Traditional and Modern Morphometrics: Review

Geleneksel ve Modern Morfometri

Gökhan OCAKOĞLU,[a]
İlker ERCAN[a]

[a]Department of Biostatistics,
Uludağ University Faculty of Medicine,
Bursa

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Yazışma Adresi/*Correspondence:*
Gökhan OCAKOĞLU
Uludağ University Faculty of Medicine,
Department of Biostatistics, Bursa,
TÜRKİYE/TURKEY
ocakoglu@uludag.edu.tr

ABSTRACT Morphometrics, a branch of morphology, is the study of the size and shape components of biological forms and their variation in the population. In biological and medical sciences, there is a long history of attempts to quantitatively express the diversity of the size and shape of biological forms. On the basis of historical developments in morphometry, we address several questions related to the shape of organs or organisms that are considered in biological and medical studies. In the field of morphometrics, multivariate statistical analysis is used to rigorously address such questions. Historically, these methods have involved the analysis of collections of distances or angles, but recent theoretical, computational, and other advances have shifted the focus of morphometric procedures to the Cartesian coordinates of anatomical points. In recent years, in biology and medicine, the traditional morphometric studies that aim to analyze shape variation have been replaced by modern morphometric studies. In the biological and medical sciences, morphometric methods are frequently preferred for examining the morphologic structures of organs or organisms with regard to diseases or environmental factors. These methods are also preferred for evaluating and classifying the variation of organs or organisms with respect to growth or allometry time dependently. Geometric morphometric methods are more valid than traditional morphometric methods in protecting more morphological information and in permitting analysis of this information.

Key Words: Morphometrics; shape; traditional morphometrics; modern morphometrics

ÖZET Morfometri, morfolojinin bir kolu olup biyolojik forma ait büyüklük ve şekil bileşenleri ile birlikte bunların populasyon içindeki değişimini incelemektedir. Biyoloji ve tıp biliminde, şekil ve büyüklükteki değişimi nicel açıdan açıklama girişimleri oldukça uzun bir geçmişe sahiptir. Morfometri alanında yaşanan tarihsel gelişmeler ışığında, günümüzde biyoloji ve tıp araştırmalarında, organ veya organizmaların şekliyle ilgili birçok soruya yanıt aramaktayız. Morfometri alanında, çok değişkenli istatistiksel analizler bu gibi sorulara yanıt aramak için kullanılmaktadır. Tarihsel olarak, bu yöntemler uzaklıklar ve açılar üzerinde uygulanmakta idi. Ancak son yıllarda morfometrik prosedürler, teorik, hesaplama ve diğer avantajlar açısından geleneksel ölçümleri daha iyi tanımlayabilecek anatomik noktaların kartezyen koordinatları üzerine odaklanmıştır. Son yıllarda biyoloji ve tıp alanlarında şekil varyasyonunu ortaya koymak için kullanılan geleneksel morfometrik çalışmalar yerini modern morfometrik çalışmalara bırakmıştır. Biyoloji veya tıp bilimlerinde organ veya organizmaların morfolojik yapılarını hastalıklar ve çevresel faktörler bakımından etkisini incelemek, zamana bağlı olarak değişimlerini büyüme veya allometri açısından değerlendirmek ve sınıflandırmak amaçlarıyla morfometrik metodların kullanımı sıklıkla tercih edilmektedir. Geometrik morfometrik metodlar, geleneksel morfometrik metodlara göre daha fazla morfolojik bilgiyi koruması ve bunu analiz etmeye olanak vermesi nedeniyle de daha geçerlidir.

Anahtar Kelimeler: Morfometri; şekil; geleneksel morfometri; modern morfometri

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Morphometrics may be defined as an interwoven set of largely statistical procedures for analyzing variability in the size and shape of organs and organisms.[1,2] Morphometrics, a branch of morphology, is the study of the size and shape components of biological forms and their variation in the population.[3] Morphometric analysis requires describable and repeatable terms to represent variation in shape.[1]

In the biological and medical sciences, there is a long history of attempts of the diversity of the size and shape of biological forms. The term "Morphometrics" was coined about 50 years ago by Robert E. Blackith, who entered the field through his engagement with the agricultural problem caused by swarming locusts. Blackith applied multivariate statistical methods to the basic carapace morphology of grasshoppers and was able to predict the development of a swarming phase in a population by pinpointing morphological changes heralding a population explosion. This approach is clearly biological and represents a method of introducing a precise biological model into a statistical analysis.[1]

Blackith noted that the earliest recorded attempts to compare the shapes of animals were made by the school founded by Pythagoras as early as the 5th century BC. Later, the ancient Egyptians embellished burial monuments with figures and scenes, carved in limestone. Gay Robins discloses that some of them retain a discernible pattern of standardized squares, marked in red "chalk", which form a framework for making the carvings. These "props" were intended to be removed from the finished work of art, but this removal did not always take place.[4] Robins noted that there was a reigning system of conventions, presumably determined by a collegium of experts, which defined the proportions of the human body to be used in adorning graves and memorials. The proportions of the limbs were standardized to a given number of squares or a part of a square. Genuine likeness could be reproduced only in the details in the head. The square standards were maintained for hundreds of years.[1]

The skillfully stylized system of the ancient Egyptians for representing human proportions was used many hundreds of years later by Durer and da Vinci, at a time when the system of rules of several thousand years earlier had neither been understood nor suspected. Durer's "Menschliche Proportionen" were little more than the standardized Egyptian squares, though now expressed as lengths in terms of fractions of total height and, at times, affinely transformed. The well-known figure of a man inscribed in a circle attributed to Leonardo da Vinci is a demonstration of the same idea, more succinctly assessed by Durer.[1] The drawing depicts a male figure in two superimposed positions with his arms and legs apart and simultaneously inscribed in a circle and square. The drawing and text are sometimes called the Canon of Proportions or, less often, the Proportions of Man.

On the basis of historical developments in morphometry, we address several questions related to the shape of organs or organisms considered in biological and medical studies: What is the average shape of a bone, organ, or structure in a population? What is the pattern of variation in a population around that average shape? How do groups differ in shape? What is the functional importance of those differences? In the field of morphometrics, multivariate statistical analysis is used to rigorously address such questions. Historically, these methods have involved the analysis of collections of distances or angles, but recent theoretical, computational, and other advances have shifted the focus of morphometric procedures to the Cartesian coordinates of anatomical points.[5]

TRADITIONAL MORPHOMETRICS

In the 1960s and 1970s, biometricians began using the full arsenal of multivariate statistical tools to describe patterns of shape variation within and among groups.[6] This approach is called traditional morphometrics or multivariate morphometrics.[7]

Traditional morphometrics consisted of applying multivariate statistical analyses to sets of traditional measurements between points with biological and anatomical meaning to define shapes called landmarks. The measurements are usually lengths and widths of structures and distances between certain landmarks, which are described as the points of correspondence on each object that matches between and within populations. Sometimes angles and ratios are used.[2,6-10]

The word "traditional" is used here to mean a body of statistical techniques available for morphometric analysis that have been widely applied in the past 30 or 40 years. These techniques include, among others, principal component analysis, principal coordinate analysis, factor analysis, discriminant analysis, canonical variate analysis, and multivariate analysis of variance.[6,8,11]

While multivariate morphometrics combined multivariate statistics and quantitative morphology, several difficulties remained. For instance, many methods of size correction were proposed, but there was little agreement on which method should be used. This issue is important because different size correction methods usually yield slightly different results. Second, the homology of linear distances was difficult to assess because many distances (e.g., maximum width) were not defined by homologous points. Third, the same set of distance measures could be obtained from two different shapes because the location of each distance measurement relative to the other distance measurements was not included in the data. For instance, if the maximum length and maximum width were measured on both an oval and a teardrop, both objects could have the same height and width values, yet they clearly differ in shape. Therefore, one expects the statistical power for distinguishing shapes to be much lower than it should be.[6]

In addition, traditional morphometrics has some severe limitations:

i) it is highly subjective;

ii) it does not preserve information, i.e., it is not possible to recover the original shape out of the morphometric variables used (distances, angles and ratios);

iii) and all variables are used, but only a small amount of the information about shape is contained in a biological object.[7]

In traditional morphometrics, it is not possible to recover the shape of the original form from the usual data matrices of distance measurements, even as an abstract representation. The overall form is neither archived nor used in the analysis. A researcher may know, for example, that several measurements share a common landmark, but this information is not used in the multivariate analyses. As a result, the analyses cannot be expected to be as powerful as they could be if that information were taken into account.[8] Finally, it was not usually possible to generate graphical representations of shape from the linear distances because the geometric relationships among the variables were not preserved (a set of linear distances is usually insufficient to represent the geometry of the original object). Thus, some aspects of shape were lost.[6,7]

Because of these difficulties, researchers explored alternative methods of quantifying and analyzing morphological shape.[6] Considering such circumstances, several scientists tried to put additional emphasis on the biological foundations of morphometric data.[12-14] Their attempt, however, was not sufficiently successful.[7]

MODERN (GEOMETRIC) MORPHOMETRICS

In traditional morphometrics, the analysis of a limited set of linear distances, ratios, or angles frequently fails to represent the complete spatial arrangement of the anatomical points (landmarks) on which the measurements are based.[2,5-7,15] As biological inquiry became more quantitative, a plethora of methods were adopted from modern statistics, some of which (e.g., significance testing) have become mandatory in published analyses of biological data. Multivariate statistics provided an entirely new collection of analytical tools. These methods could analyze entire series of observations to express the essence of form.[16]

Renewed interest in the work of D'Arcy Thompson during the latter half of the 20th century, most notably in the work of Bookstein, steered the focus from multivariate space back to the geometry of biological form. The term geometric morphometrics was first used by Corti.[5,7,16,17]

Using landmark coordinates allows the concise encoding of all the information in any subset of distances or angles between them. This complete retention of geometric information from data collection through analysis and visualization is the reason that coordinate-based approaches are generally referred to as geometric morphometrics.[5]

In geometric morphometrics, shape is defined as all the geometrical information that remains when location, scale and rotational effects are filtered out from an object.[2,9] Shape is a certain entity. Configuration, which has the encoded relationships among the points, cannot be separated into parts such as length or width. The figure for the phenotype is the most conspicuous feature, and in systematic studies with different organisms, the taxonomic category has become one of the most commonly used features. In geometric morphometrics, biological shape is defined via transformation of the original shape, which is selected as a reference shape. Thompson proposed the idea in 1942, although the method was attractive and promising for analyzing biological shape, the method did not have an analytical procedure. With the advent of computers, applications for morphometric analysis based on Thompson‘s idea became possible.

Rohfl and Marcus characterized the geometric morphometrics approach with the following points:[8]

Data are recorded to represent the geometry of the structure being studied. These data are in the form of two-dimensional (2-D) or three-dimensional (3-D) coordinates of morphological landmark points. The coordinates are much more useful than traditional measurements, and of course, the usual distance measurements can be computed from the coordinates. One can check adequacy of the points in covering the structures of interest by visually evaluating a graphical display of the landmarks. Emphasis is given to recording homologous landmarks, since this approach allows a more complete biological interpretation of the results. Rather than merely reporting that the shape has changed, one can report that certain structures have moved relative to others. When it is not possible to find such landmarks, one is forced to use pseudo-landmarks, i.e., points located at ends of structures, points at extremes of curvature of the outline of a structure, or arbitrary points along an outline. If one is interested in the overall outline or surface of a structure (or merely parts of a structure between landmarks in 2-D or a surface in 3-D), then this information can be expressed by a sequence of digitized points along the outline or over a surface. Such approaches have been used for many years.

The geometrical relationships among the landmarks are not inherent in the raw coordinates themselves. The relationship among the points is expressed by fitting an appropriate function to them in either 2-D or 3-D. The estimates of the parameters of the fitted function can then be used as variables in standard univariate and multivariate statistical analyses.

Within geometric morphometrics, comparisons between organic forms are addressed by collecting information concerning the location of discrete points, called landmarks. A set of homologous points, landmarks, provides information on the biological form, given that the points are distributed homogeneously on the organism and possess some biological meaning.[9] Data that represent the geometry of the morphological structure were of particular interest, and methods to analyze such data were developed, including methods for both outline and landmark data. Concurrent with these advances, David Kendall and other statisticians developed a rigorous statistical theory for shape analysis that allowed the combined use of multivariate statistical methods and methods for direct visualization in biological form. Bookstein referred to this as the “morphometric synthesis”.[18]

CONCLUSION

Morphometric researches are frequently used in comparison of biological structures.[19] In recent years, in biology and medicine, the traditional morphometric studies that aim to analyze shape variations have been replaced by geometric morpho- metric studies. Two-group comparison, asymmetry, growth and allometry studies are examples of the most used statistical shape analysis applications.[20-26]

In the biological and medical sciences, morphometric methods are frequently preferred for examining the morphologic structures of organs or organisms with regard to diseases or environmental factors. These methods are also preferred for evaluating and classifying the variation of organs or organisms with respect to growth or allometry time dependently. Geometric morphometric methods are more valid than traditional morphometric methods in protecting more morphological information and in permitting analysis of this information.

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