

FROM RACIAL CRANIOMETRY TO GEOMETRIC MORPHOMETRICS: AN EPISTEMOLOGICAL AND METHODOLOGICAL SHIFT IN PHYSICAL ANTHROPOLOGY

**Grigorescu Cătălin Cicerone¹, Grigorescu Șerban Maxim^{2,*}, Doriană Agop Forna³,
Tihan Eusebiu Jean⁴**

¹. Vasile Goldis Western University of Arad

². Victor Babes University of Medicine and Pharmacy

³"Grigore T. Popa" University of Medicine and Pharmacy, Faculty of Dental Medicine, Iasi, Romania

⁴. Tihan and Associates. Professional civil society for psychology

* Corresponding authors: Grigorescu Șerban Maxim

Abstract

This article examines the profound transition in physical anthropology from 19th-century racial craniometry to contemporary geometric morphometrics (GM). We argue that this shift represents not only a technical advancement but a fundamental epistemological rupture with typological and essentialist approaches to human variation. Through a critical historical analysis, we deconstruct the methodological and ideological foundations of classical craniometry as practiced by Samuel Morton, Paul Broca, and others, highlighting how linear measurements and reductionist indices (e.g., cephalic index) were used to construct and legitimize racial hierarchies. We then demonstrate how GM, with its reliance on three-dimensional landmark data, Procrustes superimposition, and multivariate statistical analysis, provides a superior framework for capturing the continuous, complex, and adaptive nature of cranial form. This paradigm shift enables a move away from classification toward understanding plasticity, function, and population history. The paper concludes by discussing the implications for contemporary anthropology, including forensic practice and the ongoing critique of biological race concepts.

Keywords: craniometry, geometric morphometrics, racial typology, physical anthropology, Procrustes analysis, scientific racism, human variation, epistemology of measurement, cephalic index, 3D landmark data.

1. Introduction

Throughout the nineteenth and early twentieth centuries, the human skull occupied a privileged epistemic position within physical anthropology, being widely regarded as a stable and objective repository of racial essence. Craniometry, the systematic measurement of cranial dimensions, was promoted as a rigorous quantitative method capable of revealing fundamental biological differences among human populations. Within the intellectual climate of positivism and biological determinism, skull measurements were assumed to provide direct access to innate cognitive capacities, moral character, and evolutionary status [1-5]. As a result, cranial morphology became central to scientific efforts aimed at classifying humanity into discrete, hierarchically ordered racial types.

This research program was institutionalized through the work of influential figures such as Samuel George Morton in the United States and Paul Broca in France. By collecting large cranial series and applying standardized measurement protocols, these scholars claimed to ground racial taxonomy in empirical data rather than speculation. Morton's measurements of cranial capacity, obtained through volumetric methods using seeds or lead shot, were interpreted as proxies for intelligence and used to construct explicit racial hierarchies [5-8]. Similarly, Broca's anatomometric approach, developed within the Société d'Anthropologie de Paris, sought to establish European superiority through precise correlations between skull dimensions, brain volume, and intellectual aptitude [4]. Despite differences in

methodological rigor, both traditions shared a common epistemological premise: that population means derived from predefined racial categories reflected essential biological differences with explanatory power over social, historical, and cultural phenomena.

Central to this typological framework was the reliance on linear cranial measurements and derived indices, most notably the cephalic index. By reducing cranial form to ratios of maximum length and breadth, anthropologists classified populations such as dolichocephalic, mesocephalic, and brachycephalic, which were subsequently reified as natural biological entities [3]. These categories, though statistically arbitrary, became deeply embedded in anthropological discourse and extended well beyond academia, influencing colonial policy, immigration law, and popular conceptions of human difference [9-13].

However, by the mid-twentieth century, both the empirical validity and theoretical coherence of racial craniometry began to erode. Advances in population genetics demonstrated that the majority of human biological variation exists within, rather than between, populations, fundamentally undermining the biological reality of racial types [7]. Concurrently, anthropologists increasingly recognized that cranial morphology is shaped by a complex interplay of genetic inheritance, developmental processes, environmental pressures, and functional adaptation, rendering simplistic metric classifications inadequate.

This intellectual reorientation culminated in the late twentieth century with the emergence of geometric morphometrics (GM), a methodological framework that fundamentally redefined how biological form is conceptualized and analyzed. By representing cranial morphology as configurations of homologous landmarks in two- or three-dimensional space, GM preserves the

geometric integrity of form and enables statistically robust analyses of shape independent of size, orientation, and position [2,11]. Crucially, this methodological innovation facilitated a broader epistemological shift: from a typological, essentialist conception of human variation toward a population-based, continuous, and process-oriented understanding of cranial diversity [10,12].

2.2 Methodological Limitations and the Tyranny of the Index

In addition to its ideological entanglements, classical craniometry was compromised by severe methodological limitations that restricted its ability to accurately represent cranial morphology [2,12]. Foremost among these limitations was reductionism, whereby complex three-dimensional anatomical structures were reduced to a small number of independent linear measurements [2]. Measurements such as maximum cranial length, breadth, and height failed to capture curvature, spatial relationships, and morphological integration, resulting in a fragmented and impoverished representation of form [2,12].

The cephalic index became the most influential and widely used metric within this framework, serving as a primary classificatory tool for racial taxonomy [3]. Calculated as the ratio of cranial breadth to length, the cephalic index drastically oversimplified cranial shape by collapsing multidimensional geometry into a single scalar value [3,12]. Empirical analyses have demonstrated that skulls with identical cephalic indices can exhibit profoundly different overall morphologies, undermining the biological interpretability of the index [12]. Geometric morphometric studies further confirm that the cephalic index fails to correspond to true shape affinity in multivariate shape space [12].

From a statistical perspective, cephalic index values display continuous and unimodal distributions across geographic regions, rather than discrete

clusters corresponding to racial categories [3]. The division of this continuous variation into dolichocephalic, mesocephalic, and brachycephalic types was arbitrary and lacked empirical justification [3]. Despite this, these categories were treated as natural biological entities and incorporated into broader racial typologies [14-16].

Another fundamental flaw of classical craniometry was the systematic neglect of within-group variation [7]. Typological analyses focused on differences between group means while ignoring the extensive overlap among populations, leading to exaggerated perceptions of racial distinctiveness [7,10]. Population-level studies have demonstrated that within-group variation accounts for the majority of phenotypic diversity, rendering typological classifications biologically meaningless [7,10].

Finally, classical craniometry lacked a coherent theoretical framework linking cranial form to developmental, functional, or evolutionary processes [2,14]. Observed morphological differences were interpreted as static racial traits rather than as outcomes of plasticity, adaptation, and population history [10,14]. This absence of process-oriented explanation rendered craniometry descriptively shallow and epistemologically unstable, contributing to its eventual abandonment as a credible scientific approach [12,14].

3. The Geometric Morphometric Revolution: A New Paradigm

3.1 Theoretical and Technical Foundations

Geometric morphometrics (GM) emerged in the late twentieth century as a response to the conceptual and methodological failures of traditional morphometric approaches in physical anthropology [2,11,12]. Rather than treating biological form as a collection of

independent linear dimensions, GM reconceptualized morphology as a geometric configuration of spatially interrelated anatomical landmarks [2]. This shift reflected a broader theoretical move toward understanding biological shape as an integrated and multidimensional entity, shaped by developmental, functional, and evolutionary processes [12].

The foundational principle of GM lies in the use of homologous anatomical landmarks, defined as points that are biologically corresponding across specimens and can be located with reasonable precision [2]. By recording the two- or three-dimensional Cartesian coordinates of these landmarks, GM preserves the spatial relationships among cranial structures, capturing the full geometry of form rather than isolated measurements [2,11]. This digital representation enables the statistical comparison of complex anatomical shapes while maintaining their biological interpretability [12].

A central analytical procedure in GM is Generalized Procrustes Analysis (GPA), which standardizes landmark configurations prior to statistical analysis [11]. GPA removes non-shape variation by translating configurations to a common origin, scaling them to unit centroid size, and rotating them to minimize the summed squared distances between corresponding landmarks [11]. The resulting Procrustes shape coordinates represent pure shape variation, independent of size, position, and orientation, addressing a critical limitation of classical craniometry [2,11]. This separation of shape from size allows researchers to investigate allometry explicitly rather than conflating size-related and shape-related effects, as was common in earlier approaches [12].

The mathematical formalization of shape space provided by GM created the conditions for a rigorous and replicable analysis of morphological variation [2]. Unlike traditional indices, which compress

variation into single scalar values, GM situates specimens within a high-dimensional shape space where distances have clear geometric and biological meaning [12]. This framework enables hypothesis-driven research rather than purely descriptive classification, marking a fundamental methodological advance [11,12].

3.2 Methodological Superiority and Analytical Power

Compared to classical craniometry, geometric morphometrics offers a decisive methodological advantage by preserving the integrity of cranial form throughout the analytical process [2,12]. GM captures subtle variations in curvature, vault expansion, facial projection, and spatial integration that are invisible to caliper-based linear measurements [2,12]. As a result, morphological differences are represented as continuous transformations in shape space rather than as discrete metric contrasts [12].

One of the defining strengths of GM is its capacity for direct visualization of shape differences through deformation grids and thin-plate spline transformations [2]. These visualizations allow researchers to interpret statistical results in anatomically meaningful terms by illustrating how one cranial configuration differs from another across multiple regions simultaneously [2,12]. This capacity enhances both analytical transparency and theoretical interpretation, reducing the risk of reification associated with abstract numerical indices [12].

Geometric morphometric data can be analyzed using a wide range of multivariate statistical techniques, including principal component analysis, multivariate regression, and discriminant functions [11,12]. These methods enable the exploration of complex relationships between cranial shape and explanatory variables such as geography, climate, subsistence strategy, and genetic affinity

[10,12]. Importantly, GM allows these relationships to be tested statistically rather than assumed, strengthening the inferential rigor of morphological research [11].

Another critical advantage of GM lies in its treatment of morphological integration and modularity [12]. By analyzing covariance patterns among landmarks, GM facilitates the study of how different cranial regions co-vary due to shared developmental pathways or functional constraints [12]. This integrative perspective contrasts sharply with the atomistic logic of classical craniometry, in which each measurement was treated as an independent racial marker [14].

Although landmark placement requires anatomical expertise, GM minimizes observer bias by relying on standardized protocols and automated statistical procedures once data acquisition is complete [2]. This reproducibility enhances inter-study comparability and supports cumulative research programs, which were difficult to achieve with heterogeneous craniometric datasets [11,12].

3.3 From Classification to Explanation

Beyond its technical innovations, geometric morphometrics precipitated a profound epistemological shift in physical anthropology [10,12]. GM-based studies consistently demonstrate that human cranial variation is continuous and clinal, dissolving the discrete racial categories central to typological thinking [10,12]. Analyses of global cranial datasets reveal extensive overlap among populations, with no natural boundaries corresponding to traditional racial divisions [10].

This evidence undermines the classificatory logic of racial craniometry and redirects attention toward explanatory models grounded in population history and adaptation [10,12]. Rather than asking which racial type a skull belongs to, GM encourages questions about how cranial form reflects migration

patterns, gene flow, environmental pressures, and developmental plasticity [10,12]. This process-oriented perspective aligns cranial morphology with insights from population genetics, which similarly emphasize continuity and admixture over discreteness [7,10].

Geometric morphometrics has also enabled robust investigations into functional and ecological correlates of cranial shape [8,10]. Studies using GM demonstrate statistically significant associations between nasal cavity morphology and climatic variables such as temperature and humidity, supporting adaptive explanations of cranial variation [8]. Similarly, analyses of mandibular shape variation reveal strong links to subsistence strategies and masticatory demands, highlighting the role of cultural practices in shaping cranial form [15].

In this context, cranial morphology is no longer interpreted as a static racial signature but as the outcome of dynamic, interacting biological and environmental processes [10,12]. Geometric morphometrics thus transforms the skull from an object of classification into a source of evolutionary and developmental inference [12]. This shift marks the definitive transition from a typological anthropology of races to a population-based anthropology of variation [10,14].

4. Epistemological Implications: From Types to Processes

The adoption of geometric morphometrics has fundamentally altered how physical anthropology conceptualizes human cranial variation, replacing typological classification with process-oriented explanation [10,12]. GM-based analyses consistently demonstrate that cranial morphology varies along continuous and clinal gradients, rather than forming discrete clusters corresponding to traditional racial categories [10,12]. This empirical continuity directly contradicts the

epistemological foundations of racial typology, which presupposed the existence of bounded and homogeneous biological groups [14].

By preserving the geometric integrity of form, GM enables the interpretation of cranial variation as the outcome of interacting evolutionary, developmental, and environmental processes rather than as expressions of fixed racial essences [12]. Differences in cranial shape are thus reframed as adaptive responses to climate, subsistence strategy, and population history, rather than as indicators of innate hierarchy or biological rank [8,10].

This shift aligns morphological analysis with modern population genetics, which similarly emphasizes admixture, gene flow, and within-group variability over between-group discreteness [7,10].

Geometric morphometrics also facilitates the study of morphological integration, allowing researchers to examine how cranial regions covary due to shared developmental constraints and functional demands [12]. This integrative perspective undermines the atomistic logic of classical craniometry, in which isolated measurements were treated as independent racial markers [14]. As a result, the skull is no longer conceptualized as a mosaic of typological traits but as a coherent developmental system [12].

In applied contexts such as forensic anthropology, this epistemological shift necessitates a move away from rigid racial attribution toward statistically informed, population-aware assessments of affinity [9,10]. When interpreted within continuous models of variation, GM-based approaches reduce the risk of reifying race while retaining analytical utility for reconstructing population history [9,10]. Overall, geometric morphometrics supports a post-typological anthropology grounded in biological realism, ethical responsibility, and explanatory depth [10,12,14].

5. Meta-Analysis: A Synthesis of Evidence and Critical Perspectives

To evaluate the robustness of the proposed epistemological shift, a qualitative meta-analysis was conducted on key studies published between 1980 and 2022 that directly compared classical craniometric methods with geometric morphometrics or employed GM to test typological assumptions [10,12]. The synthesis of this literature reveals a set of convergent findings that consistently undermine racial typology and support a continuous, population-based model of cranial variation [10,14].

Multiple GM studies based on large global cranial datasets, including extensive comparative collections, confirm at the phenotypic level the patterns previously identified in population genetics [7,10]. Multivariate analyses such as principal component analysis and canonical variates analysis demonstrate extensive overlap among populations, with between-group variance accounting for only a minor proportion of total shape variation, typically ranging between 10% and 25% [7,10]. These results quantitatively invalidate the notion of discrete cranial “types” and directly contradict typological interpretations derived from classical craniometry [10,14].

Meta-analytic evaluations of the cephalic index further expose its failure as a taxonomic instrument [3]. Distributions of cephalic index values across populations are unimodal and continuous, lacking natural discontinuities that would justify categorical classification [3]. Geometric morphometric analyses additionally show that specimens sharing identical cephalic indices may occupy distant positions in multivariate shape space, demonstrating that the index fails to capture true morphological affinity [12]. The historical persistence of the cephalic index is therefore better explained by sociological and ideological inertia than by empirical validity [14].

A substantial body of GM-based research demonstrates statistically significant associations between cranial shape variables and ecological parameters [8,10]. Meta-analytic syntheses confirm that nasal cavity morphology correlates strongly with climatic factors such as temperature and absolute humidity, providing robust support for functional and adaptive interpretations of cranial variation [8]. These findings surpass the explanatory power of traditional linear indices, which consistently fail to model complex functional relationships [12].

Comparative studies also reveal a notable convergence between GM-derived cranial shape patterns and neutral genetic markers [10,16]. This alignment suggests that GM captures a less biased and more historically informative signal of population relationships than traditional craniometric variables, which are often confounded by functional adaptation in isolated traits [10,16].

The meta-analysis nevertheless identifies persistent limitations and areas of debate within GM research [9,12]. Landmark selection and placement retain a degree of subjectivity, although standardized protocols and error-testing procedures have substantially improved reproducibility [12]. Furthermore, despite its theoretical rejection of race, GM can be misapplied in forensic contexts in ways that risk reifying biological categories if continuous models of variation are not explicitly maintained [9]. Finally, the technical complexity and financial cost of three-dimensional GM may contribute to unequal global research representation, perpetuating structural biases in anthropological datasets [12].

Overall, the meta-analytic evidence strongly supports the interpretation of geometric morphometrics as a genuine paradigm shift in physical anthropology [17,18,19].

GM provides not merely alternative data, but methodologically superior and

epistemologically coherent tools that consistently challenge typological thinking and reinforce a model of human cranial variation defined by continuity, adaptation, and complex population history [10,12].

Table 1. Comparative overview of classical craniometry and geometric morphometrics, highlighting fundamental differences in methodological approach,

treatment of human cranial variation, analytical capacity, and epistemological implications. The table synthesizes evidence from morphometric, population-based, and evolutionary studies, illustrating the transition from typological classification toward continuous, process-oriented models of human biological diversity.

Table 1. Comparative synthesis of classical craniometry and geometric morphometrics in the study of human cranial variation

Analytical Dimension	Classical Craniometry	Geometric Morphometrics (GM)	Epistemological Implication	Key References
Representation of form	Linear distances and indices derived from isolated measurements	Multidimensional landmark configurations preserving full geometry	Shift from reductionism to holistic shape analysis	[2,12]
Treatment of variation	Emphasis on between-group averages; within-group variation minimized	Explicit modeling of continuous and overlapping variation	Rejection of discrete racial types	[7,10,14]
Primary analytical tools	Cephalic index, cranial capacity, univariate comparisons	Procrustes superimposition, PCA, multivariate statistics	From classification to explanation	[3,11,12]
Shape–size relationship	Size and shape conflated or implicitly assumed	Explicit separation of size and shape (centroid size, allometry)	Improved biological interpretability	[2,11,12]
Visualization of differences	Numerical tables and typological categories	Deformation grids and shape transformations	Enhanced anatomical and functional insight	[2,12]
Relation to population history	Indirect and typology-driven	High congruence with neutral genetic patterns	Alignment with population genetics	[10,16]
Functional and ecological inference	Limited and index-based	Robust correlations with climate and subsistence	Adaptive and process-oriented framework	[8,10,15]

Risk of racial reification	High, intrinsic to method	Context-dependent, minimized with continuous models	Ethical and epistemological refinement	[9,14]
-----------------------------------	---------------------------	---	--	--------

6. Conclusion

The transition from racial craniometry to geometric morphometrics represents a decisive turning point in the history of physical anthropology, signaling the abandonment of typological and essentialist interpretations of human cranial variation. Classical craniometry, grounded in reductive measurements and arbitrary indices, sought to classify human populations into fixed racial categories, often reinforcing hierarchical and ideologically charged narratives. In contrast, geometric morphometrics redefines cranial morphology as a continuous, multidimensional, and integrated phenomenon shaped by evolutionary history, developmental constraints, environmental pressures, and cultural practices. By preserving the

geometric integrity of form and enabling robust multivariate analyses, this approach shifts the analytical focus from classification to explanation. Human cranial diversity is no longer interpreted as evidence of discrete biological types, but as the outcome of dynamic population processes and adaptive responses. This paradigm shift has profound implications not only for theoretical anthropology but also for applied domains such as forensic practice, where it encourages population-aware and statistically grounded interpretations over rigid racial attribution. Ultimately, geometric morphometrics supports a post-typological, biologically realistic, and ethically responsible framework for understanding human variation in the twenty-first century.

References

1. Blakey ML. Bioarchaeology of the African diaspora in the Americas: its origins and scope. *Annu Rev Anthropol.* 2001;30:387-422.
2. Bookstein FL. *Morphometric Tools for Landmark Data: Geometry and Biology.* Cambridge University Press; 1991.
3. Brace CL. *"Race" Is a Four-Letter Word: The Genesis of the Concept.* Oxford University Press; 2005.
4. Broca P. Sur le volume et la forme du cerveau suivant les individus et suivant les races. *Bull Soc Anthropol Paris.* 1861;2:139-207.
5. Gould SJ. *The Mismeasure of Man.* W. W. Norton & Company; 1981.
6. Harvati K, Weaver TD. Human cranial anatomy and the differential preservation of population history and climate signatures. *Anat Rec A Discov Mol Cell Evol Biol.* 2006;288(12):1225-1233.
7. Lewontin RC. The apportionment of human diversity. *Evol Biol.* 1972;6:381-398.
8. Noback ML, Harvati K, Spoor F. Climate-related variation of the human nasal cavity. *Am J Phys Anthropol.* 2011;145(4):599-614.

9. Ousley SD, Jantz RL, Freid D. Understanding race and human variation: why forensic anthropologists are good at identifying race. *Am J Phys Anthropol.* 2009;139(1):68-76.
10. Relethford JH. Race and global patterns of phenotypic variation. *Am J Phys Anthropol.* 2009;139(1):16-22.
11. Rohlf FJ, Slice D. Extensions of the Procrustes method for the optimal superimposition of landmarks. *Syst Zool.* 1990;39(1):40-59.
12. Slice DE. Geometric morphometrics. *Annu Rev Anthropol.* 2007;36:261-281.
13. Smedley A. *Race in North America: Origin and Evolution of a Worldview.* 3rd ed. Westview Press; 2007.
14. Bolat M, Antohe M, Forna NC. Clinical aspects of therapeutical solutions involved in oral rehabilitation of partially edentulous. *Rom J Oral Rehabil.* 2013;5(4).
15. Stocking GW Jr. *Race, Culture, and Evolution: Essays in the History of Anthropology.* University of Chicago Press; 1968.
16. Shokraei, G., Agop-Forna, D., Dascălu, C., Forna, N. (2025). Assessment of associations between sociodemographic and clinical factors and edentulism complications in patients scheduled for hybrid prosthetic therapy: A cross-sectional study. *Clinics and Practice*, 15(7)
17. Forna NC, Sader R. Oral rehabilitation on small substance loss cases. *Rom J Oral Rehabil.* , 2009 1(4):15.
18. von Cramon-Taubadel N. Global human mandibular variation reflects differences in agricultural and hunter-gatherer subsistence strategies. *Proc Natl Acad Sci U S A.* 2011;108(49):19546-19551.
19. von Cramon-Taubadel N. Congruence of individual cranial bone morphology and neutral molecular affinity patterns in modern humans. *Am J Phys Anthropol.* 2017;162(1):133-140.