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Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology

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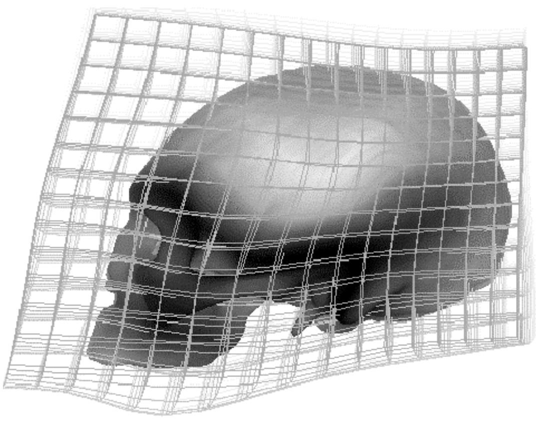

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THE USE OF 3D LASER SCANNING TECHNIQUES FOR THE MORPHOMETRIC ANALYSIS OF HUMAN FACIAL SHAPE VARIATION

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Résumé: Cette étude a pour objectif de montrer d'intérêt de l'utilisation du scanner à laser pour l'analyse de la morphologie crâniofaciale chez l'homme actuel et fossile. Nous présentons un protocole de mesure permettant l'acquisition de données surfaciques que nous avons appliqué à l'étude de possibles adaptations crâniofaciales au froid dont nous proposerons également une modélisation. Jusqu'à présent, nos résultats sont compatibles avec le concept d'une voûte crânienne fonctionnant comme un radiateur dont le rapport volume-surface varie conformément aux prédictions dérivées de la règle de Bergmann., tant pour les hommes actuels que fossiles. La surface relative de la face varie à l'opposé des prédictions dérivées de la règle d'Allen. Ceci nous amène à suggérer que la morphologie faciale observée chez les Inuits ou les Néandertaliens résulte de facteurs qui ne sont pas en rapport avec des conditions climatiques.

Abstract: The present study explores the application of laser surface scanning to the analysis of craniofacial morphology in living and fossil humans. We present a measurement procedure for the assessment of relative surface areas and apply it to examine possible craniofacial cold adaptations, for which we also present a theoretical model. In it's current state of progress, our analysis supports the idea that the braincase functions as a radiator, and that its volume-to-surface area ratio varies consistently with predictions derived from Bergmann's rule, for living human populations as well as for Neandertals. The relative surface area of the face is found to vary opposite to predictions derived from Allen's rule. This suggests that the facial morphology seen among Inuit or Neandertal populations is driven by factors that are mainly unrelated to climatic conditions.

INTRODUCTION

The morphology of the human facial skeleton has long been of interest to anthropologists and other researchers. Its particular architecture seen in Neandertals has, for decades, initiated numerous attempts to seek functional interpretations in terms of either masticatory stress or cold adaptation. Several authors have also tried to identify similar cause-and-effect relationships among human populations living under harsh climatic conditions, such as Eskimos and Fueguians.

The continuing rise of 3D imaging and measuring techniques and their application in anthropology provide new possibilities of studying functional morphology (e.g. Lyons et al. 2000). The purpose of this paper is to explore the use of 3D laser surface scanning techniques for the quantitative analysis of the human craniofacial skeleton. A special emphasis is put on morphometric aspects of cold adaptation. In the following, we propose a measurement protocol for the assessment of volume/area ratios in order to test whether the skull exhibits features that are consistent with hypothesized thermoregulatory constraints. We will also present preliminary results of this approach.

REVISITING COLD ADAPTATION

The assumption that the human face may show signs of cold adaptation in certain populations, like Neandertals and or Inuit, goes back to Hrdlièka (1910). He suggested that a narrow nasal aperture, as seen in Inuit, may increase temperature and humidity of the inspired air, an idea that was later supported by Wolpoff (1968) and Hylander (1977). The apparent contradiction with the proposed cold adaptation of the relatively broad Neandertal nose has been discussed by Hylander (1977).

Coon (1950) proposed that facial flatness and protruding malars, another feature considered to be common among Inuit, is functionally adapted to cold temperatures. This hypothesis refers implicitly to the notion that relative surface area ought to be rather small and therefore less exposed under cold climatic conditions. However, the idea was rejected by Steegman (1970, 1972) on experimental grounds. He showed that the temperature measured at the surface of the malar bone is not significantly different from that at any other facial region when exposed to cold. In the 1970 study he observed that "mongoloid" malars are larger, and that better warming occurs in the malar in Europeans rather than in Asians. In the 1972 study, he observed a temperature decrease to be correlated with malar protrusion: A protruding malar (a "mongoloid" feature) becomes colder, as it is more exposed. Regarding the thermoregulation of the braincase, Steegman (1970) suggested that the relative surface area should be smaller in cold adapted populations in order to reduce heat loss.

Finally, in a somewhat different approach to thermoregulation, Dean's model (1988) assumes that large nasal cavities and faces are advantageous for exposure to hot climates. Following this model one would expect that, inversely, small nasal cavities and small faces have an adaptive advantage in regions of cold climate.

RATIONALE

Summarizing the existing models on thermoregulation leads to the conclusion that all of them cannot be true, as they are in part contradictory: We feel that it is most reasonable to assume that any thermoregulatory process, if observable in the exoskeleton, would have to follow the rules of climatic adaptation according to Bergmann and Allen (Rensch, 1936). As discussed by Ruff (1991), the phenomenon that generally underlies cold adaptation is that an organism changes it's surface area to volume ratio in order to reduce the chances of heat loss. Therefore, the appropriate theoretical model for craniofacial cold adaptations is the following:

1. The surface area of the braincase relative to brain volume is reduced in populations exposed to cold temperatures (Bergmann's rule).
2. The surface area of the face and/or the zygomatic bone has the properties of an extremity. Its surface area relative to the skull is reduced (Allen's rule)

MATERIAL

Data were sampled from populations representing 11 different geographic regions, covering a wide range of climatic conditions (table 1). All specimens are part of the collections of the AMNH. For each population, 3 adult individuals of both sexes were sampled, yielding a total of 66 individuals. Only individuals with an erupted M3 or a fused sphenobasilar synchondrosis were considered. The sex of each individual was taken from records for most of the cases and, if not available, estimated by one of us (MF) on the basis of general cranial features. Information about the specimens' geographic origin was available from Museum records, although for some individuals this information was rather vague. For instance, all Australian skulls are reportedly from "South Australia", a province that extends roughly over 10 degrees of latitude.

In addition, mean annual temperatures were recorded for the geographic origin of each sample according to meteorological observations available online. The recorded temperatures vary from -25°C to +30°C.

We also included a series of fossil hominins, mainly Neandertals, whose facial skeletons were sufficiently well preserved or assessable through reconstruction. These comprise: La Ferrassie, La Chapelle aux Saints, Guattari 1, Shanidar 1, Amud 1, Kabwe, and Steinheim. All fossil data were obtained from high quality casts in the Department of Anthropology of the AMNH.

LASER SCANNING TECHNIQUE

The data were acquired with a Cyberware 3030 RGB, a table-sized 3D laser scanner with optional color registration. The device yields a complete 3D virtual model of the visible surface of a given object. The accuracy of the obtained data ranges between 0.25 and 0.5 mm (Frieß et al. in press).

A Laser scanner projects a light beam whose reflection from a moving object is captured by a CCD. With the device used for this study, the object is placed on a turntable that performs a linear movement during which the laser beam projects a single line onto the surface, thereby producing a scanning profile of the object from one specific viewpoint (fig. 1). Rotating the turntable and repeating the scan yields a series of profiles from a number of viewpoints determined by the user, which therefore allow a computational reconstruction of the object via triangulation. Subsequent manual editing steps are required to ascertain clean raw data sets.

Once the specimen is completely scanned and the raw data have been manually cleaned, the software (headus.com) can be used to obtain linear measurements as well as area and volume of a surface.

Following the theoretical considerations (elaborated above) we measured the surface area of the braincase, the facial skeleton, and the zygomatic bone for each cranium. In addition, we measured the cranial capacity of each individual using millet seeds.

The area measurements were defined as follows (fig. 2):

Braincase: The area of the neurocranium most likely to be exposed to external temperature while not being covered by the neck. This includes the complete external frontal (exluding the roof of the orbit) and parietal bones, the squamous portion of the occipital and the temporal (above the zygomatic arch)

Table 1 - Mean annual temperatures recorded for each geographic origin of the sample

Geographic origin	N	Mean annual temperature
Greenland "Eskimos" Smith Sound	6	-9.6
Alaska "Eskimos" Point Barrow	6	-12.6
Mongolia	6	10
Patagonia	6	11.2
Tierra del Fuego	6	5.6

Geographic origin	N	Mean annual temperature
Mexico, Tarraso	6	16.1
Thailand, Bankok	6	27.9
Egypt, Gizah	6	21.3
Tanzania, Pare & Ungueno	6	26.3
South Africa, Khoisan	6	15.9
South Australia	6	25.4

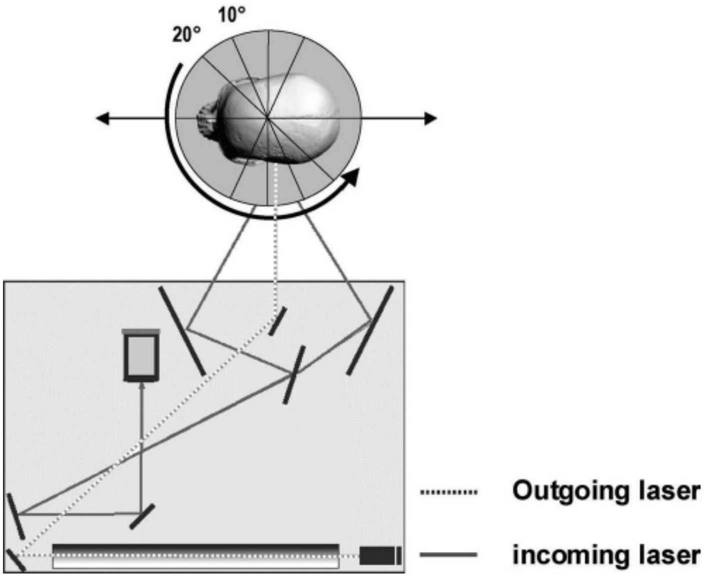

Figure 1 - Scheme of the Cyberware 3030 laser scanner (seen from above), illustrating the way it captures the surface of an object.

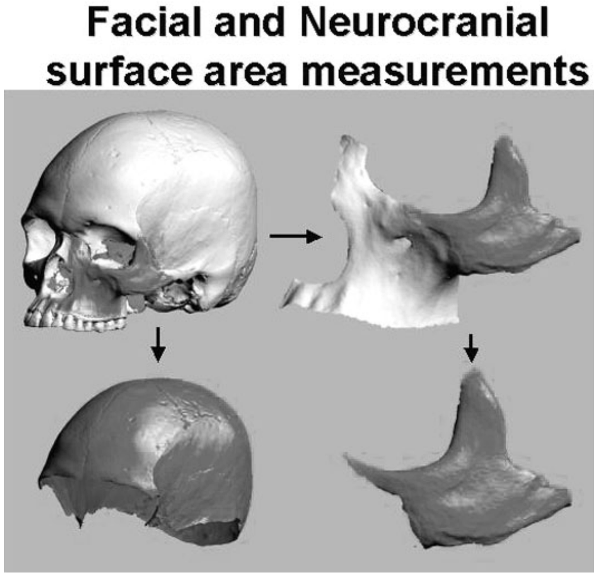

Figure 2 - Surface area measurements taken on the braincase and the face

as well as the external surface of the great wing of the sphenoid surrounded by the temporal, the frontal and the zygomatic.

Face: The external, anterior and lateral surface area of the zygomatic and maxillary bone above the alveolar arch. Measures of the maxilla were limited to the portion above the alveolar arch and anterior to the zygomatic root, considering that these are the portions most likely to be exposed to external temperature.

Zygomatic: The anterior external surface area of the zygomatic bone (thus a subset of the previous area).

Despite their potential, or at least suggested role for thermoregulation, we decided to exclude the nasal bones from the measurements. They are, frequently broken or completely absent among modern humans, and very rarely preserved in fossil hominins.

PRELIMINARY RESULTS

The overall degree of variation of the neurocranial surface area relative to cranial capacity is rather small among the different modern human samples (fig. 3). Significant differences are observed at both ends of the range, with Greenland Eskimos exhibiting the smallest relative surface area and Australian Aborigines the largest. The relative surface area (scaled to cranial capacity) of the Australian sample is certainly related to, but not fully caused by, the relatively small cranial capacity of the sample. The raw surface area of this Australian sample is also absolutely larger than the area in any other sample.

Grouping the samples together in 2 large sets, roughly equivalent to warm versus cold climate populations (see table 1 for annual temperatures) reveals a significant decrease of relative surface area with decreasing annual temperature.

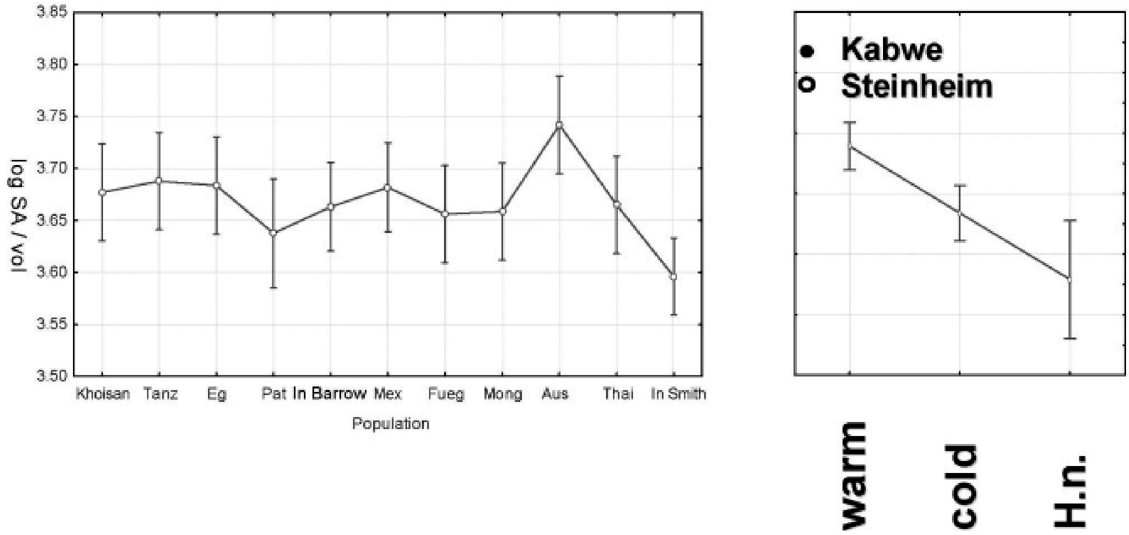

Figure 3 - Variation among extant and extinct humans of the neurocranial surface area relative to cranial capacity. Left: variation across geographic samples. Right: variation as a function of mean annual temperature. The position of fossils reflects only the relative surface area (ordinate).

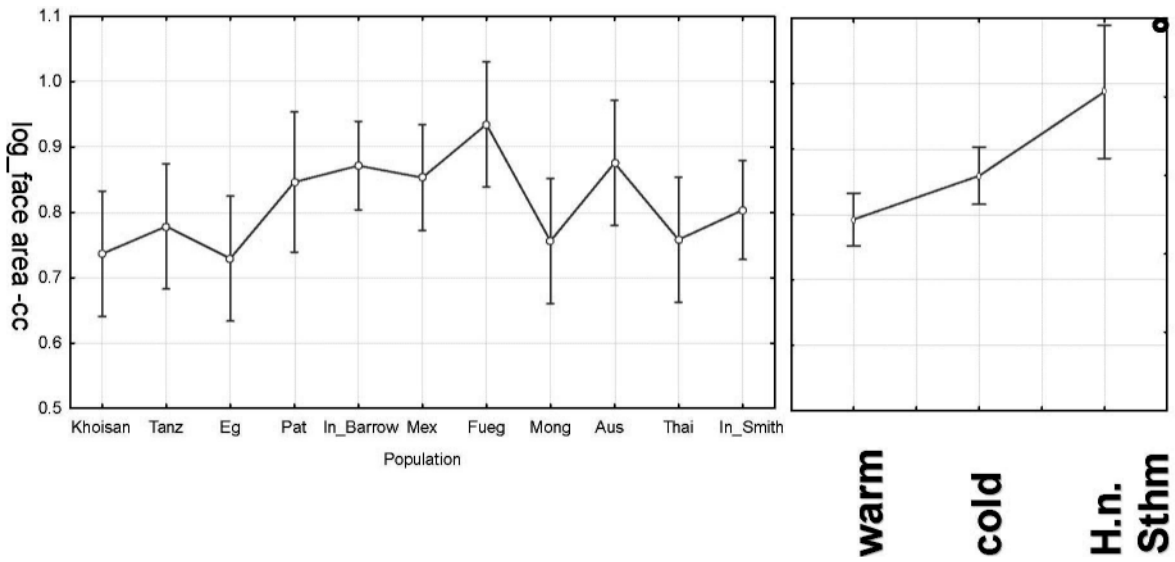

Figure 4 - Variation among extant and extinct humans of the facial surface area relative to the overall cranial surface area. Left: variation across geographic samples. Right: variation as a function of mean annual temperature. The position of fossils reflects only the relative surface area (ordinate).

Furthermore, when data from fossil hominins are compared to the scores of living humans, the result indicates that Neandertals have an even smaller relative surface area of their braincase. On the other hand, the Kabwe and Steinheim fossils exceed the modern human range of relative neurocranial surface area. Kabwe comes from an equatorial African environment, while Steinheim is generally considered to derive from a fully interglacial central European habitat comparable to those of the present day.

The facial surface area relative to the overall surface (face plus braincase) area shows the same basic pattern of variation (fig 4). While all groups taken separately show a rather heterogeneous picture, pooling warm climate populations on the on hand and cold climate populations on the other reveals a clear trend toward an increase in relative facial surface area with decreasing temperature. Data for all fossil specimens exceed the relative facial surface area of moderns, regardless of which hominid group they represent.

DISCUSSION

Given the methodological scope of this paper, one of it's major contributions is to provide a model approach to the study of volume-to-surface ratios and their functional significance in terms of thermoregulation. The technical advantages of a 3D laser scanning system are quite evident for the assessment of surface area data, which otherwise are accessible only through approximate equations using linear dimensions (Steegmann 1972). The obvious need for this type of data can be conveniently filled with this new technology.

In terms of functional considerations, the present study can provide preliminary insight into the volume-to-surface area ratios involved. The data presented so far suggest that the human head, and the braincase in particular, is adapted so as to reduce heat loss under cold climatic conditions. This observation can be made on a global scale, when generally warm climates are compared to generally cold climates. The inclusion of fossil specimens indicates that the relatively large cranial capacity of Neandertals and the associated relative small surface area of the neurocranium are adaptive for heat retention, at least when compared to modern human variation. When compared to older fossils that are not supposed to have lived in a cold climate (Kabwe and Steinheim) the Neandertal braincase still exhibits a relatively small surface area. Additional comparison and further confirmation of such a trend of reduced relative surface area among so caled "classic" Neandertals would ultimately suggest that cold adaptation is not only expressed in Neandertal postcranial morphology, but that the braincase was shaped following similar demands.

The data for the facial portions reveal a somewhat different picture. Contrary to theoretical predictions, modern humans living in a subarctic environment are characterized by relatively large facial surface areas, an observation that is consistent with earlier reports on Inuit facial dimensions (Hrdlička, 1910). Therefore, it has to be assumed, until further analyses are completed, that the relatively large faces of the Inuit and Neandertals are unrelated to climatic conditions.

SUMMARY AND CONCLUSION

The present study investigates new approaches to the study of functional morphology using a laser surface scanner. The device can be conveniently used to access surface area measurements otherwise largely inaccessible with conventional devices. An example for a possible application to paleoanthropology is given with the analysis of volume to surface area ratios of the human skull. A preliminary comparison based on 11 modern human populations as well as Late Pleistocene Neandertals and Middle Pleistocene warmer-climate fossils indicates that the braincase of populations living under subarctic conditions is adapted to reduce heat dissipation. When the face is examined under the same assumption, the data obtained so far are not consistent with models of climatic adaptations *sensu* Allen's rule. Therefore, we should either seek alternative models of cold adaptations or abandon the idea that facial morphology is the result of such adaptations.

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