On Extracting and Comparing the Shapes of Projectile Points

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Abstract

We have developed a system for extracting shape data from individual projectile points and applying methods of geometric morphometrics to study shape variation among groups of these artifacts. Data are extracted as two-dimensional coordinate positions of true landmarks (e.g., tip and mid-base landmarks) and pseudo-landmarks—evenly-spaced positions around the outline. Data are stored for whole and half points. The shapes are compared using an outline method (Theta-Rho Analysis), and three landmark-based approaches (Shape Coordinates, Least-Squares Analysis, Resistant-Fit Analysis). Each allows a rigorous and graphical analysis of the shape differences between two or more whole or half projectile points. Shape differences show as vectors of change in the position of these landmarks. We suggest that Resistant-Fit Analysis is preferred for comparisons between different projectile points and Shape Coordinates is the best for studying projectile point symmetry and asymmetry.

1 Introduction

Projectile points have been a subject of major interest to archeologists because they are artifacts that had well-defined functions for the people using them, and because they exhibit a wide range of different morphologies related not only to these different functions, but to other factors as well (e.g., available materials and historical and social factors). Traditionally, they serve their most important function as time markers. They exhibit characters that paleontologists would suggest make them perfect index fossils: they are generally widely distributed (within the context of the region being studied), they can be very abundant, and they show a significant morphological variation that provides both the means for easily identifying them to type and allows for the essential variation in this shape through time. In this paper we will discuss ways of extracting the optimal information describing the two-dimensional shape of projectile points and suggest a series of analytical approaches to comparing the shapes of two or more projectile points.

Traditionally, archeologists have been applying methods for studying projectile point shape that have a long history of successful application to problems in natural history that make significant use of disembodied linear measurements (e.g., Principal Components Analysis, Factor Analysis, Discriminant Analysis, and classic univariate and bivariate approaches; see Blackith and Reyment 1971). The problem is that these methods are actually much less successful at extracting and analyzing shape variation than methods that are currently favored by many paleontologists, evolutionary biologists, and geologists. Through the 19th century to today, these three groups of scientists have collaborated (sometimes in very caustic ways) to develop a series of methods for looking at the shape of objects in a more holistic fashion. These procedures extract much more shape information than typically can be obtained using disembodied measurements. The development of this school of methods proceeded at various speeds through this time and really started with the analysis of form by earlier artists/scientists such as da Vinci and Dürer. It was truly started in modern times by the famous Scottish biologist D'Arcy Wentworth Thompson who's classic book *On Growth and Form* (1942, first edition in 1917) influenced as many evolutionary scientists as Darwin's *Origin of Species*. Thompson's grid transformation approach, although problematic for very rigorous analyses, influenced many scientists to develop the methods used by most morphometricians today (see Benson et al. 1982; Chapman 1990; Rohlf and Marcus 1993). These procedures, often labeled geometric morphometrics but containing many approaches not truly under that official heading, offer a whole range of techniques that approach the analysis of shape within a geometrically constrained context. These approaches require that shapes be captured first in as comprehensive a way as possible while retaining the basic geometry of the shape being studied. Once done, the results of subsequent analyses can generate a much greater understanding of how shape varies among the specimens being studied.

Herein, we will discuss what we consider to be the best ways available to compare the shapes of projectile points within the contexts that, typically, are of most interest to archaeologists. The approach will start with methods for extracting the shape of projectile points and will then proceed to applying these newer analytical methods to the comparison of their shapes.

2 Approaches to Extracting the Shape Data

Extracting and measuring the shape of projectile points has been a subject of great interest to archaeologists for decades. The traditional method for extracting shape data is to take a series of disembodied measurements and subject these data for a group of projectile points to univariate, bivariate, and multivariate comparison (e.g., Greaves 1982; Lohse 1984). This is certainly an approach that can provide significant information on shape variation but suffers from two distinct limitations. First, the quality of the subsequent analyses depends heavily on the quality of and thought behind the measurements taken, and this is often problematical. Second, the use of these classic statistical approaches that use disembodied measurements, although still incredibly useful in many contexts, can either miss much of the shape variation present or make it very difficult to see that variation in the results. We will discuss these limitations in detail.

It is a statistical given that the better the measurements, the better the analyses that can be made from them. This is a variant of the old garbage in-garbage out syndrome and it still holds strongly today. When taking individual measurements, the researcher must decide on metrics that will inform him or her about that shape. This typically means using the points along the form that define geometric landmarks—such as the tip of the projectile point, the points that define the base, the points that define the maximum width, and accessory points related to notches and other features. These are exactly the types of points chosen by the best of the previous studies, such as those by Greaves (1982) and Lohse (1984). In other publications, researchers often use measurements that are much less defensible. For example, a quick survey of internet sites shows a variety of very questionable measurements that seem to be established in the archaeological literature, such as the width of a projectile point at a position ½, ¾, and 1 basal-width up (towards the tip) from the base (see Baker 1997 for an example). Such measurements are totally arbitrary and have the odd effect of simultaneously dampening the variation of interest in projectile point shape while introducing artificial shape variation that is of no scientific interest or value. If disembodied measurements are to be applied, a very significant effort must be placed in defending the measurements used.

It is also good at this time to address the potential confusion between the projectile points being studied and the points along the morphology that we use to describe the outline or from which measurements are taken. To avoid confusion with all these variations in the use of the word point, in this paper we will use points to describe the projectile points themselves and will refer to the positions on the morphology as landmarks. The landmarks that are based on strong geometric positions, like the point tip or base landmarks, we will refer to as true landmarks. Positions digitized along the outlines of the projectile points between these true landmarks will be referred to as pseudo-landmarks.

We would also make a strong statement about using measurements that are not based on true landmarks. They can be very problematic and introduce artificial variation into the analyses. This especially includes measurements traditionally defined by calipers such as maximum width or thickness. Often these values are taken at different positions on the morphology of each projectile point and, as such, actually make their interpretation in a rigorous way quite difficult. We would recommend that such measurements be avoided whenever possible. Further, any measurements that require projections of real landmarks to lines defined by other pairs of landmarks often also introduce much artificial variation, although they can at times be quite useful. Interpretation of this type of data must be done very carefully. Within geometric morphometric studies, they should be avoided.

Here we suggest capturing the shape of projectile points based not on direct linear measurements, but by taking the x- and y-coordinates of the landmarks available around the morphology of each projectile point. This is the best way to start even if the subsequent analyses will be done using disembodied measurements. In much less time than it typically takes to make caliper measurements, many more landmark points can be captured using digitizing programs. The number of linear measurements that can be calculated using coordinate data and simple mathematics (these can be programmed into a spreadsheet program and equal a two-dimensional Euclidean Distance = Pythagorean Distance) is $n*(n-1)/2$, with n being the number of landmarks. With 10 landmarks (taken typically in less time than 10 measurements using calipers) there is a potential of generating 45 measurements, along with other possibilities for angles and more complex measurements. It is best to take as many landmark coordinates as possible, even if they may not be used in the current analysis, because they take little time to digitize and allow for a tremendous potential for other analyses in the future. This approach does require time for taking an image of each projectile point. However, having an image library of all specimens studied should be standard operational procedure, especially given the ease of electronic imaging (Chapman, 2003).

3 An Easy Method for Extracting Projectile Point Shapes

As noted earlier, projectile points have greatly variable shapes and any system for capturing these shapes should allow this variation to be captured and studied. For this work we will stay with two-dimensional shape—ignoring for now the third dimension, which undoubtedly has useful information that we are just now starting to explore (see Petersen et al., CD, this volume)—and the variation of projectile points in this third axis can indeed be quite complex.

The surface of a projectile point lying flat is, typically, a relatively simple shape with a variety of and varying number of landmark points. In morphometric studies of organisms, we often talk of landmarks of various types, with the best having the same developmental (= embryological) origin. Projectile points are obviously not living organisms or parts of them, but they are the products of organisms who purposefully made them into the shape they are, with consistent landmark positions. We use these consistent positions—here defined geometrically, as often happens in evolutionary morphometrics as well—for our shape extraction. A typical projectile point will have a tip and a mid-base landmark. The positions along the outline that exhibit the maximum distance from the midline (tip to mid-base) could be used, but the methods explored in this and subsequent papers will typically allow that part of the outline to vary on its own as part of the outline, allowing us to track shifts in this position better. Other landmarks can come from a well-defined base (left and right edge positions), and from notches and other features that are consistently found as part of the projectile points being studied. The landmarks used in subsequent analyses will depend on the exact group of projectile points being studied. If studying all North American projectile point types, as we are doing in a separate work , then only two landmark points will be available in all complete specimens (the problem reduces to the smallest number found in all specimens being studied). If concentrating on basal notched points only, this number can expand to ten. This disparity was also recognized within the context of a classic linear analysis by Lohse (1984). For example, a classic Haskett point has well-defined tip and mid-base landmarks, and may also have two well-defined base edge landmarks, as well (left and right). More complexly-shape projectile points, such as the basal-notched forms, can have the main two landmarks (tip, mid-base), other base landmarks, as well as at least three more geometrically defined landmarks per side, mostly related to the notch and its shape.

Between true landmarks is the outline of the projectile point. In our system, we use evenly-spaced pseudo-landmarks along the outline to define its shape—the number of these depends on the anticipated average length of the outline segment—short segments usually require fewer points than longer ones. The more complex the outline shape, the more points should be used to describe it. For projectile points with just two landmarks, this is the outline that defines one whole side. For basal-notched points, it might include outline segments from the tip landmark to the top of the notch. Outline pseudo-landmarks may also be used for the notch segments and those to the base and within the base, but often just the landmarks in this area will suffice. The true landmarks are the most strongly defined positions of the shape. The outlines are defined by a surface of pseudo-landmarks at equal intervals. Analyzing variation in the position of these pseudo-landmarks along the outline provides data on the expansion, contraction, and other variation in the main surfaces of the projectile points.

So how do we extract these data? Rather simply. We take images of the point lying flat and bring it into a digitizing package to obtain the x- and y-coordinates of the landmarks and outline positions. We use a package called *tpsdig*, available free on the Web (SUNY Stony Brook 2005). The package is easy to download and use. Simply, we generate files that include the x- and y-coordinates of the tip and mid-base landmarks, as well as any other landmarks of interest to the subsequent analyses. We then digitize the outline positions as irregularly-spaced points along the outline. The coordinate data is then written to a file that can be viewed as a pure ASCII text file, or in a spreadsheet program. We then have programs developed by one of us (Chapman) that read these data and build the files we use for subsequent work. Outline positions are defined by their bounding landmarks and the programs automatically determine the perimeter from the first landmark to the other by calculating evenly-spaced positions along the outline segment using the irregularly-spaced digitized positions to guide the outline shape. The number of outline positions is decided before-hand by the researcher for each segment. Figures 1 and 2 provide examples of how the process works. Once the new files are generated for all the projectile points of interest, then detailed statistical analysis can proceed.

The coordinate data we use are scaled all to a base length (tip to mid-base landmarks) of one unit and all positions rescaled within that system while retaining the original geometry. The length of this baseline is calculated and stored so the original size and geometry can be restored, if of interest. However, it is important to remember that this original geometry, or shape, is never distorted, just scaled to various sizes. The programs for doing this latter work can be obtained by contacting Chapman, and this same approach has been used for various types of specimens, including tridactyl dinosaur footprints (Rasskin-Gutman et al. 1997:379).

It should be rather obvious that projectile points tend not to have sides that are intended to be either on the left or right. Very asymmetrical points may be an exception, but projectile points do not have well-defined left and right sides as organisms do (it helps to have a dorsal, a ventral, and an anterior direction). Consequently, each side of a projectile point is a separate but related experiment representing a human trying to produce a shape. Consequently, we have developed a system where we make a minimum of five files for each projectile point. One file has the data for the right side (defined arbitrarily), and a second for the left side. To compare the two sides most easily, they must be on the same side—arbitrarily here chosen to be the right side. So, a third file is made which is the left side for each projectile point mirrored (about the tip-mid base line) to look like a right side. This file and the real right side file are then used in analyses where halves are compared separately. A fourth file is generated which is the whole projectile point as digitized. This allows whole points to be compared. There is still a problem with the arbitrary left- and right-side designations, however. Consequently, the whole projectile point is also mirrored and saved as a fifth data file. When comparing whole projectile points, two different comparisons are made and the least different one used (the one with the lower distance value [see below]).

Digitizing projectile point shapes in this manner takes relatively little time. The required images of the specimens provide an accompanying image documentation set for that collection in the process (Chapman 2003). With electronic systems, the time needed for the imaging is relatively short for each specimen (less than five minutes). The digitizing process within *tpsdig* also is very rapid, taking typically less than five minutes per specimen. Once the first files are made, the production of the five final files is almost instantaneous for large groups of specimens using the programs developed by Chapman. These operate in batch mode, working for many specimens at once. Errors in the digitizing process will often result in aborted runs during this stage. This serves as a quality control mechanism for making sure the data set is correct. Consequently, large data sets can be generated in relatively short time periods.

4 Comparing Projectile Point Shapes

Historically, projectile points have been compared using a series of disembodied measurements and studied using

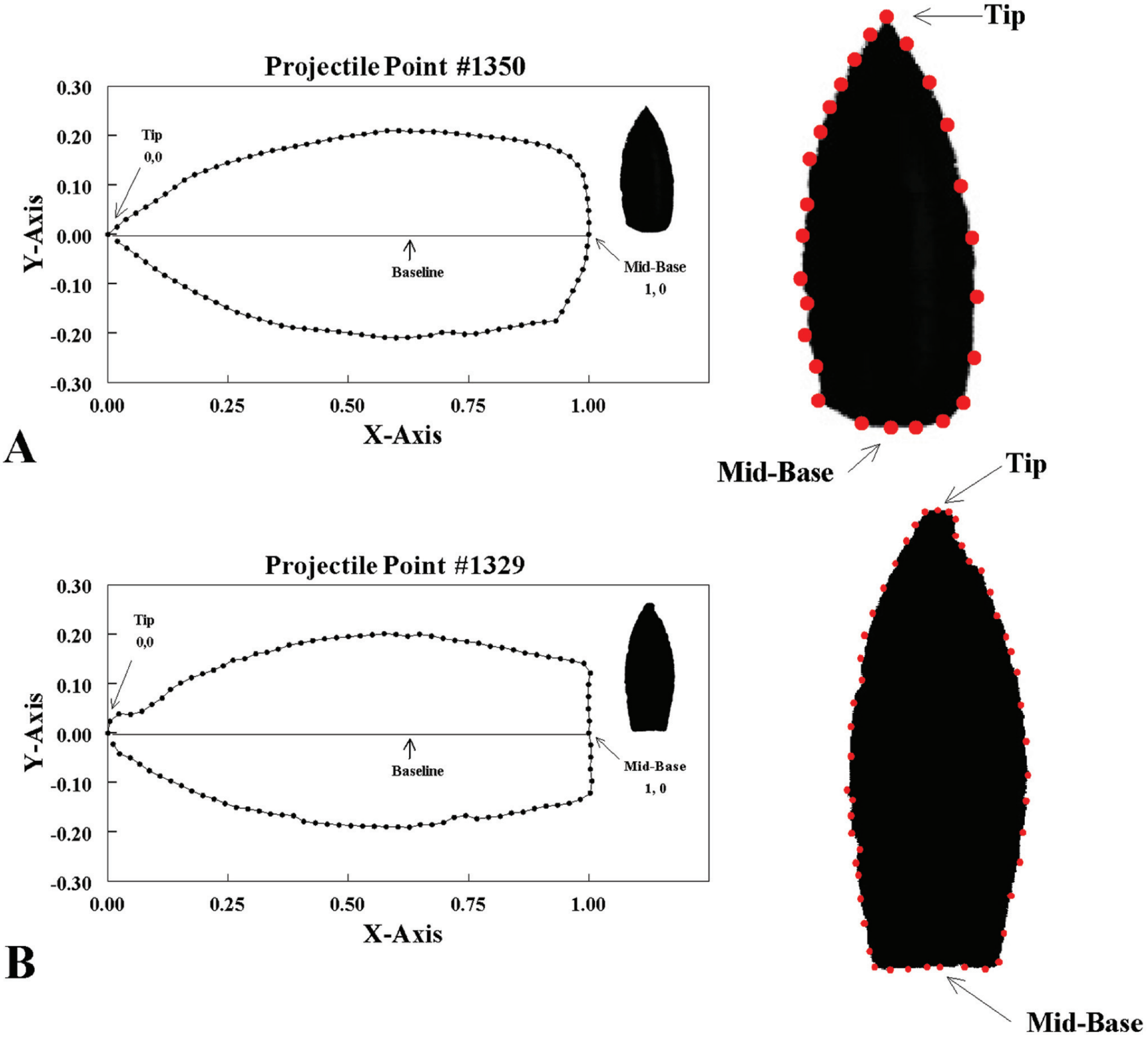

Figure 1. Digitized shape data for relatively simple-shaped projectile points; each has two true landmarks (tip and mid-base) and pseudo-landmarks along the side outlines. Each shows the final form after evenly-spaced landmarks are calculated, a superimposed silhouette, and a screen capture from tpsdig on the right with landmarks as circles (circle size depends on original image size so some will images will have larger and more apparent circles). A) The top point is a classic Mesa Verde point (IVL reference #1350). B) The bottom point is from the Washakie Mountains, Wyoming (IVL reference #1329) as reported in Frison (1983).

classic methods of univariate, bivariate, and multivariate analysis. Probably the best and most effective applications of this approach have been the monographs by Greaves (1982) and Lohse (1984). They apply multivariate procedures, such as factor analysis and discriminant analysis, to answer the questions of interest. It should be made clear that we see nothing wrong in taking this approach as it is well-established in all the natural sciences and are frequently referred to as multivariate morphometrics (e.g., Blackith and Reyment 1971). These methods certainly can provide significant information about shape variation, but the experience of a large number of scientists in the fields of paleontology, evolutionary biology, and geology have led to the development of new methods of geometrically-oriented shape analysis (including the most common approach called geometric morphometrics; Benson et al. 1982; Chapman 1990; Rohlf and Marcus 1993). These methods often can extract much more information about shape variation than is possible with these more conventional approaches. Selecting the proper approach to use between these two morphometric philosophies depends on the application. For example, if you are a paleontologist studying dinosaur skeletons that include skulls and long bones, then there is no standard positioning of these elements across specimens that would allow geometric approaches to be used. Therefore, conventional morphometric procedures that use disembodied measurements are called for, and significant shape data will be extracted by this approach. However, if you are a paleontologist studying skulls, where a standard orientation is established from specimen to specimen, then geometric methods should be the preferred approach.

This brings us back to projectile points. As discussed

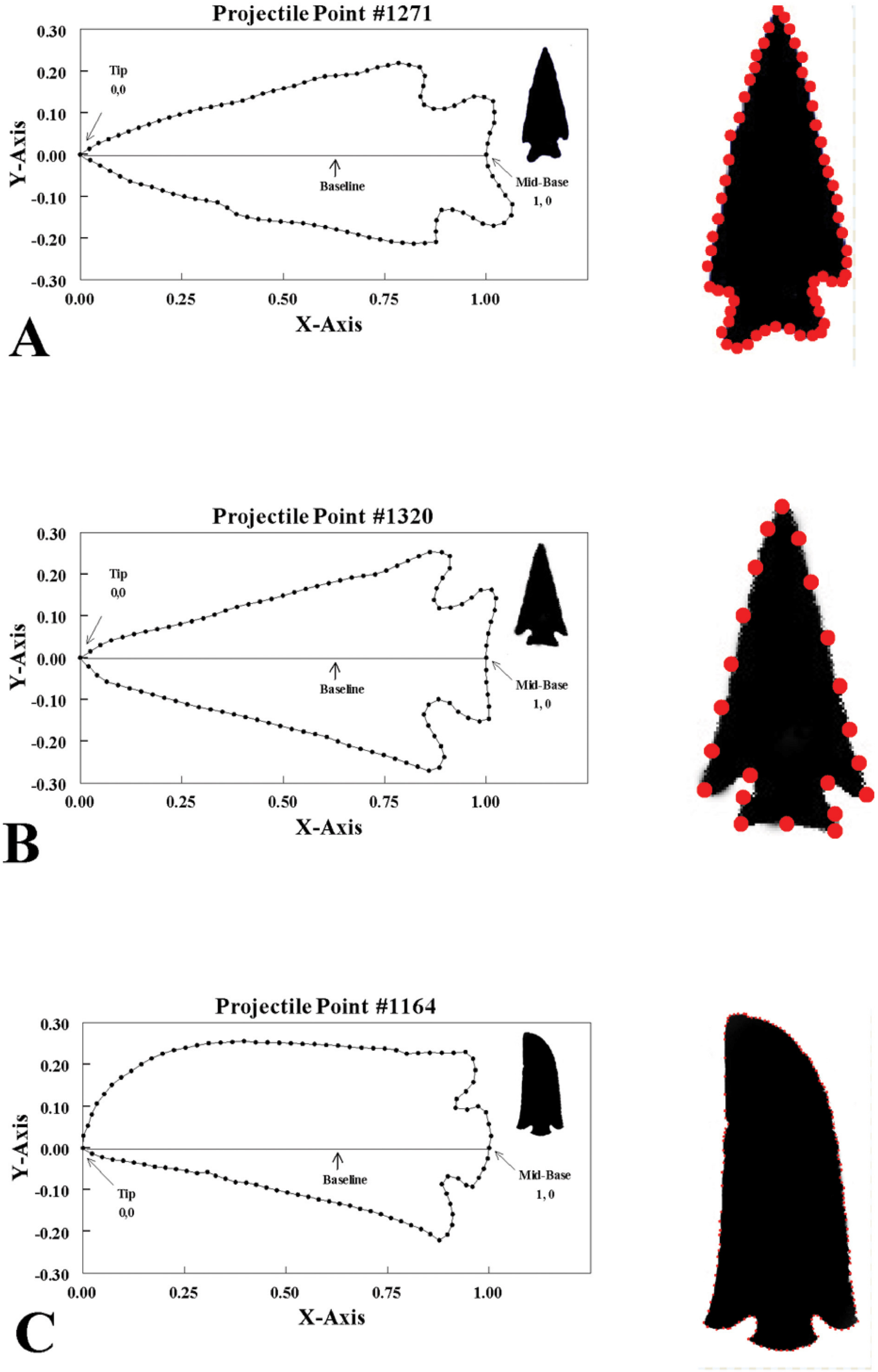

Figure 2. Digitized shape data for more complex-shaped projectile points; each has two true landmarks (tip and mid-base; up to ten could be used for these specimens) and pseudo-landmarks along the side outlines. Each shows the final form after evenly-spaced landmarks are calculated, a superimposed silhouette, and a screen capture from tpsdig on the right with landmarks as circles (circle size depends on original image size so some will images will have larger and more apparent circles). A) The top point is a Shuswap Horizon point (IVL reference #1271) taken from Prentiss and Kuijt (2004). B) The middle point is an Elko corner-notched point (IVL reference #1320) as reported in Webster (1978). C) The bottom point is a very asymmetrical point (IVL reference #1164). It is a Hopewell Blade from Ohio, reported in Brose et al. (1985).

above, we will concentrate on two-dimensional shape under the assumption that a reasonable system for analyzing shape variation in the third dimension still needs to be developed (Petersen et al., CD, this volume). Single measurements of thickness can be of some use, but they need to be taken more consistently than is typically done in most studies—defined by landmarks and not by calipers. Standard caliper thickness measurements simply obfuscate the real variation present in thickness and should be taken for other reasons (e.g., developing proper storage spaces) rather than for analytical analysis.

Starting with disembodied measurements, care must be taken to make sure the measurements used are equivalent for all specimens. Examination of the univariate distribution of data is standard statistical procedure—it is always nice to see if the data are normal or skewed and if any bimodality or polymodality is present. With bivariate comparisons, especially where lines are fit to data, it is important to use the proper procedures. In most cases in projectile point shape studies, this is not the classic model of simple linear regression (e.g., Zar 1999:324-412), often referred to as least-squares regression (e.g., Shennan 1997:127-181). This method assumes one measurement is an independent variable and for most common shape comparisons—such as projectile point length versus width—there is no equivalent to an independent variable. Instead, correlation based models are superior, especially the reduced major axis, which is easy to calculate and gives better intuitive results (e.g., Imbrie 1956).

This brings us to ratio calculations and comparisons. Ratios are a particular favorite amongst archaeologists, just as they are for many systematic biologists and paleontologists. They should be avoided in most cases, however, because they are extremely difficult to use correctly. As shown in Figure 3, if fitting a line to a set of morphometric data, ratios can be misleading. The ratio of the two measurements used will exhibit a different value at one end of the line relative to the other, unless the line just happens to go through the origin, which is rare. Consequently, calculating ratios and giving their range for a group of projectile points means little unless also accompanied by the size associated with each ratio value. This makes ratios much less convenient than with their conventional use—and ratios are used because they are thought to simplify shape statements. It is simply better to make bivariate comparisons graphically. Such bivariate comparisons can still be incredibly useful; the study of projectile point allometry, especially relative to their function or material of manufacture, is still a very understudied area in archaeology.

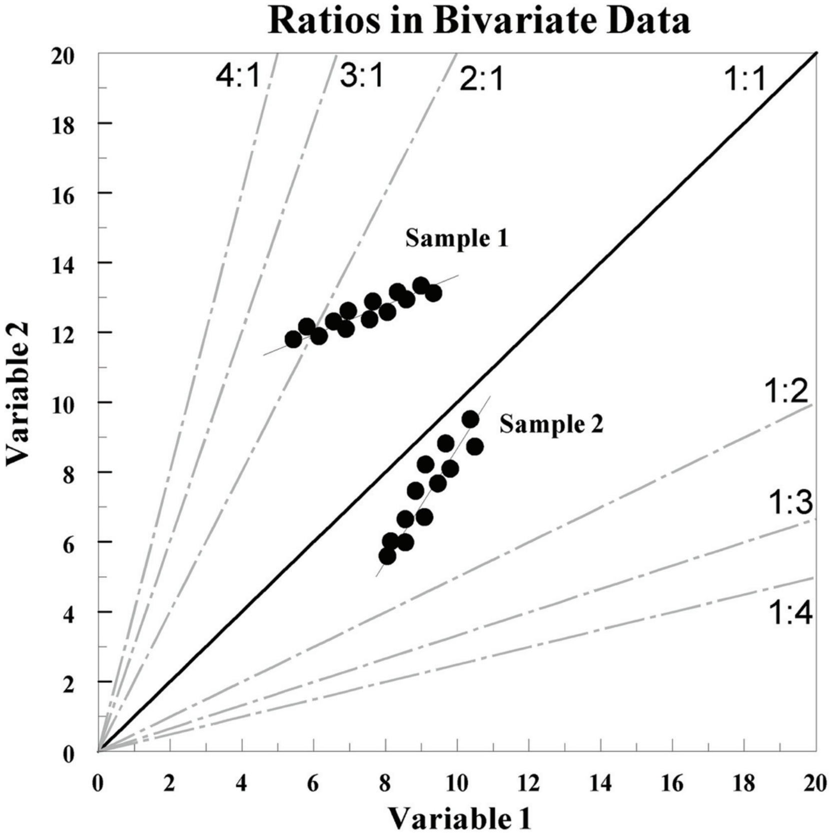

Figure 3. Properties of ratios for bivariate data. Long lines going through the origin show consistent ratios as labeled. Even lines parallel to these long lines will not have consistent ratios. Circles show two hypothetical samples of projectile points (e.g., measurements for length versus width) with lines fit through them. Note that the ratio for Sample 1 changes from about 2.1:1 on the left to about 1.5:1 on the right. The ratio for sample 2 changes from about 1:1.6 on the left to about 1:1.1 on the right.

Above two dimensions, concerns about homoscedasticity and multivariate normality make applications such as Principal Components Analysis (unrotated methods are preferred usually over rotated methods for eigenvector approaches) and Discriminant Analyses more useful as exploratory methods but difficult to take to the next level of making rigorous statistical tests. Instead, we recommend the use of Non-Metric Multidimensional Scaling (NMS; McCune and Grace 2002:125-142) as being best for exploring the shape space occupied by projectile points, as it does not rely on these generally unmet assumptions.

This leads us to geometric methods of shape analysis which can be very powerful if the data allow them to be used, and projectile point shape data are usually well suited to using these methods. Following the method for data extraction outlined above, we have many options available for using the landmark and outline (pseudo-landmark) position data.

One family of geometric methods allows the analysis of the outlines directly, treating all landmarks and pseudo-landmarks as part of a single outline. Traditionally used methods for this type of data apply some form of harmonic analysis to these outlines (e.g., Fourier Analysis). Such analyses can be done using a landmark (e.g., projectile point tip) as a starting position, or the analysis can be independent of a consistent starting point. Our experience is that the latter approach is less useful for natural history applications (see Rohlf 1986). The outlines are then deconstructed into a series of harmonics and their defining coefficients, and comparisons and analyses made using these harmonic coefficients. From our experience, Elliptical Fourier Analysis (e.g., Rohlf 1986) has the greatest potential for providing interesting results, but even this approach is very difficult to do well and interpretation is especially difficult because the researcher is so removed from the original data set by the end of the analysis. A first approach to using outlines was taken by Lohse et al. (2004) and Schlader et al. (In Press). They used a routine for the automated extraction of outlines and then applied a neural network to develop an automated system for identifying projectile points to typology.

For this type of approach using outlines, we suggest a simpler and more effective method called Theta-Rho Analysis developed by Benson (1967) for studying ostracodes (a typically jellybean-shaped crustacean). Here, all outline positions are recalculated in polar coordinates (as the name implies) derived from a single, typically more centrally located position: either the center of form (for two dimensions) or another landmark point. These are then plotted as angles (theta) from 0° to 360° relative to a standard baseline and distances (rho) from that central point. The average rho value typically is scaled to a single and consistent value (usually unity) for ease in making comparisons among different specimens. In this system, a circle is a straight line and other morphologies exhibit characteristic differences from this straight line (see Figure 4). This method is shown in Figures 4 and 5 for theoretical shapes and three projectile points. There is some small distortion in the values, typical of any approach that uses angles, but the ease in observing and comparing the results maintains the usefulness of this approach. If an estimate is needed of how different two outlines are, a single distance value can be calculated as the mean squared distance between equivalent positions on the outline. So, the squared distances between equivalent positions are summed and divided by the total number of these positions, yielding an average distance value between the two specimens. Theta-Rho Analysis provides all the usefulness of an outline method but without the complexity associated with Fourier and related methods; you see the shape variation directly in the graphics.

As we have already mentioned, landmark-based methods are the most powerful shape analysis procedures and there are a number of options available. All remove overall size in some way in favor of direct comparisons of shape. As such, they can be referred to as Procrustes-style methods in that they reduce every object to a single base size, although this term has been most-often used by some to describe solely the approach we will mention below using a least-squares fitting approach.

The first method is based on Shape Coordinates (e.g., Bookstein 1984, although they go all the way back to Francis Galton), where two baseline points are chosen that are given a length of one unit, with the first landmark (we use the tip of the projectile point) given a coordinate position of 0,0 and the second (we use the base mid-point) a coordinate position of 1,0. All other positions are then recalculated to fit within this space without distorting the original geometry. Distance values between specimens can be calculated as above with Theta-Rho Analysis, although the number of distances is two fewer as two of these positions are invariant by design. A great strength of this and the subsequent methods is the ability to view graphically the amount and distribution of these differences as vectors of change. Figure 6 gives an example of such an analysis. Brande and Saragusti (1996) used this approach for looking at stone tool shape.

The next two methods, Least-Squares and Resistant-Fit (Benson et al, 1982; Chapman 1990) are similar in that

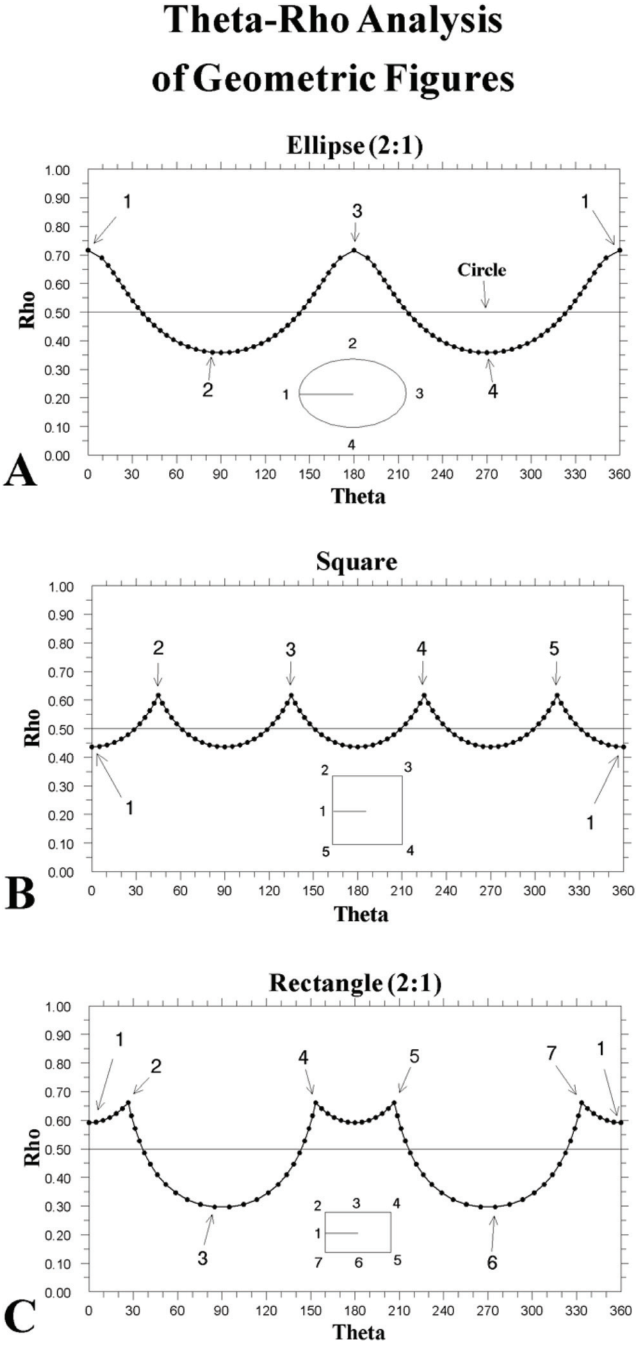

Figure 4. *Theta-Rho Analysis (TRA) of basic geometric shapes. In all figures the straight line represents a circle. A) TRA of ellipse with major axis: minor axis ratio of 2:1. B) TRA of square. C) TRA of rectangle with 2:1 ratio of long side to shorter side. Critical positions are labeled for both basic shape and TRA representation.*

none of the landmarks are constrained to be the same but, instead, constellations of these landmark points are superimposed onto each other using an algorithm that makes basal assumptions about the fit. In the Least-Squares Analysis, the average squared difference between equivalent landmarks is minimized. In Resistant-Fit analysis, this fit is calculated based on medians and the distance is not minimized but, instead, the fit allows areas of localized change to be more defined. The best visualization of this would be with the literary character Pinocchio, whose nose would grow longer if he told a lie. If you were to analyze Pinocchio's head pre-lie and post-lie you would get different results with these two methods. With Least-Squares Analysis, the nose would indeed be seen as longer, but the whole head would shrink to accommodate this change. Nose landmarks would have large vectors of change and the other head landmarks, smaller but distinct differences suggesting a reduction in overall head size—like pulling a section of a balloon out. With Resistant-Fit analysis, the nose landmarks would have a huge change and nothing else would exhibit any differences (as long as you have more landmarks in the head than nose).

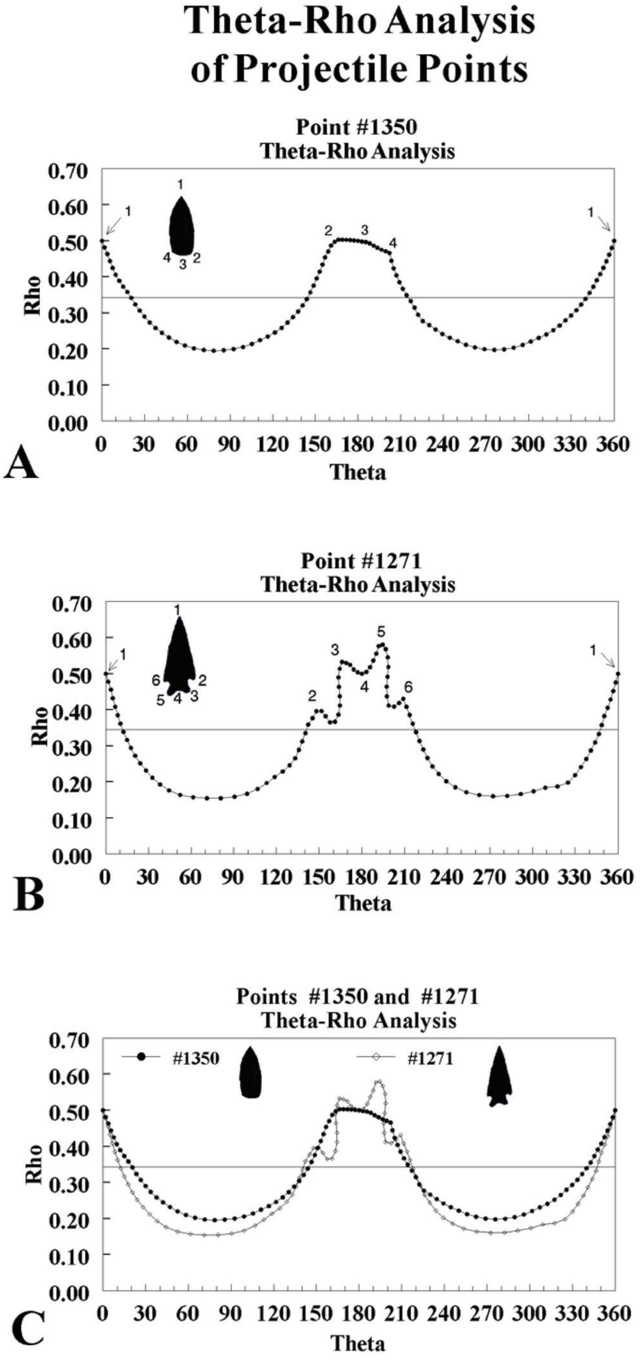

Figure 5. Theta-Rho Analysis (TRA) of simple projectile point (A; Point #1350), more complex point (B; Point #1271), and the two points compared (C). Note small distortion in evenly-spaced points at edges and the generally similar shape the two projectile points exhibit as an oval with extra complexity.

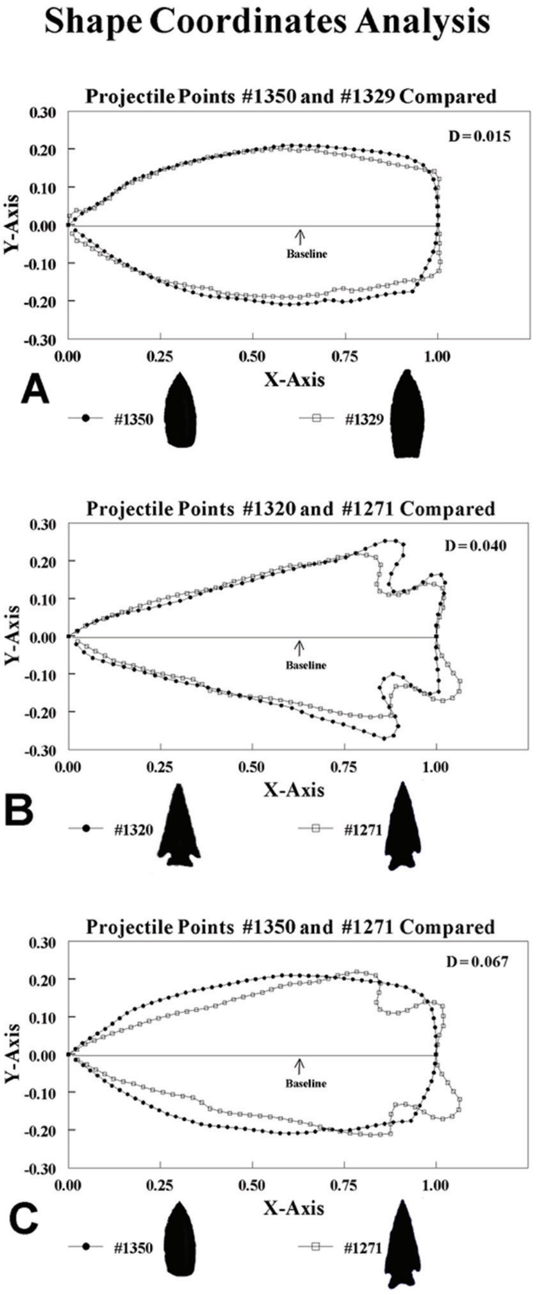

Figure 6. Shape Coordinate Analysis for A) two simple-shaped projectile points (#1350 and #1329), B) two more complex points (#1320 and #1271), and C) between a simple point (#1350) and a more complex one (#1271). D values are the average distance between the two points; the higher the value, the more different the specimens. Note the fit is done using just the baseline between the two true landmarks.

The application of these methods is shown in Figures 7 and 8. The choice of these methods for any particular analysis depends on what model makes sense for the specimens being studied. Although the Least-Squares approach is currently favored in many biological analyses, the Resistant-Fit algorithm most often makes more sense in comparisons where detailed shape differences are being studied. Examples of the application of this approach are given in Benson et al. (1982), Chapman (1990), and Rasskin-Gutman et al. (1997:379), and Chapman can assist anyone interested in trying these methods. These two approaches can be more powerful than shape coordinates but there are situations, such as the analysis of symmetry (Chapman 2002), where we know that the two base landmarks are indeed the exact same positions and should not show differences among the specimens being studied. In this case, the use of shape coordinates is probably preferred. Regardless, each of these methods provides a powerful, graphical, and rigorous documentation of the shape differences that exist between two or more points in a form that is easily visualized by the researcher. The results of the three methods are usually quite congruent.

For both Least-Squares and Resistant-Fit methods, when the newly superimposed positions of the landmarks are graphed, vectors can be superimposed to view the positional changes most easily. Often, if there are significant numbers of true landmarks, the fit is made using only these, and the pseudo-landmarks on the outlines are transformed using the coefficients determined using the true landmarks. In other cases, all landmarks, true and pseudo, are used to make the fit. Projectile points often exhibit very few true landmarks, so the use of pseudo-landmarks is often required. These analyses provide direct data on the distance and direction of change for each landmark. Large outline areas can easily be visualized as surfaces shifting in overall shape. Further, an overall distance value—an estimate of how different two specimens are—can be calculated as outlined above.

A real bonus with all these methods (Theta-Rho Analysis, Shape Coordinates, Least-Squares Analysis, Resistant-Fit Analysis) is the ability to take a sample of the same style point, do an analysis, and generate a mean shape for the sample. This way, the average shapes of two different levels or sites can be compared for differences. Variation around the mean shape can also be calculated for each landmark position. These methods also can provide a standard data matrix—coordinate positions of the various landmarks—as a starting point for applying more classic multivariate procedures. You start by superimposing a whole series of specimens onto one basic position or specimen. The next step can make use of clustering procedures and ordination methods to analyze the multivariate data. The coordinate data are used to generate a Euclidean Distance matrix as a

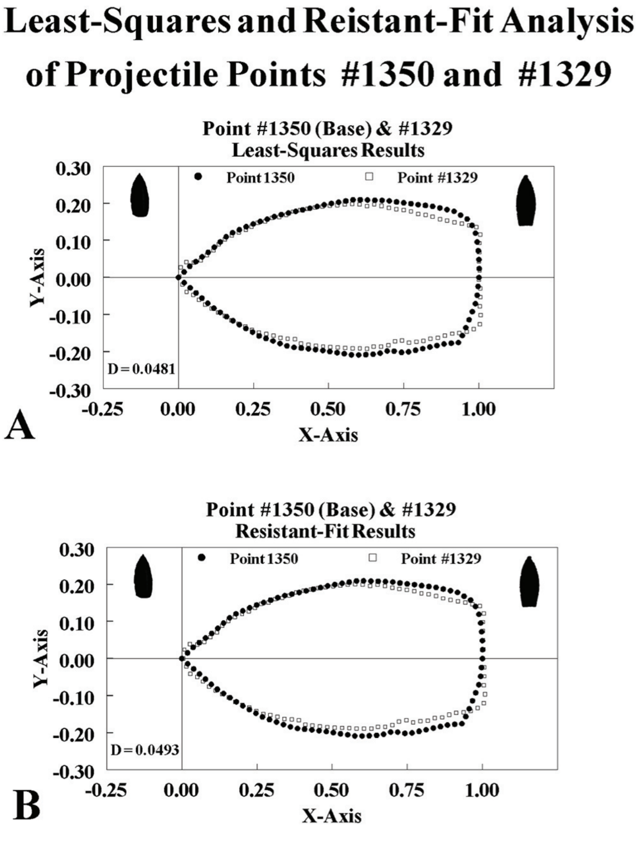

Figure 7. Least-Squares (A) and Resistant-Fit (B) analyses of shape differences between two simple-shaped projectile points (#1350 and #1329). In this case, #1350 is the base specimen and the change is to the shape of #1329. D values are the average distance between the two points; the higher the value, the more different the specimens.

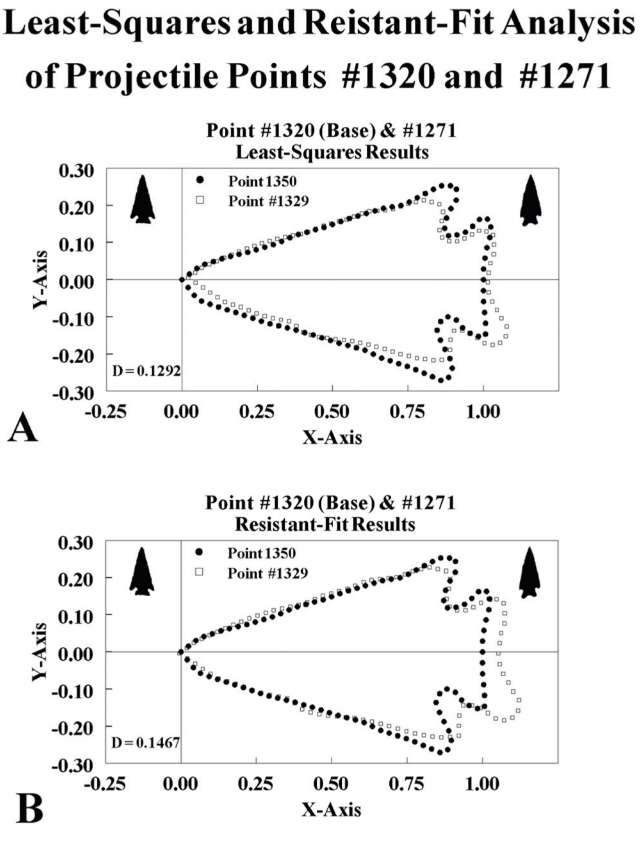

Figure 8. Least-Squares (A) and Resistant-Fit (B) analyses of shape differences between two more complex-shaped projectile points (#1271 and #1320). In this case, #1320 is the base specimen and the change is to the shape of #1271. D values are the average distance between the two points; the higher the value, the more different the specimens.

second step, which is then used for the clustering or ordination. We recommend Non-Metric Multidimensional Scaling for ordinations as it provides the optimum ordination for the number of axes requested. A researcher can see the difference in position between pairs of specimens in this new space (typically two or three dimensions) as well as examine how all specimens are distributed. NMS does not distort the new space as much as classic eigenvector approaches (e.g., Principal Components Analysis) typically do. Generation of such a space, a shape space, defines what evolutionary biologists and paleontologists refer to as a morphospace (e.g., McGhee 1998), which are powerful exploratory methods for studying variation in any objects. In a separate study, we are exploring these possibilities in detail for projectile points.

5 Symmetry and Asymmetry

Finally, it is very easy to examine symmetry in individual projectile points using this approach of data extraction and comparison. Here the degree of symmetry (or asymmetry) is measured as the difference of shape of the two halves of the same projectile point. The two halves, as discussed above, are defined by the baseline that runs from the tip landmark to the mid-base landmark. Symmetry can be studied by somehow superimposing one half on the other. Storing data in a file of the left side mirrored to look like a right side is very easy with our approach, and any of the main methods of comparison discussed herein can be used. However, we favor Shape Coordinates (see Chapman 2002, as well) because we know, *a priori*, that the two base points used for the fit are identical in both forms. We demonstrate such an analysis in Figures 9 and 10. Using the methods outline above, or any of the shape analysis methods developed here, it is easy to calculate a single distance value that documents just how asymmetrical a projectile point is based on the data extracted for it, and these values can be tracked for various samples of projectile points. As above, there is the bonus of being able to calculate an average of the two sides and produce a mean symmetrical projectile point based on the average of the two different sides. This would probably best approximate the shape the person making the point was trying to achieve, within the limits of his abilities.

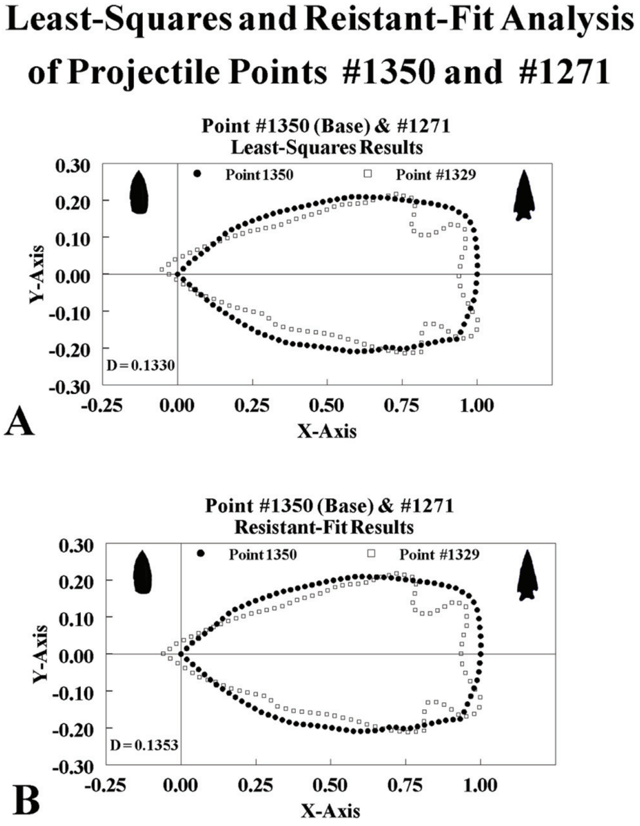

Figure 9. Least-Squares (A) and Resistant-Fit (B) analyses of shape differences between a simple (#1350) and a more complex-shaped projectile points (#1271). In this case, #1350 is the base specimen and the change is to the shape of #1271. D values are the average distance between the two points; the higher the value, the more different the specimens.

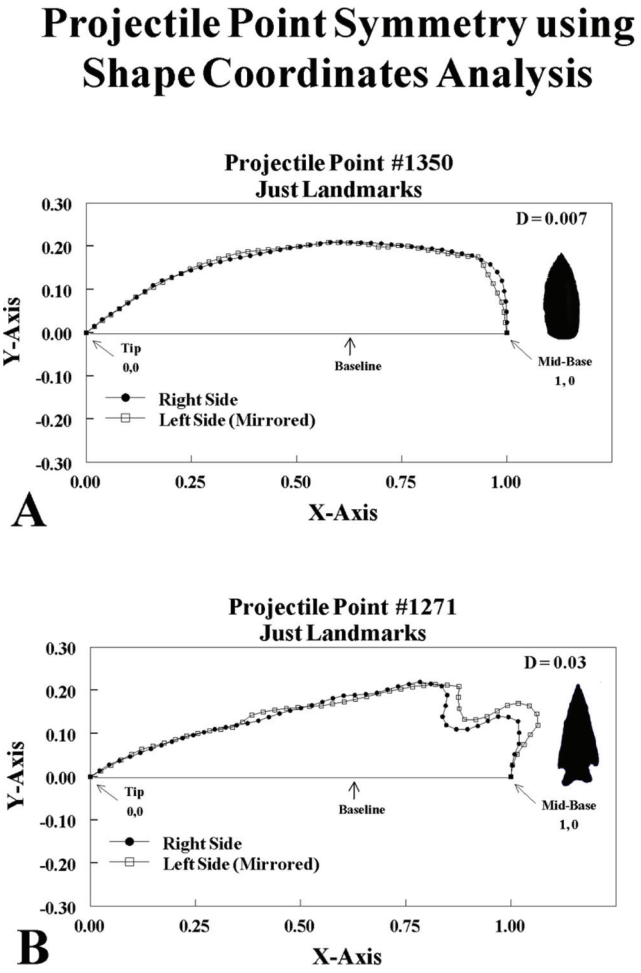

Figure 10. Analysis of symmetry in projectile points using Shape Coordinates. A) Symmetry in simple-morphology point (#1350). B) Symmetry in more complex point (#1271) – note asymmetry towards the base in this latter specimen. Distance values – the level of asymmetry – are given as a single value; the higher the value, the more different the halves.

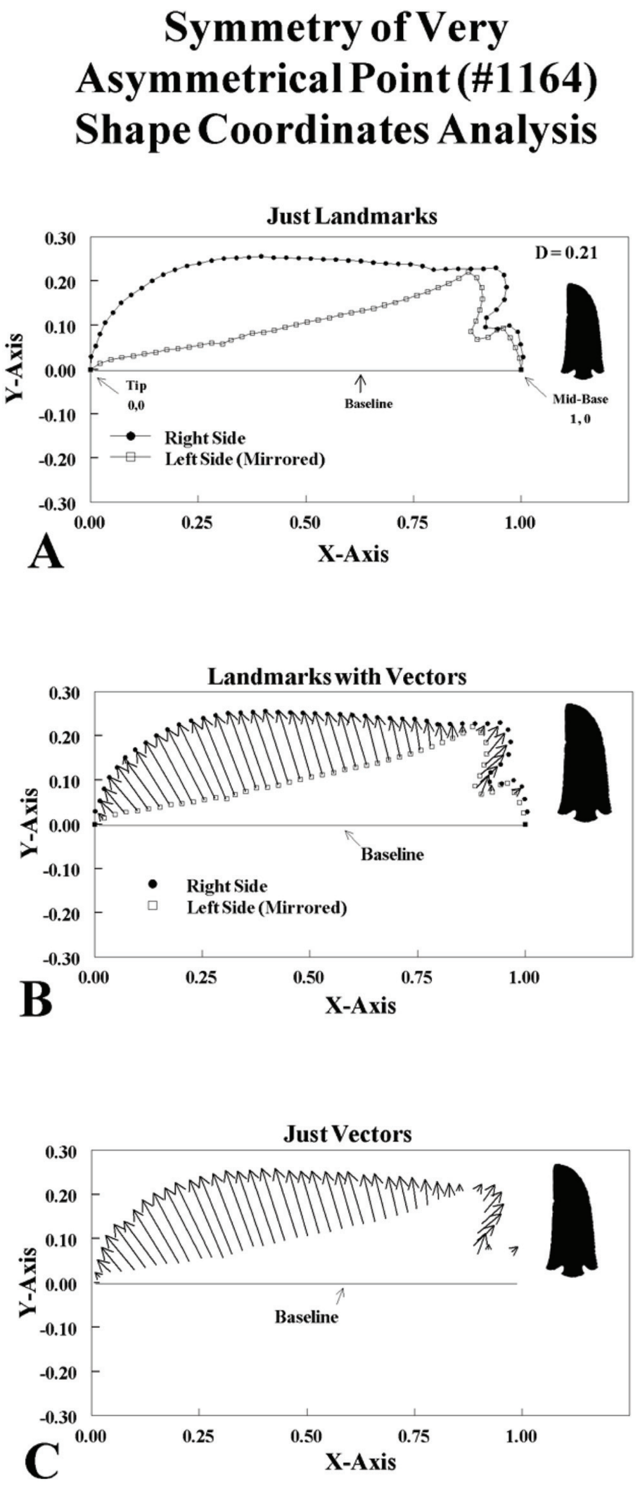

Figure 11. *Analysis of symmetry in a very asymmetrical projectile (#1164) point using Shape Coordinates. The very high distance value and big difference in position of landmarks show this high level of asymmetry. Shown is A) basic comparison of landmark positions, B) the same with vectors included showing positional shift, and C) just the vectors to show the shape difference as expanding surface.*

6 Conclusions

Archaeologists have many options for studying the shape of their projectile points powerfully and rigorously. Essential is the extraction of the shape of these artifacts in a logical and comprehensive way using landmark positions digitized using two-dimensional images of the projectile points. Regardless of the subsequent technique used to analyze the data, measurements and landmarks need to be chosen reflecting reasonable criteria of what is worth measuring. Landmark data should be digitized from projectile points and stored in files for easy manipulation. Using digitizing programs such as *tpsdig*, this process is very rapid and many projectile points can be studied with relatively little effort. Taking images of the projectile points at the start provides a long-term image documentation file for the project, always recommended for research projects now that the process is easy to accomplish. Although many linear measurements can be easily generated using these data, we suggest that landmark data will provide the optimal data for doing the most powerful shape analysis.

The analytical approach to use for subsequent analysis depends on the object of the study. If plain outlines are primarily of interest, then we suggest combining Theta-Rho Analysis and Resistant-Fit Analysis. For studies of symmetry and asymmetry, we recommend Shape Coordinates. For basic shape studies, we suggest that Resistant-Fit methods will provide the optimal results.

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