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Applying Craniofacial Metrics to Adapt 3D Generic Head Models

Katrina E. Wendel-Mitoraj¹ and Michael E. Osadebey²

¹*Tampere University of Technology*

²*NeuroRX Research Inc.*

¹*Finland*

²*Canada*

1. Introduction

Traditionally, the fields of anthropology and biomedical engineering are two diverse areas of science. Over the last few years various subfields of biomedical engineering have been trending towards personalized medicine. Presently there are a limited number of models that neuroscientists use to evaluate theory and solve application problems, thus depersonalizing medicine. This chapter introduces a novel integration of how anthropology can lend to and improve personalized neuromedicine through the study of physical characteristics, the relationship of races, and gender. By integrating anthropometric and craniofacial data, future head models should accommodate race, gender, age, and size to better approximate personalized medicine on a wide-scale approach.

2. Motivation

The absence of anthropometrically accurate generic head models limits the field of computational neuroscience to either simplistic, geometric models or complex, personalized models. Implementation of a universal descriptor for describing three-dimensional (3D) geometry and variations in geometry of similar anatomic structures, such as the human head, extends the efficacy and applications of most systems developed to aid tasks in the fields of computational modeling, automated medical image analysis, image guided surgery and 3D anthropometry. This technique is known as the radial vector representation.

This chapter opens with reviewing and evaluating various head models ranging from spherical to personalized complex models in sections 3 and 4, respectively. Then section 5 spans the gap between the simple and complex models to describe a range of adaptable generic models. Next, section 6 explains the geometric descriptor of the radial vector technique, and then section 7 demonstrates the application of craniofacial data using the radial angular matrix (RAM). The RAM describes, preserves, and spatially reconstructs magnetic resonance image (MRI) data. Therefore, the example modifies various ethnic groups and sub-groups according to Farkas et al. (2005). The resultant generic models depict the benefits of employing this technique. The chapter concludes with a discussion based upon the craniofacial morphing of the generic models.

3. Spherical and elliptical models

The forward problem has a unique solution (Malmivuo & Plonsey, 1995; Wendel, Väisänen, Malmivuo, Gencer, Vanrumste, Durka, Magjarević, Supek, Pascu, Fontenelle & Grave de Peralta Menendez, 2009), but the model it is based upon is still only an estimate of the anatomy and physiology of the human head. The human head can be modeled and analyzed as a sphere or an ellipsoid. These simplistic geometries can only explain the theory of how something works regarding neuroscience but are incapable of identifying accurate results. The spherical model was introduced by the seminal works of Rush & Driscoll (1968; 1969). They proposed three concentric spheres to represent the brain, skull, and scalp. In the last four decades, several studies have used this configuration (Gordon et al., 2006; Malmivuo et al., 1997; Ryyänänen et al., 2004a;b; Wendel & Malmivuo, 2008; Wendel et al., 2007; Wendel, Narra, Hannula, Kauppinen & Malmivuo, 2008; Wendel, Väisänen, Kybartaitė, Hyttinen & Malmivuo, 2010). The CSF has been added as the fourth shell to the spherical model (Ferree et al., 2000; Wendel & Malmivuo, 2008; Wendel et al., 2007; Wendel, Narra, Hannula, Kauppinen & Malmivuo, 2008; Wendel, Väisänen, Kybartaitė, Hyttinen & Malmivuo, 2010; Zhou & van Oosterom, 1992). Consequently, these models are referred to as 3-shell and 4-shell models.

These 3- and 4-shell spherical models contribute to neuroscience by theoretically explaining the lead field and volume conductor currents of how a lead measures from the tissue beneath it. Although the resolution of the spherical and elliptical models is of a few centimeters (Crouzeix et al., 1999; Roth et al., 1993), they explain the general theory. Investigations that continued this pursuit of a general understanding of the neuroelectric phenomena involved often tailor spherical models to address specific issues such as local variations (Cuffin, 1993), noise (Ryyänänen et al., 2006), conductivity values (Ryyänänen et al., 2006), electrode properties in 2-D and 3-D (Ollikainen et al., 2000; Suesserman et al., 1991), source localization (Vanrumste et al., 2001), and spatial resolution (Malmivuo & Suihko, 2004; Malmivuo et al., 1997).

3.1 Simple generic models

Simple generic models in the most simplistic form can be represented by geometrical shapes such as spheres and ellipsoids. The elegance of these simple models is inherent in that they can be solved analytically. The analytical method has a direct solution, hence it does not require an iterative numerical solver. This simplicity is extended through to the ellipsoid and perturbed spheroid solutions (Nolte & Curio, 1999). However, when realistically-shaped electrodes replace the point electrode model, a numerical method is necessary to solve either the forward or inverse problem using the spherical volume conductor model (Gordon et al., 2006; Ollikainen et al., 2000; Wendel & Malmivuo, 2008; Wendel et al., 2007; Wendel, Narra, Hannula, Kauppinen & Malmivuo, 2008).

Several electroencephalography (EEG) or related head modeling publications consistently reference the same or similar measurements all relating to a larger male head of Northern European caucasian descent. These correlations match hat and wig sizes, which correlate with anthropometric, craniometric, and cephalometric data (Department of Defense, 1997; Donelson & Gordon, 1991; Farkas et al., 2005; Howells, 1973). This implies that there is a paucity of analysis for head sizes that are not represented (Yusof, 2007).

In Wendel, Narra, Hannula, Kauppinen & Malmivuo (2008) we previously derived the external radius for our spherical head models from transverse circumferential cephalometric

dimensions separated by gender (BestWigOutlet, 2005; 2009; HatsUK, 2005; 2012; TheHatSite, 2005; WigSalon, 2005; 2012). WigSalon (2005; 2012) assesses that 92% of women have heads circumferentially measuring between 54.6 cm and 57.2 cm. The average-female cephalometric circumference equates to 55.4 cm per common head accoutrements; thus, the average-female head radius measures 8.82 cm. Likewise calculating the average-male head circumferential measurement of 58 cm, the average head radius of a male calculates to 9.23 cm; therefore; the average male head is 0.4 cm larger in the radial direction than the average female head concerning racial and ethnic neutrality.

Furthermore, several sources either reference one set of spherical radii or very few sets of realistic data for an entire population. The majority of these references use radial and thickness measurements that fall inline with an average male head size or larger of Northern European, Central European or caucasian North American descent (Cuffin, 1995; 1996; Ferree et al., 2000; Malmivuo & Plonsey, 1995; Ogoshi et al., 2003; Rush & Driscoll, 1969; Zhou & van Oosterom, 1992). These larger values instantly disregard youths and females in these racial ethnicities and both males and females of other ethnicities in terms of the size and shape variation between genders and across cultures (Adeloye et al., 1975; Farkas et al., 2005; Lynnerup et al., 2005).

4. Realistic individual models

The poor sphericity of the viscerocranium and the frontal and temporal lobes of the brain led researchers into improving the geometry beyond the spherical model (Hämäläinen & Sarvas, 1989). Realistically-shaped models specifically correspond to a unique individual and could represent other individuals that are of the same gender, same ethnic group, very similar craniofacial structures and a similar age. Consequently, these models increase the model complexity in order to reduce errors in source localization, source imaging, and scalp potentials Babiloni et al. (1997); Cuffin (1995); Gevins et al. (1991); Huiskamp et al. (1999); Michel et al. (2004). These complex models require numerical solutions such as the boundary element method (BEM), finite element method (FEM), or finite difference method (FDM) (Hallez et al., 2007; Wendel, Väisänen, Malmivuo, Gencer, Vanrumste, Durka, Magjarević, Supek, Pascu, Fontenelle & Grave de Peralta Menendez, 2009).

Realistic models are constructed from a set of segmented image slices, usually originating from one of the primary medical imaging modalities — computed tomography (CT), MRI, or a matched MRI-CT set (Cuffin, 1995; Haueisen et al., 1997; Huiskamp et al., 1999; Wendel, Narra, Hannula, Kauppinen & Malmivuo, 2008). Considering their pros and cons, CT more accurately images the skull due to its sensitivity to hard tissue via radiation, whereas MRI better images soft tissues such as the skin, cortex, and the gray matter-white matter boundary and is safe. The differences between the three-layer CT- and MRI-based models in (Huiskamp et al., 1999) illustrate significant differences at the base of the skull.

Unfortunately, diagnostic equipment that is available to adults is not optimal for children in terms of safe radiation limits. Such imaging modalities include CT, PET, and SPECT, which use ionizing radiation or radioactive tracers. Due to the nature of these technologies, children will only obtain such screening in extreme cases Yusof (2007). Magnetoencephalography (MEG) is safe, but it is often limited by the availability of smaller helmets, which locate the gradiometers closer to the scalp surface. EEG is also safe and readily adaptable to various head sizes due to the elastic nature of most EEG caps. Therefore, analyses that require

computational modeling require generic models to better represent subpopulations that the patient shares geometrical congruency.

5. Generic models

Computationally-tractable head models that represent various populations and subpopulations demand that we examine the anatomy of the neurocranium, basicranium, and splanchnocranium i.e. the cranial vault, cranial base, and the face (Venes, 2005) as well as how head models are typically constructed. Generic models comprise a wide range of models attempting to encompass a range of ages, genders, and ethnic groups. From the models that exist in literature, two classes of generic models exist – simple and complex. For the purpose of this discussion, the complex models are additionally referred to as adaptable. A few three-dimensional (3-D) atlases of large data sets provide the data to form the models (Yusof, 2007).

5.1 Smoothed generic models

Simple generic models simulate down-sampled and smoothed tissue boundaries (Kybic et al., 2006; Wendel, Osadebey & Malmivuo, 2008; 2009). These models represent larger groups of people through their approximated shapes and sizes. Their sources are originally derived from the specific realistic images, and subsequently they are geometrically adapted to correspond with wider groups of gender, race, ethnicity, and age. These models are best suited for evaluating and analyzing how different parameters affect the sensitivity distributions applicable to EEG, bioimpedance, and transcutaneous electric neural stimulation (TENS).

Whether researchers build spherically or realistically shaped models, it is important to obtain measurement data representative of a population when making observations about that particular population. Clearly, the best model for a particular patient matches his image data exactly; however, it is not always possible or feasible to have an exact model that fits every patient, so an appropriate generic model is warranted (Darvas et al., 2006; Wendel, Osadebey & Malmivuo, 2009). Therefore, it is of utmost importance to obtain data representative of the population that a patient can be represented by in order to make quick utility of the likely closest-fitting, realistic model.

5.2 Complex generic models

The current and near future of time-efficient and cost-effective EEG source localization models lies in the progression of deformable head geometries (Wendel, Osadebey & Malmivuo, 2009). Anthropometric data currently exists detailing deformations in craniometric landmarks (Department of Defense, 1997; Donelson & Gordon, 1991; Farkas et al., 2005; Howells, 1973); however, a database of landmark sizes coupled with age (Wendel & Malmivuo, 2006; Wendel, Väisänen, Seemann, Hyttinen & Malmivuo, 2010), gender (Wendel, Osadebey & Malmivuo, 2009; Wendel, Väisänen, Seemann, Hyttinen & Malmivuo, 2010), ethnic origin (Wendel, Osadebey & Malmivuo, 2009), and head shape (Wendel, Osadebey & Malmivuo, 2009) would improve the accuracy beyond the overly used fixed-geometry of highly complex models such as from the Visible Human Project (Ackerman, 1991; National Institutes of Health (NIH), 1995).

5.3 The future of adaptable head models

Future studies that will advance the field of source imaging will save time and money. They will optimize the deformation, i.e., adaptability, of head models by minimizing the need for expensive MRIs and CTs, and eliminating the segmentation time. As scalp and skull tissue atlases are compiled and analyzed across age, gender, and ethnicity, the understanding of how to apply changes to a template will improve a model to match the non-imaged patient (Wendel, Osadebey & Malmivuo, 2008; 2009). Ultimately, incorporating the exact electrode locations to guide the deformation according to the patient's scalp surface would improve this method (Darvas et al., 2006; van 't Ent et al., 2001).

6. Radial vector representation

Borrowing from the field of cranial anthropology, we mathematically transform a universal head model to reflect the size of an average female of other ethnic groups. The basis for the universal head model is the Visible Human Woman (VHW) from the Visible Human Project (National Institutes of Health (NIH), 1995). Our goal is to make deformable generic head models readily available for individuals who have not been medically imaged. The radial vector technique was briefly described in Wendel, Osadebey & Malmivuo (2008; 2009). The full mathematical description of the radial vector technique manipulating the radial angular matrix (RAM) can be found in Wendel et al. (2012).

We started with a segmented head of the VHW measuring 640 by 530 by 670 pixels per dimension, having a 0.33 mm resolution per each axis unit. Ultimately, we constructed a four tissue model extending from the vertex down to the nasion. We constrained our slice-selection criteria for each tissue beginning with the apical slice after the noise removal from the first few slices of the radial- angular distances, i.e. the length measured from the tissue centroid to the tissue boundary for each slice. According to image analysis, we optimized our geometry based on the variation of the major and minor radial-angular axes of the transverse slice sections. The radial vector technique uses the cylindrical coordinate system, which is origin-centered through each tissue centroid. The RAM is a matrix of radial angular geometric descriptors forming atlases of any tissue segmented within the human body. This technique requires imaged and segmented image sets usually based upon a patient's MRI.

7. Application of the radial vector representation

A few cultural groups were presented in our previous study (Wendel, Osadebey & Malmivuo, 2009). In this chapter we present the full range of racial groups studied by Farkas et al. (2005). In this section we provide example mathematical functions to manipulate the RAM to generate several ethnic subgroups. We calculate the deformed geometry of a realistically shaped female head model based on the Visible Human Project woman dataset (Fig. 1). We used the cylindrical coordinate system to parametrically deform the template according to the modulation of the power function

$$f(x) = ax^b + c, \quad (1)$$

where b is the exponent of 0.01 used to deform the parietal lobe and a and c are derived from the coordinates of the template. We used the elliptical curve to reshape the frontal and

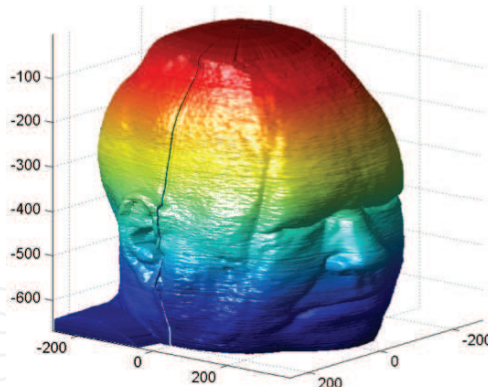


Fig. 1. Generic template of the adult female of Caucasian American origin.

occipital lobes evaluating

$$x = h + a\cos(t) - b\sin(t)\sin(\phi) \quad (2)$$

$$y = k + b\sin(t) + a\cos(t)\sin(\phi). \quad (3)$$

We set the major-to-minor axis ratio to 0.3 and the orientation to 25° .

7.1 Results

We alter pre-existing individual realistically-shaped head models by applying modulation of the power and elliptical functions (Fig. 2 & 3). We simply scale the template according to anthropometric statistics reported by Farkas et al. (2005) that belongs to each ethnic subpopulation to generate a new model. While deriving multiple generic head models, we use stochastic factors to generate a set of anatomical possibilities and constraints to prevent subsequent models with nonhuman and atypical human shapes and sizes. When applying too large exponents or major-to-minor axis ratios we yielded cone-head shaped models, which do not represent normal humans.

7.2 Discussion

In order to improve upon the state of current models, we must refine the basic geometric models in accordance with particular subpopulations. However, simply analyzing the diameters of the cranium is an older technique used to study cranial evolution. Contrastingly, the current analysis of spatial relationships between different anatomical structures can be applied to inter- and intra-ethnic comparisons (Bruner, 2007). We can alter pre-existing individual realistically-shaped head models by applying translation, rotation, scaling, warping, or applying more advanced metrics such as elliptical and power functions (Figs. 2 and 3). For instance we could simply scale one individual that belongs to the same subpopulation to generate a congruent model to represent another size of perhaps a different age. While deriving multiple generic head models, we can use stochastic factors to generate a set of anatomical possibilities and constraints to prevent subsequent models with nonhuman and atypical human shapes and sizes. A more encompassing approach would make use of a multivariate analysis of 2D and 3D anatomical features across numerous models (Bruner, 2007). Furthermore, these analyses and constraints can be applied not only to wide-ranging generic head models but additionally to various ethnic groups to create subpopulation-specific generic models.

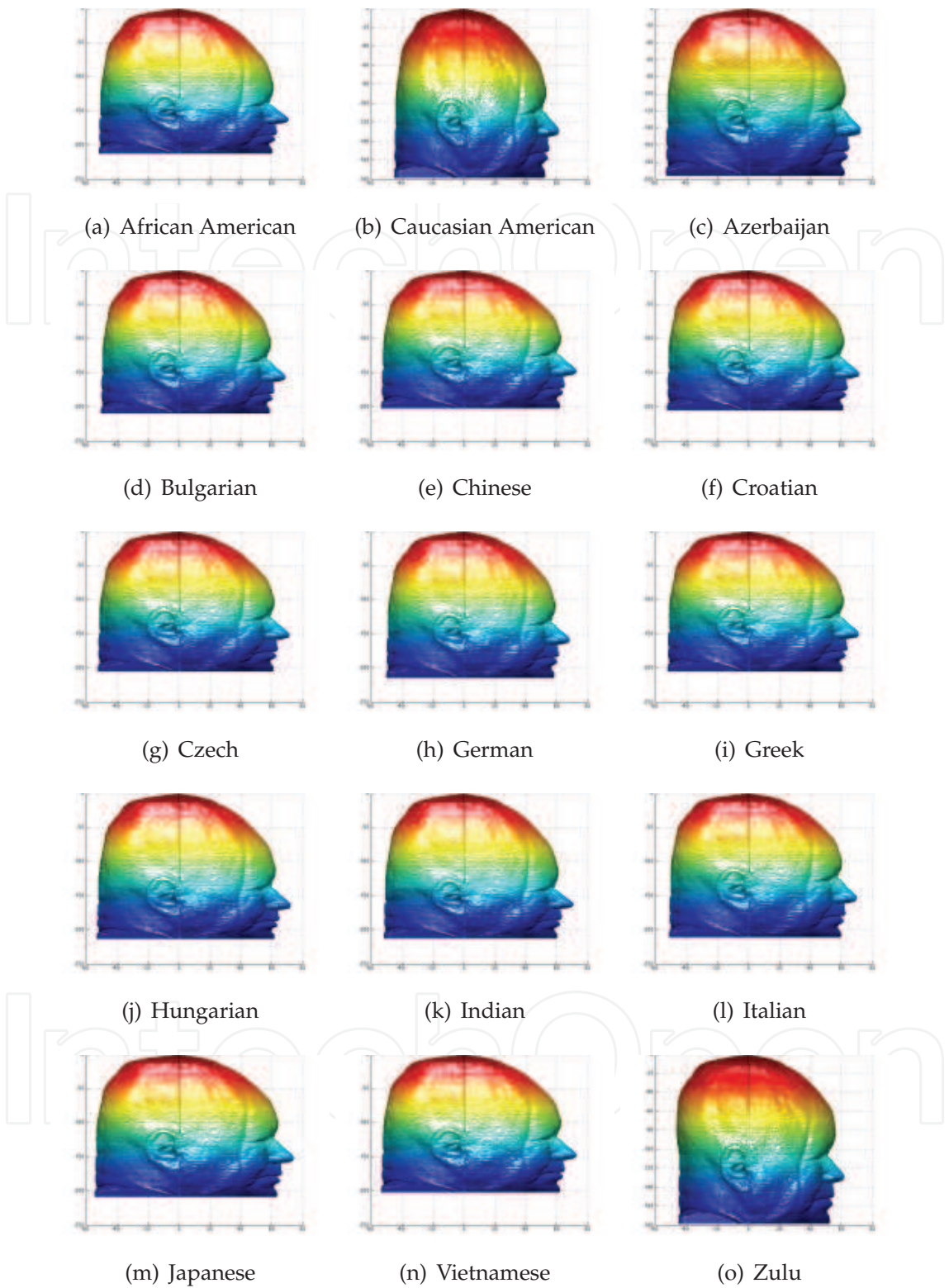


Fig. 2. Generating Generic Ethnic Head Models: (a-o) adult female heads of average size per ethnic group. All heads are scaled accordingly and modified with an exponential function of 0.01.

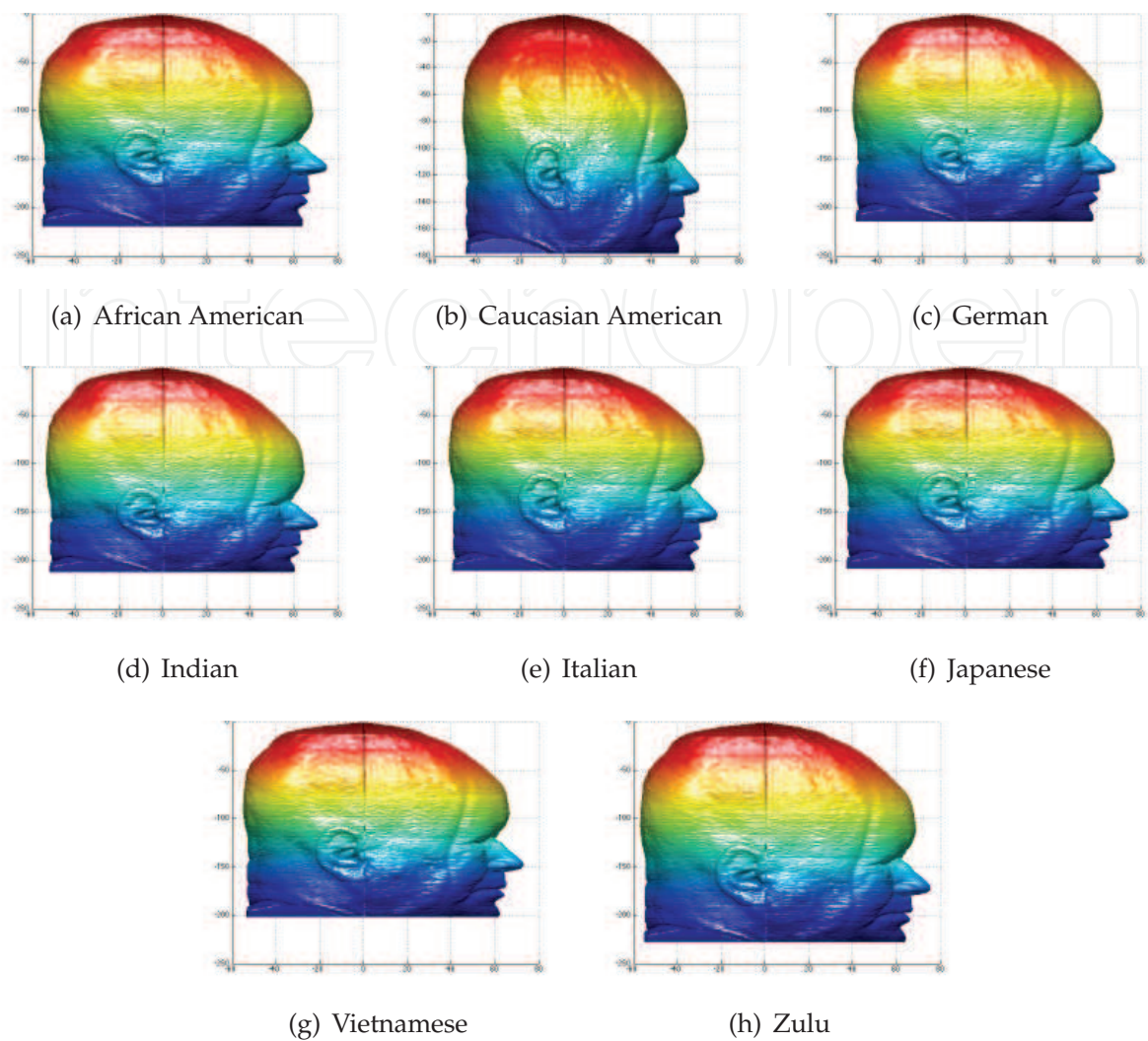


Fig. 3. Generating Generic Ethnic Head Models: (a-h) adult female heads of average size per ethnic group. All heads are scaled accordingly and modified with an elliptical curve having a ratio of the major axis length to the minor axis length of 0.3 and orientation of 25 degrees.

When we want to evaluate a method or an analysis, it is critical that we evaluate the appropriateness of the geometry of the model that we are claiming as a basis of a set of results. We believe that when authors state certain claims regarding a certain subpopulation, they should validate that their model corresponds within statistical significance of the experimental subpopulation possibly within the context of race, ethnicity, gender, and age.

Archeological studies analyzing the cranial structures of prehistoric man use covariation of multiple traits to investigate the evolutionary changes of man via computational geometric analyses supported by multivariate statistics. Stochastic factors generate a set of anatomical possibilities and constraints in the determination of prehistoric evolution, which can be applied to the shape and size distinctions of various subpopulations according to ethnicity and gender. Currently, the key areas of development that we can adopt are morphological modularity, anatomical integration, and heterochrony.

We can further look to cranial morphology to enhance our models. Bruner (2007) investigated the evolution of the cranium through the scope of allometry, indicating that the size and shape of the skull changes due to adaptations as well as stochastic factors. They attributed the increase in volumetric cranial capacity as one of the primary factors affecting the cranial shape. Additionally, the neocranium, face, and base of the skull change in shape and size as a result of the growth of the internal organs, primarily the brain, thus leading us to the connection between modern man, the *Homo sapiens*, and his three prehistoric counterparts originating from *Homo ergaster*.

Many anthropologists no longer accept that modern man has evolved from one sole ancestor but has independently evolved in parallel through at least 3 differently evolved human species: *H. sapiens* in Africa, *H. neanderthalensis* in Europe, and *H. erectus* in Asia Bruner (2007); Manzi (2004); Rightmire (1998; 2001); Stringer (2002). It is clearly evident that different ethnic groups today have different shapes both in the cranial features as well as the cranial case. We can plausibly relate the cranial capacity of various ethnic groups to their prehistoric differences Bruner (2007). In 1870 Huxley (1870) mildly focused on cranial shape. By 1962 Coon (1962) described five racial types (i.e. skull shapes) based upon craniofacial features: *Caucasoids* from Europe, West Asia, and parts of India; *Capoids* from South Africa; *Congoids* from sub-sahara Africa; *Australoids* from Australia, New Guinea, and Melanesia; *Mongoloids* from East Asia and arctic North America. Capoids and Congoids are the two main branches of the single African race known as negroids.

Today forensic anthropometry and reconstructive surgery utilize and apply racial types to obtain appropriate craniofacial metrics. Depending on the specific requirements, only three racial types are considered instead of five - Caucasoids, Mongoloids, and Negroids. We concur that using a normalized representative of each of these three groups as the basis for mathematical manipulation will allow us to more plausibly derive the different head shapes across different ethnic groups belonging to each class with localized deformations such as in the frontal, temporal, or occipital lobes. Mathematically it is easier to make these manipulations while staying within one racial type due to the complex relation of multiple craniofacial metrics. If we consider the midsagittal profile, most Caucasoids have a rounded profile, Mongoloids have an arched profile, and Negroids have a flat profile.

We should consider the effects of shape versus size changes. Whether we reference our current universal base model or these three representative racial base models, mathematical congruency associated with growth will have the same effect Bruner (2007). Figs. 2 and 3 correctly scale each ethnic model in terms of head breadth, length, and depth per international anthropometric surveys Farkas et al. (2005); Howells (1973). Contrastingly, our exponential and elliptical transformation of our universal caucasian model across racial types does not fully exhibit the cranial or facial metrics of the new (target) ethnic groups of the target racial type. In the instance of the cross racial transformation the new model fails to assume the correct shape of the midsagittal profile of its racial type. In order to accomplish this, we need to further employ a combination of multiple deformations considered together and to increase our statistical survey according to Farkas et al. (2005) or we need to define a few generic templates to truly capture the behavior of the skull.

8. Conclusion

The current and near future of an exposition on EEG measurement sensitivity distributions will benefit many clinical neurophysiologists such as anesthesiologists, neurologists, and cognitive neuroscientists. These benefits will come from the adaptation of highly detailed generic volume conductor models assessing different electrode types and locations (Wendel, Väisänen, Seemann, Hyttinen & Malmivuo, 2010). Anthropometric data currently exists detailing deformations in craniometric landmarks; however, a database of landmark sizes coupled with age (Wendel, Väisänen, Seemann, Hyttinen & Malmivuo, 2010), gender (Wendel, Väisänen, Seemann, Hyttinen & Malmivuo, 2010), ethnic origin (Wendel, Osadebey & Malmivuo, 2009), and head shape (Wendel, Osadebey & Malmivuo, 2009) would improve the accuracy of the overly used fixed-geometry in highly complex models.

We found that mathematically deformed generic models can represent various ethnic groups. We applied the power function and elliptical function to more accurately reflect the profiles associate with each ethnic group. We can partially mathematically reflect the new shape of the midsagittal profiles of the target racial type. In our goal of EEG modeling, we aim to primarily fit the cranial case to the patient although the facial features may represent another individual. According to the field of anthropometry, we found grounds for requiring three base models destined for mathematical manipulation – one of each racial type: *Caucasoid*, *Mongloid*, and *Negroid* or the need to acquire more statistically databased medically-imaged data according to ethnicity.

9. Acknowledgements

The authors would like to thank the Academy of Finland (project number 123159: 2008 – 2011), the Ragnar Granit Foundation, the International Graduate School on Biomedical Engineering and Medical Physics (iBioMep), the Alfred Kordelin Foundation, and the Department of Biomedical Engineering, Tampere University of Technology for funding this work. Furthermore, we would like to express our gratitude to Prof. Jaakko Malmivuo, who guided us in the field of EEG.

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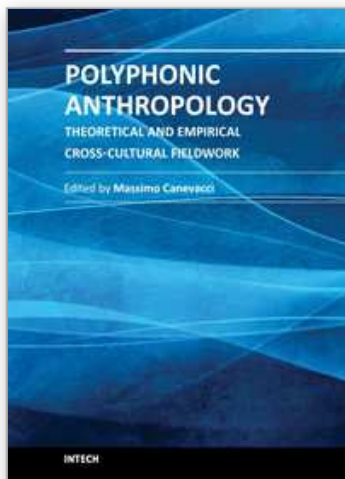
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Polyphonic Anthropology - Theoretical and Empirical Cross-Cultural Fieldwork

Edited by Prof. Massimo Canevacci

ISBN 978-953-51-0418-6

Hard cover, 242 pages

Publisher InTech

Published online 23, March, 2012

Published in print edition March, 2012

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How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Katrina E. Wendel-Mitoraj and Michael E. Osadebey (2012). Applying Craniofacial Metrics to Adapt 3D Generic Head Models, Polyphonic Anthropology - Theoretical and Empirical Cross-Cultural Fieldwork, Prof. Massimo Canevacci (Ed.), ISBN: 978-953-51-0418-6, InTech, Available from:

<http://www.intechopen.com/books/polyphonic-anthropology-theoretical-and-empirical-cross-cultural-fieldwork/applying-craniofacial-metrics-to-adapt-3d-generic-head-models>

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Phone: +86-21-62489820
Fax: +86-21-62489821

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