Abstracts of select publications

Friess, M. (2006, accepted for publication) **The study of craniofacial growth patterns using 3D laser scanning and geometric morphometrics.** Proc. SPIE Three-Dimensional Image Capture and Applications.

Throughout childhood, braincase and face grow at different rates and therefore exhibit variable proportions and positions relative to each other. This well-known growth allometry is the object of the present investigation. Using a 3D imaging technique, laser surface scanning, the geometry of the head and face of 840 children, aged 2 to 19, can be captured and analyzed. From each scan, a series of 18 landmarks is extracted interactively, as fully automatic extraction of landmarks is still in an exploratory state. The landmarks are registered using General Procrustes Analysis (GPA). GPA eliminates unwanted variation due to position, orientation and scale by applying as least-squares superimposition algorithm to individual landmark configurations. This allows the investigator to test for differences in size, shape as well as the interaction between the two (allometry). With this statistical toolbox at hand, it is possible to test whether the craniofacial growth in boys and girls follows the same trajectory, or whether there are allometric differences. Another advantage of this approach is the ability to visually represent differences in size and shape between various age groups or between the sexes. This allows the investigator to create a complex 3D model of head and face and their variation through life time. The results of this study show that throughout adolescence, boys and girls follow a different growth trajectory, leading to marked differences not only in size, but also in shape. These differences can be observed during early childhood, but become most noticeable after the age of 13 years, when craniofacial growth in girls slows downs significantly, whereas growth in boys continues for at least 3 more years.
Understanding the direction and exact magnitude of these craniofacial differences, which is crucial for many ergonomic applications, can be vastly improved by the recourse to advanced 3D measuring methods and the use of geometric morphometrics for the quantification of size and shape variation.

Friess, M. (2005 in press) **Multivariate accommodation models using traditional and 3D anthropometry.** SAE 2005 Transactions, Journal of Aerospace.

Various statistical approaches have been advocated that aim at creating statistically meaningful and representative models of human variation. While they all have in common the idea to summarize the critical space needed by the user population by a discrete number of cases, substantial differences exist as to how exactly these cases are identified. The choice of statistical procedures also impacts the number of representative cases (i.e. the efficiency of the model) as well as the actual percentage of the accommodated population (accuracy of the model). The purpose of the paper is to test strengths and fallacies of some of the more commonly found approaches using real as well as simulated data. Furthermore, an extension of multivariate accommodation models to 3D coordinate data, which can be used in CAD/CAM environments, are presented.
The results suggest that while overall accommodation percentages tend to improve when the number of variables and representative cases increases, various other factors can be identified that can significantly reduce or even invalidate the model

accuracy. Consequently, simplistic approaches based on multiplying variables/cases do not necessarily guarantee pertinent models. Rather, optimization strategies must be sought to reconcile model efficiency and accuracy.

Baylac, M. & Friess, M. (2005) **Combining Procrustes Superimposition and Fourier descriptors: Analysis of midsagittal cranial outlines. In DE Slice (ed.):** Modern Morphometrics in Physical Anthropology**. Kluwer: 145-165**

The increasing use of geometric morphometric approaches for the quantification of shape variation, particularly in anthropology, has put the emphasis on landmarks rather than outlines. We propose a combination of a landmark based approach, Generalized Procrustes Analysis (GPA), and Elliptic Fourier Analysis (EFA) for the quantitative shape analysis of cranial profiles. This approach combines the advantages of a multiple point registration with the detailed modeling of outlines using elliptic Fourier harmonics. We applied it to a sample of two-dimensional cranial profiles of four different populations in lateral view. The samples include circumferentially (C) and anteroposteriorly (AP) deformed crania from Peru, as well as two undeformed populations (Japanese and Peruvians). Centered and size-normalized outlines were superimposed using the rotation parameters of the Procrustes superimposition of homologous control-points (i.e. landmarks). Nine control points were chosen on the cranium, and seven on the vault. Due to the high number of variates generated by the outlines, we used dimensionality reduction approaches based on principal components. The number of retained components was determined so as to minimize the cross-validated misclassification rates calculated using linear and k-nearest neighbor discriminations. We used concurrently the broken stick and Jolliffe's rules to reduce the number of components. Among the different rules used to select the number of components, neither the broken stick nor the Jolliffe's rule yielded subsets of components allowing to retrieve the lowest misclassification rates. KNN discrimination although less dependent of the number of retained components, provided mixed results that were systematically worse than linear discrimination.
Datasets derived from Fourier coefficients consistently achieved lower cross-validated misclassification rates than landmark based ones. Nevertheless, we demonstrate the interest to combine outline and landmark analyses in order to gain insights into the geometric scale and the regionalization of the shape differences. Our results clearly point out that AP and C deformed crania both exhibit a significant modification of the basioccipital and facial parts of the skull. They also clearly highlight the particular importance of this region to discriminate the AP crania. Generalized Procrustes analyses of the control points provided classification percentages as good as the analyses of outlines in the case of AP deformations. In the case of C deformation, outlines out-performed the landmark analysis, while landmarks yielded similar discrimination power for the vault and the entire cranium.

Friess, M., Rohlf, F.J., Xiao H. (2004) **Quantitative assessment of human body shape using Fourier analysis. In: Brian D. Corner, Peng Li, Roy P. Pargas (Eds.) (2004):** Proc. SPIE Vol. 5302, Three-Dimensional Image Capture and Applications VI p. 117-124

Fall protection harnesses are commonly used to reduce the number and severity of injuries. Increasing the efficiency of harness design requires the size and shape variation of the user population to be assessed as detailed and as accurately as

possible3. In light of the unsatisfactory performance of traditional anthropometry with respect to such assessments 7, we propose the use of 3D laser surface scans of whole bodies and the statistical analysis of elliptic Fourier coefficients. Ninety-eight male and female adults were scanned. Key features of each torso were extracted as a 3D curve along front, back and the thighs. A 3D extension of Elliptic Fourier analysis4 was used to quantify their shape through multivariate statistics. Shape change as a function of size (allometry) was predicted by regressing the coefficients onto stature, weight and hip circumference. Upper and lower limits of torso shape variation were determined and can be used to redefine the design of the harness that will fit most individual body shapes. Observed allometric changes are used for adjustments to the harness shape in each size. Finally, the estimated outline data were used as templates for a free-form deformation of the complete torso surface using NURBS models (non-uniform rational B-splines).

Friess, M. Corner, B.D. (2004) **From XS to XL: Statistical Modeling of Human Body Shape Change using 3D Surface Scans.** SAE 2004 Transactions, Journal of Aerospace**, Volume 1: 215-220.**

The increasing trend towards larger body mass in work force and consumer populations poses a challenge for accommodating and fitting the shifting range of variation. The change of body shape and proportions under the influence of weight can be addressed with multivariate statistical approaches, common in allometry studies that use whole body models. We present results of a multivariate allometry study applied to the human body. 3-dimensional outline data were extracted from whole body surface scans (CAESAR) and analyzed using a combination of geometric morphometrics techniques and Elliptic Fourier Analysis. The results show that there is an overall allometric effect of relative body weight onto body shape, but that different portions of the population are affected differently by this allometry. The results can be used to accurately predict body shape associated with an increase in body weight, and therefore provide data that are of value to a wide range of manufacturing and design applications.

Friess, M., Bradtmiller, B. (2003) **3D Head Models for Protective Helmet Development. SAE Technical Papers Series** Proceedings of the SAE 2003 Digital Human Modeling Symposium**, Montreal, Canada, June 2003.**

In order to improve the fit and comfort of helmets, we developed digital head models that represent the anthropometric and morphometric variability found in the U.S. Navy. We analyzed the size and shape variation using two related approaches. First, we used Procrustes superimposition, which minimizes the distances between all landmarks of all subjects. This allowed us to visualize the variation in landmark distribution of the face and to test for statistical differences. Second, we extracted curvatures along the surface of the head. This allowed us to characterize the variation in the shape of the head. To create a series of sized digital models, we used principal component analysis (PCA) to organize the variation in both the traditional measurements as well as the locations of the 3D landmarks. Using an adaptation of multivariate accommodation modeling we identified representative individuals who characterize 95% of the variation in size and shape. Simultaneously, we used traditional dimensions to divide the population into a specified number of sizes, and then used the shape contours to create a summarized head form representing the individuals in each size.

Friess, M. (2003) **3D modeling of fall protection harnesses.** Proceedings of the XVth Triennial Congress of the International Ergonomics Association 7th Joint Conference of Ergonomics Society of Korea/Japan Ergonomics Society**. Seoul, August 24-29 2003.**

This paper presents an analysis of human torso shape in 3 dimensions with the goal of improving the design and accommodation efficiency of fall harnesses. For this purpose, a sample of 98 male and female adults of mixed ethnic background were scanned using a Cyberware 3D whole body scanner. The initial scan data, representing the body as a high density polygon mesh, were post-processed in order for key features to be extracted and registered as Cartesian coordinates. The data analysis was limited to the individuals' torso as the principal body portion the harness has to fit and support. The coordinates form landmark data that were used to describe the spatial relationship of body shape and harness design under 'normal' and suspended conditions. The shape analysis of the landmarks was performed using Generalized Procrustes Analysis (Rohlf, 2000). This approach, also known as geometric morphometrics, has several advantages over traditional morphometrics, such as aligning spatial data in a least-squares type approach, which makes shape variation independent of predefined body planes and orientations. It also provides a better control of size and size effects that are relevant for the design of the harness. Finally, the derived parameters of size and shape variation can then be used as input to a computer analogue of the human torso, which can serve in the design process as well as in virtual reality animations.

Friess, M. (2003) **An application of the relative warps analysis to problems in human paleontology - with notes on raw data accuracy.** Image analysis and stereology **22: 63-72.**

This study investigates the use of geometric morphometrics as well as methodological aspects specifically related to its application in paleoanthropology. Based on lateral photographs taken from a fossil sample of 58 specimens, relative warps analyses were computed in order to assess the variation of cranial shape among various hominin groups. The fossil sample represents Middle and Late Pleistocene populations commonly assigned to *H. erectus*, *H. neanderthalensis*, archaic *H. sapiens* as well as anatomically modern *H. sapiens*. The preliminary results indicate that several fossil skulls considered as belonging to archaic *H. sapiens* have a distinct shape compared to modern humans. The results suggest that these hominins are not as closely related to modern humans as previously thought. Instead, their morphometric affinities suggest that they are as distinct from modern humans as are the Neandertals. Methodological aspects, such as raw data accuracy and the use of type 2 and 3 landmarks that are directly related to this type of quantitative analysis and that potentially affect their results, are discussed.

Friess, M. & Baylac M. (2003) **Exploring artificial cranial deformation using Elliptic Fourier Analysis of Procrustes aligned outlines.** Am. J. Phys. Anthropol**. 122 (1): 11-22.**

The anatomical effects of artificial cranial deformation on the face and the base have been subject to various metric approaches, including standard linear as well as finite element techniques, and have produced controversial results (Antón [1989] Am. J. Phys. Anthropol. *79:*253– 267; Kohn et al. [1993] Am. J. Phys. Anthropol. *90:*147–158). It can be argued that diverging observations partly result from methodological constraints. The present study compares samples of intentionally

deformed and undeformed human crania, using elliptic Fourier analysis (EFA), a morphometric approach which has been shown to be particularly appropriate for characterizing the shape of two-dimensional outlines and associated shape changes. We improve the standard EFA approach by adding a preliminary orientation of the outlines following the rotation parameters of a Procrustes superimposition, using multiple homologous landmarks called control points. The results confirm that circumferentially deformed skulls exhibit modifications of the basioccipital region, together with increased anterior and inferior facial projection. However, the degree to which basioccipital flattening is modified in circumferentially deformed Peruvians was found to be less marked than changes observed in the face. Some of the modifications observed here can be related to morphological trends existing in the population from which our sample was taken. The observation of other modifications may be subject to methodological constraints of standard morphometric approaches.

Reddy, D.P., Frost, S., Friess, M., Marcus, L.F. & Delson, E. (2002). **An interactive database for primate morphometric studies.** Am. J. Phys. Anthropol. Suppl. 34 **(abstracts): p 129.**

Preparation, organization. and screening of data is a major task in many conventional and geometric morphometric analyses. In addition, formatting data sets for use in various software packages for statistical and morphometric analysis can be very time consuming. We have built a database that incorporates diverse formats of morphometric data from our sample of over 5000 measured primate specimens from worldwide collections. These data include linear dimensions collected by calipers on both cranial and postcranial elements, 2 and 3 dimensional landmarks, 3D space curves (connected sets of landmarks), laser-scanned 3D surfaces, photographs and other 2D images, and volumetric data such as CT images. Individual specimens are referenced by taxon, collection data, body part, locality coordinates and other geographic parameters.

The database interface uses an HTML browser to construct Structured Query Language (SQL) queries to the database, allowing subsetting, iterative refining, and assembling of morphometric data using-forms based web pages. Subsetted data sets then can be formatted for convenient data analysis in morphometric and statistical software packages. A demonstration version of the database is currently available over the world wide web [http://research.amnh.org/nycep]. This work was supported by NSF grants (ACI-9982351 to AMNH and BIR 9602234 for the NYCEP RTG).

Friess, M. (2002) **Revisiting human cold adaptation - craniofacial shape assessed by 3D laser scanning.** Am. J. Phys. Anthropol. Suppl**. 34 (abstracts): p 72.**

The morphology of the face in modern as well as fossil human populations has been the focus of debates about cold adaptation and / or masticatory stress. Published theoretical models are not conclusive as to exactly how the underlying mechanisms of cold adaptation might affect the face. In this study, a generalized cold adaptation model following Bergmann's and Allen's rules is proposed, and its applicability to present and past populations is tested. For this purpose, relative surface areas as well as volumes were measured using a 3D laser surface scanner. The modern human samples comprise supposedly cold adapted populations such as Inuit and Fuegians, as well as several populations from intermediate and warm climates

(Mongolia, Tanzania, Egypt, South Africa). Data were also collected from casts of fossil hominids representing Neanderthals, *H. heidelbergensis*, and *H. erectus*.

Results to date indicate that cold response in the human cranium tends to follow Bergmann's and Allen's rules at a global scale of comparison and that Neanderthals fit this general model. However, when populations are compared at a more localized level, the findings are not consistent with theoretical predictions. It is concluded that cold adaptation does play a certain role in craniofacial variation, but further investigation is required in order to differentiate its effects from those of other influential factors, such as masticatory stress.

Delson, E., Friess, M., Marcus L.F. & Reddy D.P. (2002) **Assessment of quantitative characters in the distal humerus among hominids (great apes and hominins).** Am. J. Phys. Anthropol. Suppl. **34 (abstracts): p 61.**

The articular morphology of the distal humerus is known to reflect adaptation to patterns of locomotion in living primates. It has been argued that the more arboreal orangutans are characterized by relatively deep fossae, whereas the large-bodied knuckle walkers have relatively larger articular surfaces than smaller-bodied ones. Numerous studies have provided comparisons based on conventional and landmark morphometrics, some of which are restricted to 2D. However, a three dimensional model of the humerus was expected to contain significantly more information about the functional variability of the distal articulation. We collected data with a Cyberware 3D laser surface scanner having a physical resolution of 0.1mm. We sampled articular surfaces of great apes (*Pongo*, *Pan*, *Gorilla*), as well as living and fossil humans. These data allow for a comparative analysis of terrestrial versus more arboreal quadrupedal locomotion, as well as the unique bipedal pattern of humans. Ultimately, one of the goals was to assess the morphometric affinities of hominin fossils whose phylogenetic position remains unclear, such as TM 517 and KNM-ER 739. Area to Volume ratios were determined for different functional components and compared across taxa. Size-related variations, such as sexual dimorphism, were also taken into account for extant taxa. Major differences at the generic level can be seen in the size of the articular surface relative to the entire humerus, and in the relative size of the capitulum. Our results suggest different allometric patterns in chimpanzees compared to australopiths, contradicting previously claimed affinities.

Friess, M., Marcus, L.F., Reddy, D.P. & Delson, E. (2002) **The Use of 3D Laser Scanning Techniques for the Morphometric Analysis of human Facial Shape Variation. In Bertrand Mafart and Hervé Delingette (eds.):** Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology *Acts of the XIVth UISPP Congress**, University of Liège, Belgium.*** **BAR S1049.**

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 it's 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.

Castex, D. & Friess, M. (2001) **Ein Pestsommer in der Provence. Demographische Anomalien im Zusammenhang mit Epidemien. In A Kemkes-Grottenthaler & W Henke (eds.)** Pein und Plagen. Aspekte einer Historischen Epidemiologie**. Edition Archaea, Frankfurt a. M.**

Friess, M. (1999b) **Some aspects of Cranial Size and Shape, and Their Variation among Later Pleistocene Hominids.** Anthropologie (Brno) **37/3 : 231-238.**

This paper investigates allometric relationships in later Pleistocene fossil humans using geometric morphometrics. The purpose is to re-evaluate variation of cranial size and shape and to differentiate pure shape change from size-induced trends. Cartesian coordinates were collected from 63 fossil specimens, mostly originals, as well as from a large modern sample. Based on Bookstein's relative warps analysis (Bookstein 1991, Rohlf 1993), shape variation was examined and related to centroid size. Results confirm on the one hand strong affinities between Near-Eastern Middle Palaeolithic humans and clearly modern populations, and reveal on the other a common archaic vault shape among the Neanderthals and archaic *Homo sapiens*. The role of allometric phenomena for facial morphology is also discussed. It is concluded that the evidence for a gradual evolution towards modern *Homo sapiens* in Africa (Bräuer 1984) is poor.

Friess, M. (1999a) Taille et conformations crânienne chez les Hominidés de la fin du Pléistocène. Contributions de la morphométrie géométrique au débat sur l'origine de l'homme moderne**. BAR International Series 799, Oxford: 241 p.**

This volume is a slightly abridged version of my PhD thesis, as it was submitted at the University of Bordeaux. An extended English summary was added.

Friess, M. (1997b**) Analyses de formes crâniennes fondées sur la photogrammétrie.** Biom. Hum. et Anthropol**. *15(1-2)* : 19-22.**

In the past years, several new analytical techniques for the description of shape variation and shape change have been made available tp Morphometricians (see Richtsmeier et al. 1992 for a review). Since the majority of these methods require some sort of landmark or outline data, raw data are mostly taken from graphic representations of specimens. We evaluate the use of photogrammetric methods for the data acquisition. The results of our experiments using casts of fossil crania show that the mean measurement error can be less than 1mm as long as some basic photo-optical principles are respected. Therefore, photogrammetry is not only a reliable and efficient method, but also a very useful tool for the above mentioned analysis techniques.