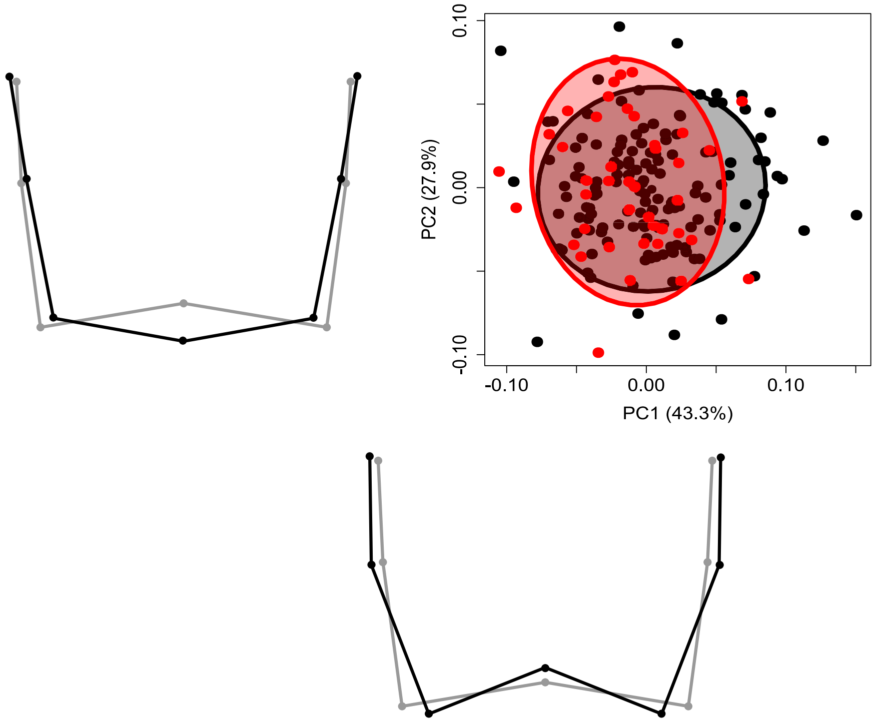

Fig. 7. The modular shape space of the stem landmarks reflects shape variation due to local factors in the stem. The figure shows the first two PC scores of this space. The shape changes corresponding to the positive (black wireframe) and negative (grey wireframes) scores of each PC are shown. 80% equal probability ellipses are shown for the Bird IV (black) and Bird V (red) points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differently affect groups of phenotypic characters, to decompose and analyze the shape of lithic projectile points.

In a previous paper on a similar sample (Charlin and González-José, 2012), we suggested that shape variations observed on the full shape space can be seen as the result of a complicated interaction among original design features and the effect of reduction techniques aimed to rejuvenate the tool after damage. Specifically, we showed that the effect of maintenance activities is more accentuated on the blade, rather than on the stem (Charlin and González-José, 2012), as suggested elsewhere (Flenniken and Raymond, 1986; Buchanan, 2006; Shott et al., 2007; Hunzicker, 2008; Thulman, 2012). Using a combination of geometric morphometric shape indicators and classical measurements, we also suggested that a clearer separation among different weapon systems can be obtained using a composite analysis combining shape information along with blade-stem length ratio, tip-angle (two classical proxies to estimate the degree of reduction), asymmetry, and overall size (González-José and Charlin, 2012). However, these previous approaches can be seen as model-free approaches, since they attempt to classify the tools as more or less reduced by inferring *a posteriori* how the different aspects of size and shape are affected by reduction. This pitfall is evident when trying to interpret the above-mentioned results in the light of design versus maintenance activities logic: variation on the blade length, tip angle, and shoulder lateral expansion observed on the first PCs describing the full shape space are the kind of shape variations attributable both to design differences and reduction. Furthermore, excepting specific experimental studies or direct ethnographic observations, to separate the effects of design versus maintenance activities on archaeological samples is very difficult to do.

Here we aim to evaluate projectile point changes on a model-bound framework, using the Factor Model as a tool to separate the effect of common and local factors, and relying on the basic assumption that design is an overall, important common factor defining the integrated aspects of blade and stem, and that use and maintenance are the main local factors affecting changes in the blade and the stem shape independently.

We find that changes expressed along the first two dimensions of the integrated shape space (Fig. 5) are in agreement with previous studies based on archaeological and ethnographic data that proposed similar variables as the best discriminating factors between arrow and spear points: a combination of maximum length, width, thickness and neck width (Thomas, 1978) or shoulder width as the best single-variable discriminator (Shott, 1997). Maximum width (sensu Thomas, 1978) or shoulder width (sensu Shott, 1997) is an important attribute because it corresponds to the part of the weapon that cuts the hole for the shaft to enter; thus penetration depth largely depends on it (Hughes, 1998; Sisk and Shea, 2009). Indeed, Thomas (1978) and Shott (1997) have reported a significant difference among dart and arrow foreshaft diameters and, more important, a significant correlation between maximum/shoulder width and foreshaft diameter. Our analyses demonstrate that changes in maximum/shoulder width clearly occur in the integrated morphospace of the common factors, thus supporting the idea that these attributes are an important part of the original, functional designs rather than a by-product of use and maintenance cycles.

Differences on functional demands of an arrow versus a spear are likely to force such design variations covering both modules (the blade and the stem) in an integrated way, since a balance between point size and shaft size (reflected on hafting area size, i.e. the stem) is needed to ensure an adequate flight trajectory and penetration of the target (Hughes, 1998). Considering the above, it is interesting to note that important stem shape differences appears along the first CF, but not on the axes of variation depicting the full-shape space. In other words, stem differences are evident mainly on the integrated space spanned by the first CF: the most important variations on stem shapes can only be intended as linked to specific blade attributes, and vice versa. Within-group variations on the integrated space remain very similar to the levels observed on the full shape space (Fig. 4): a slightly greater variation is observed on the Bird V group, particularly when the complete extension of the variation is considered (area of the convex hull approach). Between group differentiation is also significant in this morphospace (Hotelling's $T^2 = 152.28$; $p < 0.0001$).

Concerning modular shape spaces, variation in the blade seems to reflect a different pattern when compared to the full and integrated morphospaces. Specifically, the patterning of inter and within-group variation is altered in the blade morphospace. Thus, shape changes along the first two PCs of the blade modular shape space seem to be indicative of different patterns of reduction. Since Bird IV and V points are made from different rock types, the observed diverging patterns of damage/breakage need to be discussed considering the lithic raw material mechanical properties. While most of Bird IV points are made using volcanic rocks (dacites, andesites and basalts, Charlin, 2009; Ratto, 1994; Banegas et al., 2013) presenting high hardness, cohesion and compactness along with medium tenacity (the reaction to stressful forces acting upon the rock, Ratto, 1994; Ratto and Nestiero, 1994), the majority of Bird V types are made in chalcedony, a brittle silica mineral which is least resistant to stresses (Luedtke, 1992). Thus, according to their physical—mechanical properties the potential damage/breakage should be greater in the latter. However, the blade modular morphospace depicts greater damage levels among Bird IV points, suggesting that damage/breakage does not depend directly on the raw materials but on the experienced stress levels. Higher frequencies of shoulder damage are compatible with low-velocity projectiles, since barbed shoulders are an advantageous trait to keep the weapon in the wound, maximizing the killing by cutting and bleeding instead of deep penetration and lethal impact (Flenniken and Wilke, 1989; Hughes, 1998). In general, barbed or tapered shoulders suffer breakage when they are extracted from the wound since they commonly get stuck behind a muscle or ligament (Hughes, 1998). Ethnographic data compiled by Gould (1970) on the Australian Western Desert Aborigines clearly shows that barbed thrusting spears increased the seriousness of wounds. The same effect is achieved by blade serration, which is a feature sometimes present in Bird IV points. Moreover, if we consider Bird's (1988) alternative proposal about the use of Bird IV as hafted knives and/or the hypothesis suggesting the reutilization of Bird IV points as knives and notches at the end of their use-life (Charlin and Gónzalez-José, 2012:237; Ortiz Troncoso, 1972), then use may be the most important factor accounting for shape changes. Also, use is relevant in the context of damage/breakage expectations since using a point as a knife or notch can lead to all sorts of twisting and prying forces that would produce a wider variety of damage patterns and shape differences.

Regarding the shape changes observed across the second PC of the blade-modular space, it is worth noting that damages on the tip are usually produced by the impact in both arrow points and darts and thrusting spears (Frison, 1986, 1989; Odell and Cowan, 1986; Shea et al., 2001; Hunzicker, 2008, see Dockall, 1997 for a comprehensive review). However, recent controlled experiments have identified fracture type and size as a function of velocity and impact angle release (Iovita et al., 2013), as well as a relationship between "loading rate" of the impact event (estimated from the velocity of the fracture according to microscopic ripple marks on the fracture surface) and velocity launching (Hutchings, 2011). Both detailed studies have shown that high-speed projectile points (arrows and darts) can be distinguished from low-speed ones (handthrowing and thrusting spears), although no difference between arrows and darts is evident based on both macroscopic and microscopic damage patterns (Hutchings, 2011; Iovita et al., 2013). Nevertheless, what is clear is that longitudinal macrofractures (pseudo-burin-like and flute-like fractures) and higher fracture velocities (dynamic loading) on the tip become more frequent as speed increases. Note that the nippled-like tip characteristic of the positive values on the second PC (Fig. 6) facilitates skin penetration, since a sharp point concentrates the force in a small area reducing the energy needed to break a hole (Hughes, 1998). From an optimal engineering framework, the damage/breakage patterns and resharpening strategies detected on the blade modular morphospace for Bird IV and V points reflect both different stresses during use and different performance goals in each case. In general our results derived from variations in the integrated space and the blade modular morphospace suggest Bird V and IV point designs and damage/maintenance cycles are related to high and low velocity weapons, respectively. However, and even when non significant, our analysis of the stem modular space indicates some shape differences across the first PC (Fig. 7).

The approach used here enables several parameters to be investigated through geometric morphometrics and the Factor Model (Mitteroecker and Bookstein, 2007, 2008). For instance, the amount of shape variance due to original design intended as a common factor and maintenance activities intended as local factors can be extrapolated from comparing levels of internal variance on the full, integrated, and modular shape-spaces, as we have shown on Fig. 4. In our sample, much of the original shape variance is retained on the integrated space, where we assume that differences in style should be observed. Conversely, maintenance activities explain a relatively minor variance proportion. As a complementary result, it is observed that variation on the shoulders, sorted on the first PC of the modular blade space, appears sorted only on the fifth PC of the full shape space, explaining 2.25% of the total variation, and the strong resharpening of the blade tip depicted along the second PC of the modular blade space is detected on the sixth PC of the full shape space, accounting only for a 1.03% of total variance (see Inline Supplementary Fig. S1). As a whole, these results indicate that Bird IV and V design differences are greater in proportion than the blurring effects that maintenance activities could add to the total shape variation observed in the sample (Fig. 4, see Inline Supplementary Fig. S1). Factors or processes affecting morphology only locally, such as reduction, may respond to selection more easily than common factors like design that may lead to deleterious side effects and hence are expected to be more conserved.

Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.jas.2013.08.013.

Another advantage of the approach proposed here is that it enables the visualization of both design and reduction shape variation on an independent way and avoiding mutually noisy effects. In this context, regions on the integrated morphospace can be assumed to be informative of the adaptive/functional value of the different types observed. In this case, for instance, a large blade relative to the stem can be seen as the mandatory trait defining Bird V arrows, whereas robust stems and shorter blades seem to be the characters defining spears in Southern Patagonia. Regarding the information obtained in the modular morphospaces we suggest that it can be of utility to detect the regions suffering the most compelling damage according to its function. For instance, it was demonstrated on experimental analyses that the most damaged region is the tip, regardless if it is an arrow or a spear tip (Frison, 1986, 1989; Odell and Cowan, 1986; Shea et al., 2001; Hunzicker, 2008; Sisk and Shea, 2009; Iovita et al., 2013). However, there is little evidence regarding modifications in the shoulders, since most of experiments were done on stemless points (references above). Our results suggest that shoulders are more exposed to breakage and resharpening among spears than among arrows (Fig. 6).

Most of previous researches (cited here and elsewhere) are based only on two-dimensional outline data, which is a valuable research strategy in many cases. However points are essentially 3D objects that possess other salient attributes (e.g., thickness and its variation, cross-section form/areas) that escape 2D analysis. Future works should expand this kind of analysis by capturing three dimensional size and shape attributes (e.g. using 3D scans) and then applying specific and “model-bound” analyses such as the approach used here.

5. Conclusions

The extrapolation of biological concepts/methods to archaeological science is not free of problems. However, we suggest that the Factor Model is of great utility to study archaeological artifacts conceived in a modular way. This method is specifically aimed to deal with landmark coordinate configurations and explicitly developed to separate the effects of common factors promoting integration from local factors triggering parcellation/modularity. Even when further research on ethnographic and/or experimental samples is needed to corroborate our conclusions, we think that concepts and methods derived from the Evo-Devo field, such as the genotype–phenotype map and the Factor Model, can be used to explore patterns of covariation on cultural remains whose original design is modified due to life-cycle particularities (using, damage, repairing). Such applications are useful to investigate the particularities of design and its functional and adaptive value. In addition the approach proposed here is of utility to disentangle the particularities of maintenance activities linked to distinctive stress ratios and loading forces related with different functional demands of low and high speed weapon systems.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

Sample points used in this study were surveyed thanks to funding from projects PICT-ANPCyT N°15, UBACyT 20020100100957, PIP-CONICET 112-200801-00589, PICT-ANPCyT N°2046, PIP-CONICET N° 5676, and PICT-ANPCyT N° 04-9498. We thank the following people and institutions for access to the points collections: Patricia Campán from Museo Regional Provincial “Padre Manuel Jesús Molina” (Río Gallegos, Argentina); Paola Grendi and Christian Otzen from Museo Regional de Magallanes (Punta Arenas, Chile); Norma Perez from Instituto de Antropología (Buenos Aires, Argentina); Alfredo Prieto and Pedro Cárdenas from Instituto de la Patagonia (Punta Arenas, Chile) and Julieta Gómez Otero from Centro Nacional Patagónico-CONICET (Puerto Madryn, Argentina). Prof. Michael J. Shott and two anonymous reviewers provided helpful comments on earlier versions of this manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jas.2013.08.013.

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