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The 3D Facial Norms Database: Part 1. A Web-Based Craniofacial Anthropometric and Image Repository for the Clinical and Research Community

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Supplementary Data

Tables containing age- and sex-specific summary statistics as well as distance growth curves (with standard centiles) for all measurements in the 3DFN dataset are available in a supplement to this article.

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Abstract

Objective—With the current widespread use of 3D facial surface imaging in clinical and research environments, there is a growing demand for high quality craniofacial norms based on 3D imaging technology. The principal goal of the 3D Facial Norms (3DFN) project was to create an interactive, web-based repository of 3D facial images and measurements. Unlike other repositories, users can gain access to both summary-level statistics as well as individual-level data, including 3D facial landmark coordinates, 3D-derived anthropometric measurements, 3D facial surface images and genotypes from every individual in the dataset. The 3DFN database currently consists of 2454 male and female participants ranging in age from 3–40 years. These subjects were recruited at four US sites and screened for a history of craniofacial conditions. The goal of this paper is to introduce readers to the 3DFN repository by providing a general overview of the project, explaining the rationale behind the creation of the database, and describing the methods used to collect the data.

Supplement—Sex and age-specific summary statistics (means and standard deviations) and growth curves for every anthropometric measurement in the 3DFN dataset are provided as a supplement. These summary statistics and growth curves can aid clinicians in the assessment of craniofacial dysmorphology.

Keywords

3D Facial Imaging; Stereophotogrammetry; Norms; Anthropometry

The Importance of Normative Craniofacial Data

The success of investigations into the underlying causes and effective treatment of craniofacial malformations depends on the acquisition of objective, reliable, and carefully collected data on the craniofacial phenotype. Many individuals with congenital anomalies that affect the head and face present with subtle morphological disturbances. Implicit in any description of facial dysmorphology is the notion that the phenomenon under consideration represents a deviation from some “normal” or baseline state. Thus, all descriptions of dysmorphology are inherently comparative by nature. As a consequence, an understanding of what constitutes the range of normal variation for craniofacial features is essential. Although attempts to quantify the human face date back to antiquity, standardized methods for measuring the human face were only developed in the early 20th century (Hrdlicka,

1952; Kolar and Salter, 1997). In response to the need by the clinical community for population-based norms, large datasets comprised of standardized facial anthropometric or cephalometric measures were eventually constructed (Feingold and Bossert, 1974; Saksena et al., 1987; Farkas and Munro, 1987; Farkas, 1994). In order to fully capture the variation present in the general population while simultaneously providing age-, sex- and ethnicity-specific normative data, large numbers of healthy individuals were required for these databases. These normative datasets are routinely used by clinicians and researchers to determine how measurements from where a particular patient or subject compare to those of their peers (e.g., by constructing Z-scores) and to perform group-based morphological comparisons (e.g., Kolar et al., 2010). When quantitative measurements are combined with genomic information within a single craniofacial database, the possibility of mapping the genes that underlie normal variation in craniofacial traits becomes possible (Paternoster et al., 2012).

Existing Craniofacial Normative Repositories and their Limitations

Available collections of normative data on facial measures typically suffer from one or more major technical and/or demographic limitations. Almost all existing databases are comprised of measures derived entirely from either cephalometry (Saksena et al., 1987; Love et al., 1990; Bhatia and Leighton, 1993; Basyouni and Nanda, 2000) or traditional anthropometry (Garrett and Kennedy, 1971; Feingold and Bossert, 1974; Hajnis, 1974; Juberg et al., 1975; Dekaban, 1977; Jones et al., 1978; Sivan et al., 1984; Farkas and Munro, 1987; Méhes, 1987; Gordon et al., 1989; Farkas, 1994; Borman et al., 1999; Porter and Olson, 2001; Bozkir et al., 2003; Farkas et al., 2003; 2004; Cho et al., 2006; Du et al., 2008). Because cephalometry results in a flattened 2D representation of complex 3D structures, measures based on this imaging modality are inherently limited in their ability to accurately capture important aspects of facial morphology (Moyers and Bookstein, 1979, McIntyre and Mossey, 2003). In addition, the imaging process involves radiation exposure. For normative craniofacial data resources based on traditional anthropometry, measures are taken manually with calipers, angle finders and/or rulers (Lohman et al., 1988; Hall et al., 1989; Farkas, 1994; Kolar and Salter, 1997). This process is time consuming, requires specialized training, and is often poorly tolerated by very young children. In addition, the calibration of measurement protocols across examiners can be difficult, particularly when measurements are being collected by different research teams at different sites (as is often the case when collecting very large datasets). The most well known and most comprehensive dataset of this kind was compiled by Dr. Leslie Farkas and colleagues in the 1980’s and 1990’s (Farkas, 1994). Kolar (1993) has pointed out numerous problems with this particular dataset, the most serious of which stem from inconsistent data collection protocols. Another major source of normative facial anthropometric measures are military datasets (Garrett and Kennedy, 1971; Gordon et al., 1989; Young, 1993), however these generally contain a very limited number of craniofacial measures, many of which are not included in the medical anthropometry canon, and are confined to a narrow age range.

Regardless of their target population, available craniofacial anthropometric databases all share some additional demographic limitations. For example, biomedically-oriented datasets rarely include measures on individuals over the age of 18 years, and often use overly broad

age intervals for very young individuals. Many of these sources are comprised of data collected decades ago, opening up the possibility that their norms are no longer relevant due to secular population trends (Jantz et al., 2000). Likewise, very little data are currently available for non-European Caucasian samples. A further limitation relates to the fact that currently available normative databases present only summary data; i.e., only age- and sex-specific means and standard deviations are available for various anthropometric measures. Lack of access to the original source material (i.e., individual-level data) severely limits the ability of outside investigators to perform additional analyses. Unfortunately, many researchers, in their desire for convenient normative data, have simply ignored these limitations. For example, older adult subjects are sometimes matched against database norms for much younger individuals, despite ample evidence that the face continues to change throughout the lifespan (Baer, 1956; Behrents, 1985). Clearly, new and expanded normative craniofacial resources are needed.

The Need for Craniofacial Norms in 3D

Standard anthropometric data on the head and face can also be obtained in 3D using a variety of imaging modalities. Not all modalities, however, are amenable to large-scale normative phenotyping. Although 3D CT technology is readily available, the scanning costs and radiation exposure make this imaging modality problematic. While MRI does not expose subjects to radiation, it has similar cost constraints. Moreover, neither imaging modality is optimized for capturing facial surface data on living subjects, in part due to their long scan times. Non-contact surface-based 3D imaging devices are, however, perfectly suited for this task. Laser scanning devices, although used principally in engineering and industrial design applications, have been adapted for medical imaging (Moss et al., 1989; Aung, 1999; Da Silveira et al., 2003). Although highly accurate 3D models are possible with laser scanning, relatively slow capture times, limited facial surface coverage and patient concerns about lasers are persistent problems. Due to these limitations, alternative surface imaging technologies have largely taken the place of laser scanning for craniofacial applications.

The latest generation of 3D digital stereophotogrammetry devices, for instance, allow for extremely fast (1/500 second) captures of the entire facial surface in a completely noninvasive manner (Jacobs, 2001; Weinberg and Kolar, 2005; Carnicky and Chorvat, 2006; Lane and Harrell, 2008). Briefly, in 3D digital stereophotogrammetry, the participant’s face is simultaneously captured by multiple imaging sensors with overlapping fields of view. During image capture, a light pattern is typically projected onto the facial surface, which guides stereo-triangulation algorithms to construct a geometrically accurate 3D surface model comprised of thousands of discrete points with known XYZ coordinate locations. The resulting 3D model can be visualized as a simple mesh surface or rendered in a photo-realistic manner, with surface features like skin color and texture mapped in high-resolution onto the underlying geometry. The accuracy and precision of anthropometric measures derived from 3D stereophotogrammetric images is now well established (Ayoub et al., 2003; Weinberg et al., 2004; Aldridge et al., 2005; Losken et al., 2005; Krimmel et al., 2006; Wong et al., 2008). Over the last decade, these devices have become more streamlined and

affordable, and now “turnkey” stereophotogrammetry systems are commonplace in many research and clinical centers (Heike et al., 2009).

Although, in principle, measures derived from 3D surface images can be compared to data in traditional anthropometric databases, this is far from ideal. Many measurements simply do not translate well from one method to the other (Weinberg and Kolar, 2005). Furthermore, the results of studies designed to compare measures from 3D images to direct anthropometry are equivocal at best; some 3D systems perform better than others, and some kinds of measurements are more consistent across methods than others (Aung et al., 1995; Baca et al., 1994; Shaner et al., 1998; Douglas et al., 2003; Weinberg et al., 2004). This problem is compounded when the normative data being compared against were collected by an independent set of examiners several decades earlier. These facts argue that *3D imaging methods ultimately require 3D normative data*. Consequently, because comprehensive 3D normative anthropometric databases have generally not been available, researchers have been required to collect their own private control samples in order to carry out proper morphological comparisons. This amounts to an inefficient duplication of effort and may even negatively impact study quality, since research groups must direct substantial time, energy and finances at recruiting controls instead of more cases.

Despite the many benefits and widespread use of 3D facial surface imaging, few comprehensive normative anthropometric datasets based on this technology currently exist (Hammond and Suttie, 2012). While there have been several notable efforts to acquire 3D facial images on large numbers of healthy individuals (Ferrario et al., 1999; Yamada et al., 2002; Sforza et al., 2004; Marcus et al., 2009; Evison et al., 2010; Gor et al., 2010; Lipira, 2010; Toma et al., 2012), these 3D datasets unfortunately share many of the same limitations as more traditional anthropometric datasets. For example, these datasets are typically limited in terms of demographic coverage or employ sampling strategies that severely limit their use as norms. More importantly, though, these existing 3D datasets – in particular the raw individual-level data that comprise these datasets – are generally not accessible by outside researchers. They effectively exist as private datasets, with access limited by design and collected with the intention of being used by only a small group of investigators. Furthermore, none of these datasets currently provide any means for the broader research and clinical community to interact with them in a meaningful way. These limitations severely diminish the usefulness and potential of existing 3D facial datasets to impact scientific discovery and clinical care.

The 3D Facial Norms Project

For all of the reasons highlighted above, the 3D Facial Norms (3DFN) project was initiated in 2009 as part of the FaceBase Consortium (https://www.facebase.org), a National Institute of Dental and Craniofacial Research (NIDCR) initiative. In its initial configuration, the FaceBase consortium consisted of 10 interlinked projects focused on generating craniofacial research data (e.g., tissue-specific gene expression arrays, phenotypic image atlases, genotype-phenotype databases) across multiple organisms and a central bioinformatics hub whose mission is to integrate these datasets and make them available to the broader scientific community (Hochheiser et al., 2011). The principal goal of the 3DFN project was to

construct a large, web-based, interactive craniofacial normative database comprised of 3D facial images, morphometric variables, qualitative descriptors, and genomic markers for both the clinical and research community (https://www.facebase.org/facial_norms). Through its web interface users can perform highly customizable searches of the 3DFN database and – assuming they have the proper permissions – download individual-level data, including 3D images and genotypic markers, for their own analyses. No other normative craniofacial database allows this type of interactive querying and downloadable access to original source data. The remainder of this paper will provide a basic overview of the 3DFN database.

Recruitment and Screening of Participants

During the initial five-year phase of the 3DFN project, the goal was to recruit 3500 unrelated individuals ranging in age from 3–40 years. This total recruitment figure was based on the ideal scenario of recruiting 50 males and 50 females at each age category (Kolar and Salter, 1987). The current dataset contains 2454 individuals: 952 males and 1502 females. The basic age categories and the age and sex distribution are provided in Table 1. Recruitment for this first phase was limited to individuals of recent European ancestry. Ancestry was self-reported by participants, who were asked to confirm that all of their maternal and paternal grandparents were of European descent. Both the age and ancestry restrictions in the initial project phase were due largely to issues of feasibility and cost, and our goal is to expand the database to capture additional racial/ethnic groups and ages in the future.

Individuals were recruited for the 3DFN project at four US sites across the country: Pittsburgh PA; Seattle, WA; Houston, TX; and Iowa City, IA. The strategy for recruitment involved a combination of targeted advertisement, peer referral, leveraging existing research registries, and participation at public venues (e.g. museums, state fares). Participants were pre-screened either prior to appointments or on-site by study recruiters. Participants or their parents were asked to verify their ancestry and age. Additional exclusion criteria included any of following: (1) personal history of facial trauma, (2) a personal history of facial reconstructive or plastic surgery, (3) a personal history of orthognathic/jaw surgery or jaw advancement, (4) a personal history of any facial prosthetics or implants, (5) a personal history of any palsy, stroke or neurological condition affecting the face, (6) a personal or family history of any facial anomaly or birth defect, and/or (7) a personal or family history of any syndrome or congenital condition known to affect the head and/or face. Further, we excluded individuals with non-removable facial piercings other than small studs and/or the presence of prominent facial hair. Participants who arrived for study appointments with an unacceptable amount of facial hair were given the opportunity to shave on-site or return at a later time.

Phenotyping Protocol

The entire study protocol was completed in less than 30 minutes for most participants. Following informed consent, each participant was assigned a unique alphanumeric sequential study ID. A brief demographic questionnaire was then administered to capture the participant's self-reported age, sex, ancestry, height and weight. Using Oragene collection kits (DNA Genotek Inc., Ontario, Canada), a single saliva sample was obtained for

participants over the age of five; for participants under five years of age, two samples were obtained to ensure adequate DNA yield. All participants were asked not to eat or drink anything for at least 30 minutes prior to their appointment, so as not to interfere with saliva collection. For children unable to spit into the collection tube, Oragene sponge applicators were used to collect saliva directly from the oral cavity. Participants who experienced difficulty producing adequate saliva were offered packets of sugar to stimulate saliva flow. Each kit was labeled using a matrix barcode containing the participant's coded study ID to facilitate electronic sample tracking and processing.

Following saliva collection, a series of five craniofacial measurements were obtained on each participant using traditional spreading calipers. These measurements were deemed important for providing a complete description of the craniofacial phenotype (e.g., head width and length) but are difficult to obtain indirectly from 3D surfaces (Weinberg and Kolar, 2005). These measurements are listed in Table 2.

Participants then had their facial surface captured via 3D stereophotogrammetry. All recruitment sites used the same validated 3D surface imaging technology from 3dMD (Atlanta, GA); all sites used two-pod 3dMDface systems, while one site also used a multi-pod 3dMDcranial system designed to capture 360-degree images of the head. In preparation for facial imaging, participants were asked to remove any jewelry or accessories that could interfere with the capture process. When necessary, the participant's hair was pinned back to keep it from obscuring the ears and forehead. Selected landmarks were labeled directly on the participant's face using skin-safe markers (e.g., tragion, gnathion and pronasale) in order to facilitate later landmark identification from the resulting 3D surface images. Participants were positioned in front of the imaging system with their head facing forward and titled slightly back to ensure coverage under the nose and chin. During capture, participants were instructed to keep their eyes open and their lips gently closed, to maintain a neutral facial expression, and to keep their face relaxed. Each capture was inspected on the spot to ensure 3D surface quality and additional captures were obtained as needed.

Saliva Sample Processing

Completed Oragene kits were sent via mail from each recruitment site to the coordinating center (University of Pittsburgh) for processing. Upon receipt, the barcode ID labels were read with a scanner and entered into sample tracking log spreadsheet. Using standard protocols, the DNA was extracted from each sample and aliquots were stored for genotyping.

3D Image Processing, Landmarking and Inter-landmark Distance Calculation

3D facial surface files were transmitted electronically from each recruitment site to the coordinating center on a rolling basis. At the coordinating center, the 3D surfaces were inspected for initial quality and cleaned. Cleaning involved discarding extraneous portions of the 3D model such as excessive hair and portions of the neck and shoulders. The trimmed 3D model was then rotated to a standard face-forward position and re-saved, preserving the

new orientation. No surface smoothing or hole-filling routines were run on any of the facial surfaces. A standard set of 24 facial surface landmarks was then collected from each 3D facial model (Figure 1). The choice of facial landmarks was based on providing the maximizing facial coverage while minimizing the error associated with landmark identification on 3D surfaces. A detailed account of the procedures used to identify these landmarks on 3D facial surfaces can be found on the “Technical Notes” section of the 3DFN website: https://www.facebase.org/facial_norms/notes. The final image processing step involved exporting the cleaned 3D facial model as an object wavefront (.obj) file.

Using an automated process, the 24 landmark coordinates collected from each 3D facial surface were combined into a single relational database. A set of 29 inter-landmark facial measurements was then generated automatically. These distances correspond to traditional anthropometric facial measurements (Farkas, 1994) and were chosen primarily on the basis of clinical utility. The calculated anthropometric measurements are listed in Table 2.

Quality Control of Phenotypic Data

Quality control starts at 3D image acquisition. Study staff at each recruitment site were trained on proper acquisition technique and how to evaluate 3D facial surfaces for quality and coverage (Heike et al., 2010). Once 3D surfaces were received at the central coordinating center, trained raters again evaluated the surfaces for initial quality. Only if a 3D surface was deemed of sufficient quality to proceed did trained evaluators proceed to landmarking. To ensure quality and consistency, each evaluator engaged in landmarking completed a three-phase training process prior to working with any 3DFN surfaces. In the first phase, presumptive evaluators were required to familiarize themselves with landmark definitions and identification strategies. In the second phase, evaluators were introduced to the landmarking software environment (3dMDvultus) and asked to identify all 24 landmarks on a test set of 10 different facial surfaces of varying age and sex. An independent expert then reviewed the placement of the landmarks and provided feedback to the evaluator regarding any problems. In the third phase, the evaluator must landmark an additional test set of 20 surfaces twice, with at least 48 hours between landmarking sessions. The degree of Intra-observer error was then assessed by comparing the x,y and z components of each landmark across the two sessions with intraclass correlation coefficients. The threshold for acceptable intra-observer error for each landmark in each of the three principal axes is 0.90. Values below this threshold indicate that additional practice is required, and evaluators may not proceed to working on 3DFN data until they have successfully remediated.

Following collection, additional quality control measures are in place to check the resulting landmark data and derived measurements. Using a semi-automated process, the 24 landmark coordinates collected from each 3D facial surface were screened for common errors such as incorrect order and left-right reversals. This was accomplished by visually inspecting the landmark configuration for each subject as a simple wireframe using a locally developed program and subjecting the landmark coordinate data to simple logic rules based on expected spatial patterns.

Each of the automatically generated set of 29 inter-landmark distances for each participant was then screened for outliers by calculating sex and age appropriate Z-scores. Z-scores greater/less than 3.0 were flagged and the participant's 3D surface was checked manually for errors in landmark placement or potential problems with the participant's age.

Demographic information and traditional caliper measurements were collected using machine-readable data collection forms. These forms were transmitted as PDFs from the recruitment sites to the coordinating center, where they were scanned, verified and automatically uploaded to a database. All form data collected were screened for outliers and discrepancies.

Exploring and Interacting with *Summary-Level* Phenotypic Data

3DFN data are available for investigators at both the summary and individual level. Summary-level data are aggregated and include linear facial measurements averaged for the various age and sex groups. These summary data are akin to the traditional tabulated norms available from direct anthropometry by Farkas and others, except they are derived from 3D surface images. Means and standard deviations are available for the entire set of 29 3D-derived linear distances and the handful of additional measurements obtained manually using calipers; they are available for males and females separately and the sexes combined, at each age category from 3–40 years. For the summary statistics, age categories were set at one year intervals from 5–30 years. From age 3–5 years, the data were divided into half-year intervals, to better capture the rapid facial growth during this period (Table 1). For ages above 30 years, participants were lumped into two year age intervals. Figure 2 shows a partial screenshot from the 3DFN web interface showing age- and sex-specific summary statistics for a given measurement.

In addition to basic search and viewing, website users can interact with summary data through a Z-score calculator tool. With this tool users are able to compare measurements obtained from an outside research subject or patient to the 3DFN Dataset (Figure 3). The user simply enters the sex and age of the subject to be compared and selected the measurement of interest. This can be done for multiple measurements simultaneously, providing the clinician with an overall picture of how similar (in standard deviation units) a given patient is to the average of their sex and age-matched peers. Of course, the validity of such comparison assumes that the patient's measurements being compared are collected using similar methods. Those who wish to use the mean and standard deviation data in order to carry out their own comparisons are also able to download the full summary statistics for each measurement in the 3DFN Dataset as a *.csv* file; this can be accomplished directly through the project website.

Through the FaceBase Consortium all phenotypic summary data belonging to the 3DFN Dataset are available *unrestricted* to the craniofacial research and clinical community as well as the general public. In addition, summary statistics and growth curves (with standard centiles) for each measurement are available in a supplement to this article. General terms of use, including requirements for attribution, are described in a Data Use Certification document available through the FaceBase website.

Querying and Obtaining *Individual-Level* Phenotypic Data

One of the major advantages of the 3DFN Database is that users need not be limited to the simple summary statistics provided through the web interface. In 3DFN, *the raw phenotypic data for each individual participant in the repository are also obtainable*. Available individual-level phenotypic data include the entire set of 24 3D facial landmarks (and their associated x,y,z coordinate positions), all 34 anthropometric facial measurements (inter-landmark distances) and basic demographic and physical descriptors (e.g., height) for every participant in the 3DFN Database. In addition to the variables listed above, *the entire set of 2454 3D facial surfaces is available* to researchers and clinicians with the proper credentials. These 3D surfaces have been stripped of identifying color and texture surface features, leaving only the surface geometry and are available in the non-proprietary object wavefront (*.obj*) format, which can be opened with a wide variety of commercial and free 3D image visualization programs (e.g., Meshlab).

The individual-level data can be queried through a simple point-and-click graphical web interface where users can define search parameters (Figure 4). For example, users can limit queries to only one sex or a specific age or range of ages. Further, users can limit searches to specific variables of interest: landmarks, linear distances, 3D facial surfaces, etc. Through this contextualized search, users can investigate how many individuals in the 3DFN Dataset have specific phenotypic data of interest. Searches can be very narrow or very broad. A user, for example, could construct a very narrow query to ask how many five-year old males in the dataset have a single measurement available. Alternatively, a user could investigate all measurements in both males and females across all possible ages. Once the query is submitted a results page is returned showing the number of individuals contained within the 3DFN Dataset that meet the under-defined criteria and the frequency of missing data. The search process can then be repeated, revising the criteria each time.

An important point for potential users to understand is that access to individual-level phenotypic data in 3DFN is controlled. Outside investigators must apply for access directly through the FaceBase Consortium. The application process involves several steps: (1) preparing a Data Access Request form specifying the type(s) of data being sought and the nature of the research being conducted, (2) signing a Data Use Certification document that specifies the rules and obligations investigators must adhere to should they be granted access, and (3) providing evidence of appropriate IRB or local ethics committee review of the proposed work. The level of IRB/ethics review required depends in part on the exact type of data being requested. A data access committee led by the NIDCR reviews each data request. More details regarding access to human datasets can be found on the FaceBase website.

Once access is granted, investigators have the ability to work with the full dataset locally; the data will be delivered as a standard flat file, which can be opened by any spreadsheet program. Guides to variable naming, definitions and coding is available on the “Technical Notes” portion of the 3DFN website. With these data in hand, investigators can perform any number of analyses using the landmark coordinates and/or measurements provided, or new and additional measurements can be derived. If the investigator requests and is granted

access to the 3D facial surfaces, a virtually unlimited number of phenotypes can be derived opening up a multitude of possibilities for analysis.

To our knowledge, 3DFN is the only dataset currently available that allows interaction with and access to large-scale, individual-level craniofacial anthropometric data, including raw 3D facial surfaces.

Availability of Genomic Data

Another critical element that makes the 3DFN Database unique is the availability of genotype data in addition to phenotypic measurements and 3D facial surfaces. In collaboration with the Center for Inherited Disease Research (CIDR), subjects in the 3DFN Database have been genotyped using a genome-wide association (GWA) array consisting of 964,193 SNPs (Illumina OmniExpress+Exome v1.2) plus an additional 4322 custom SNPs chosen based on prior craniofacial genetic studies. The genetic dataset has been imputed using the 1000 Genomes reference panel and quality checked according to protocols developed at the University of Washington CIDR Genetics Coordinating Center. The availability of high-resolution genetic markers in conjunction with derived anthropometric phenotypes and 3D facial surfaces makes the 3DFN Dataset a powerful resource for the craniofacial research community. The genomic data will be available to researchers through dbGaP's controlled access repository (http://www.ncbi.nlm.nih.gov/gap) starting in 2016 (accession number: phs000949.v1.p1).

Potential Uses for the 3DFN Database

Control Data for Craniofacial Comparisons

Collecting craniofacial control data for comparison purposes is essential for many research questions involving facial morphology. This can be a time consuming and expensive effort, and very often the resulting control samples are too small to adequately capture the range of normal human facial variation. As a source of normative control data, the 3DFN Database is designed to facilitate the comparison of facial morphology. Because age, sex and ancestry are available for every subject in the 3DFN Dataset, comparisons that require strict matching are possible. Further, morphological comparisons can be based on traditional linear distances, 3D landmark coordinates and/or entire 3D facial surfaces, allowing users to employ a wide variety of morphometric analysis methods. As an example, the 3DFN dataset was recently used in a comparative study of nasal asymmetry in orofacial clefting (Hong et al., 2015).

Analyses of Human Craniofacial Variation and Growth

The 3DFN Database is an excellent resource for exploring questions relating to patterns of human facial variation and growth. For example, one can investigate how the face changes over the lifespan, how sex differences are manifested in facial structure, or how various facial structures are integrated during growth. These questions are of particular interest to those working within the fields of physical anthropology, orthodontics and forensics. In a recent analysis, the 3DFN database was used to investigate the relationship between prenatal

sex hormone exposure (estimated from second-to-fourth digit ratio) and facial shape in male adults (Weinberg et al., 2015).

Genomic Studies of Quantitative and Qualitative Craniofacial Traits

One of the principal goals of the 3DFN Database is to provide researchers with the raw materials to explore the genetic basis of normal human facial variation. As mentioned above, genome-wide SNP markers for individuals with phenotypic information contained in the 3DFN Dataset will be made available through the dbGaP repository. Importantly, the genomic data can be used as an extension and/or replication arm for existing or planned GWA analyses of normal human facial traits. Several large-scale genotype-phenotype studies of this type have been carried out in recent years (Paternoster et al., 2012; Liu et al., 2012).

The Development of Novel 3D Image Analysis Methods

The large number of 3D facial surfaces available through the 3DFN Database provide a unique resource and testing platform for computer science and computer vision experts engaged in the development of novel methods for representing and analyzing human facial surfaces. For example, the 3DFN dataset has been used recently to develop improved methods for automated facial landmarking (Liang et al., 2013).

Limitations

Although in many ways the 3DFN database is one of the most comprehensive resources of its kind, it is not without limitations. Most obviously, the current dataset is limited to individuals living in the US who by self-report consider themselves white, non-Hispanic and of recent European ancestry. The lack of availability of non-white craniofacial norms continues to be a major problem. A handful of 3D studies have begun to address the problem (Yamada et al., 2002; Lipira et al., 2010), but these datasets are still limited in scope and scale. The situation needs to be rectified, but the prospect of obtaining multi-ethnic 3D norms, while maintaining adequate numbers in each age and sex category, is both daunting and expensive. An undertaking of this magnitude would undoubtedly take a coordinated effort involving many investigators over a number of years.

The 3DFN dataset is also limited in the ages covered, most seriously at the younger end of the spectrum. We opted to set the lower age cutoff at three years for practical reasons. Consequently, there remains a serious lack of adequate craniofacial norms for very young children – whether 3D or traditional. Currently available craniofacial norms also do not provide fine enough age intervals to capture the rapid rate of craniofacial growth during this period. The Farkas dataset (Farkas 1994), for example, provides data at only two intervals during the first year of life: 0–6 months and 6–12 months. Such intervals are far too broad to be of any practical use. A comprehensive project to capture 3D norms at very fine age intervals during the first few years of life would be of great importance to the clinical community, as surgical corrections for virtually all of the major craniofacial anomalies occur during these years.

As it currently stands, the 3DFN dataset also suffers from inadequate representation in certain age groups within the available 3–40 year span. Particularly problematic are the numbers in the 14–17 year old age range. Despite our best efforts to recruit older adolescents we did not meet our minimum targets. As a result, users should exhibit particular caution when comparing against or making conclusions based on data from these more poorly represented ages. Depending on the nature of the research being conducted, it may be possible to combine some of these ages together, thereby increasing the sample size. Because users can gain access to the raw individual-level measurement data, the 3DFN database provides this type of flexibility.

Despite these limitations, the 3DFN database remains a valuable resource for the clinical and research community. Because the database was built to be scalable, it can be expanded to accommodate additional age groups and ethnicities in the future.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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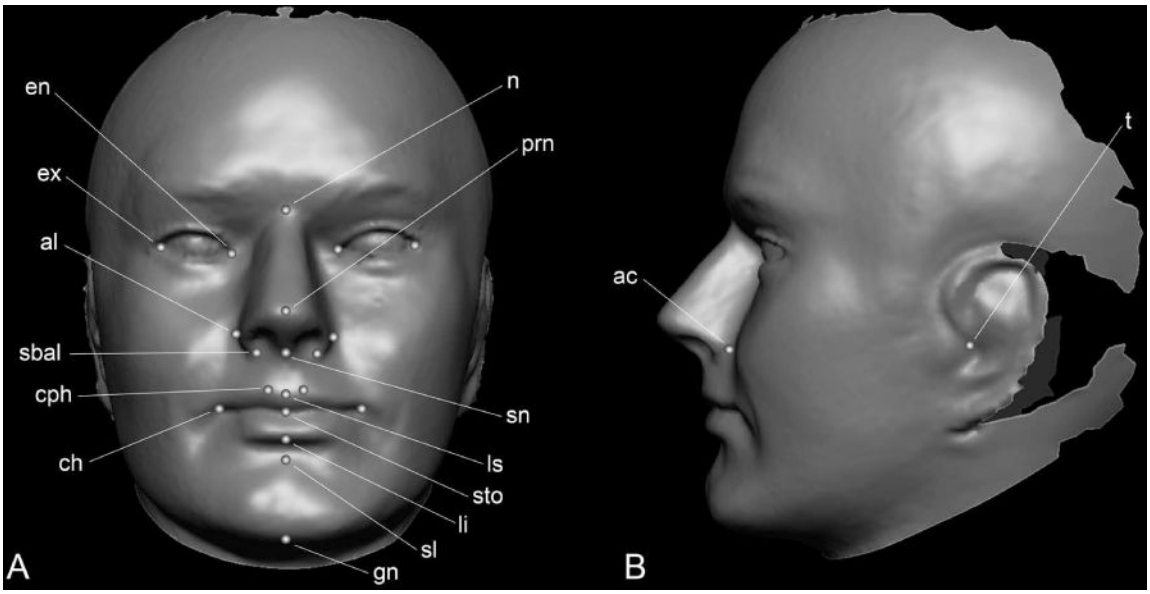
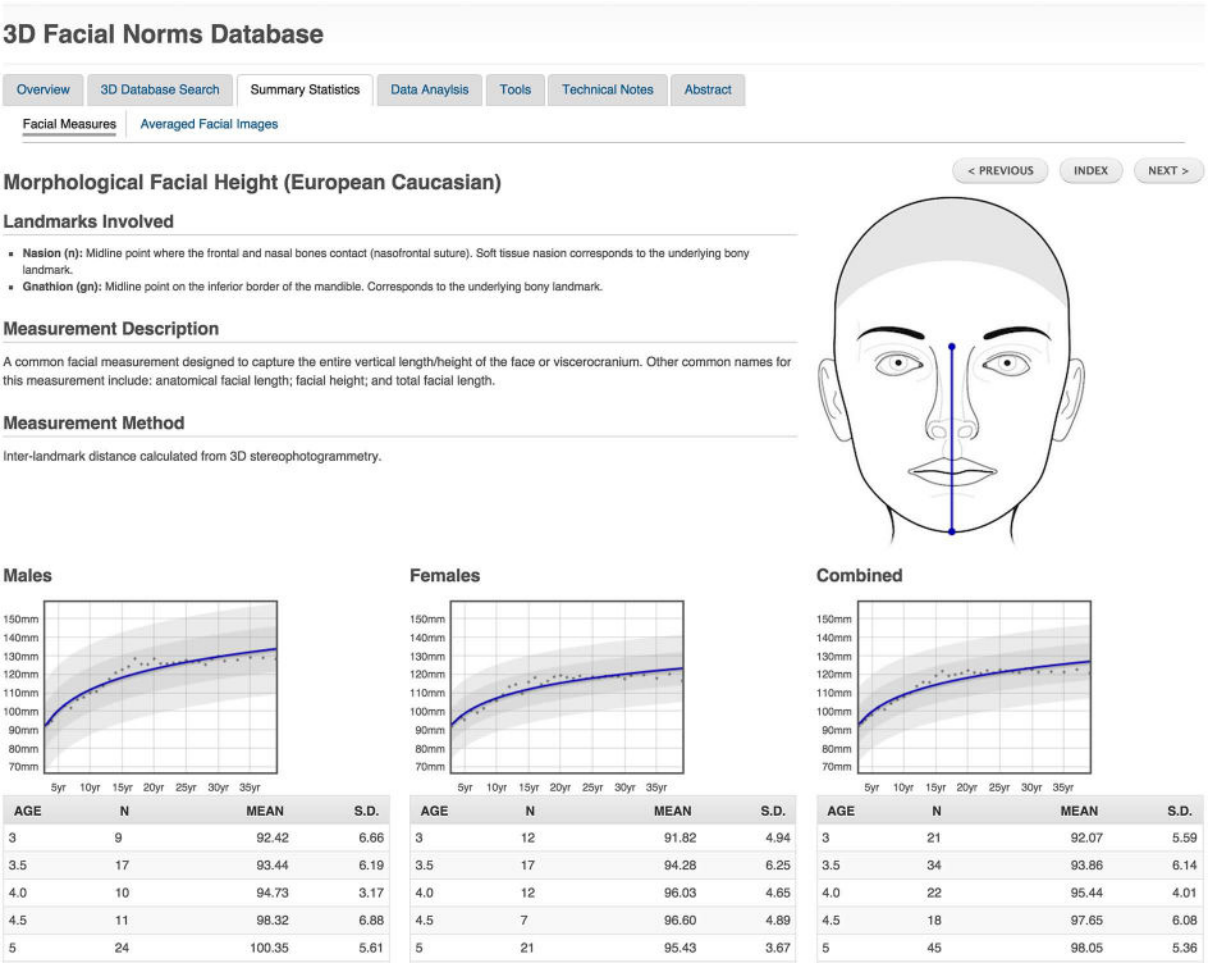


FIGURE 1.

3D facial surface model showing the 24 standard landmarks included in the 3DFN database. Landmarks shown in frontal view (A) include: n = nasion; prn = pronasale; sn = subnasale; ls = labiale superius; sto = stomion; li = labiale inferius; sl = sublabiale; gn = gnathion; en = endocanthion; ex = exocanthion; al = alare; sbal = subalare; cph = crista philtra; ch = chelion (for bilateral points only right side labeled). Landmarks shown in the lateral view (B) include: ac = alar curvature point and t = tragion (only left landmark shown for these two bilateral points).



AGE	N	MEAN	S.D.
3	9	92.42	6.66
3.5	17	93.44	6.19
4.0	10	94.73	3.17
4.5	11	98.32	6.88
5	24	100.35	5.61

AGE	N	MEAN	S.D.
3	12	91.82	4.94
3.5	17	94.28	6.25
4.0	12	96.03	4.65
4.5	7	96.60	4.89
5	21	95.43	3.67

AGE	N	MEAN	S.D.
3	21	92.07	5.59
3.5	34	93.86	6.14
4.0	22	95.44	4.01
4.5	18	97.65	6.08
5	45	98.05	5.36

FIGURE 2.

Partial screenshot from the 3D Facial Norms website interface (https://www.facebase.org) showing an example of the kind of summary statistics available. Users can download summary statistics tables for all measurements in the database as a .csv file.

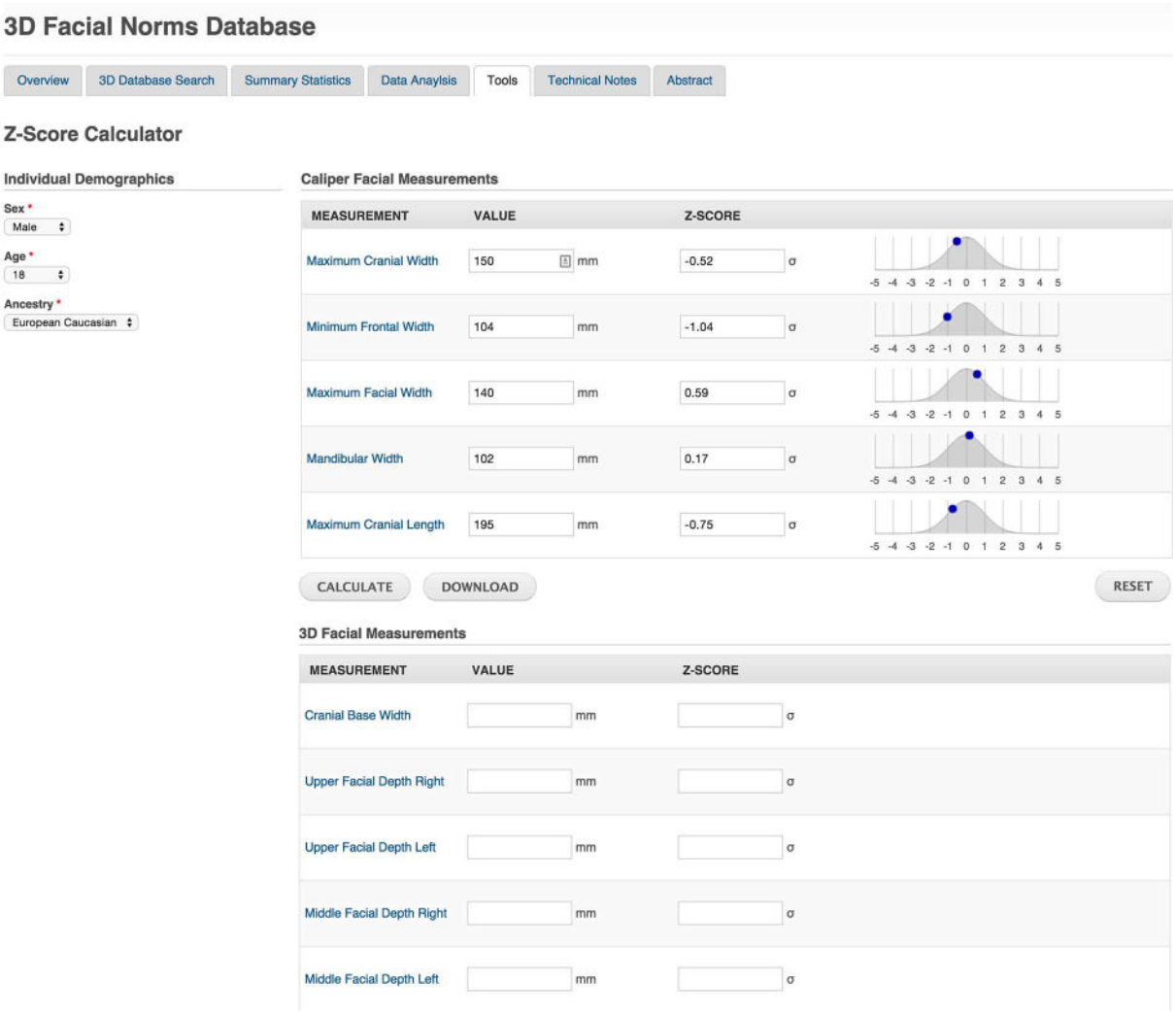


FIGURE 3.

Partial screenshot from the 3D Facial Norms website interface (https://www.facebase.org) showing the Z-score calculator tool. The example here uses measures from a hypothetical 18 year old male individual for illustration purposes. Users can save a report containing all of the Z-score results for a given individual.

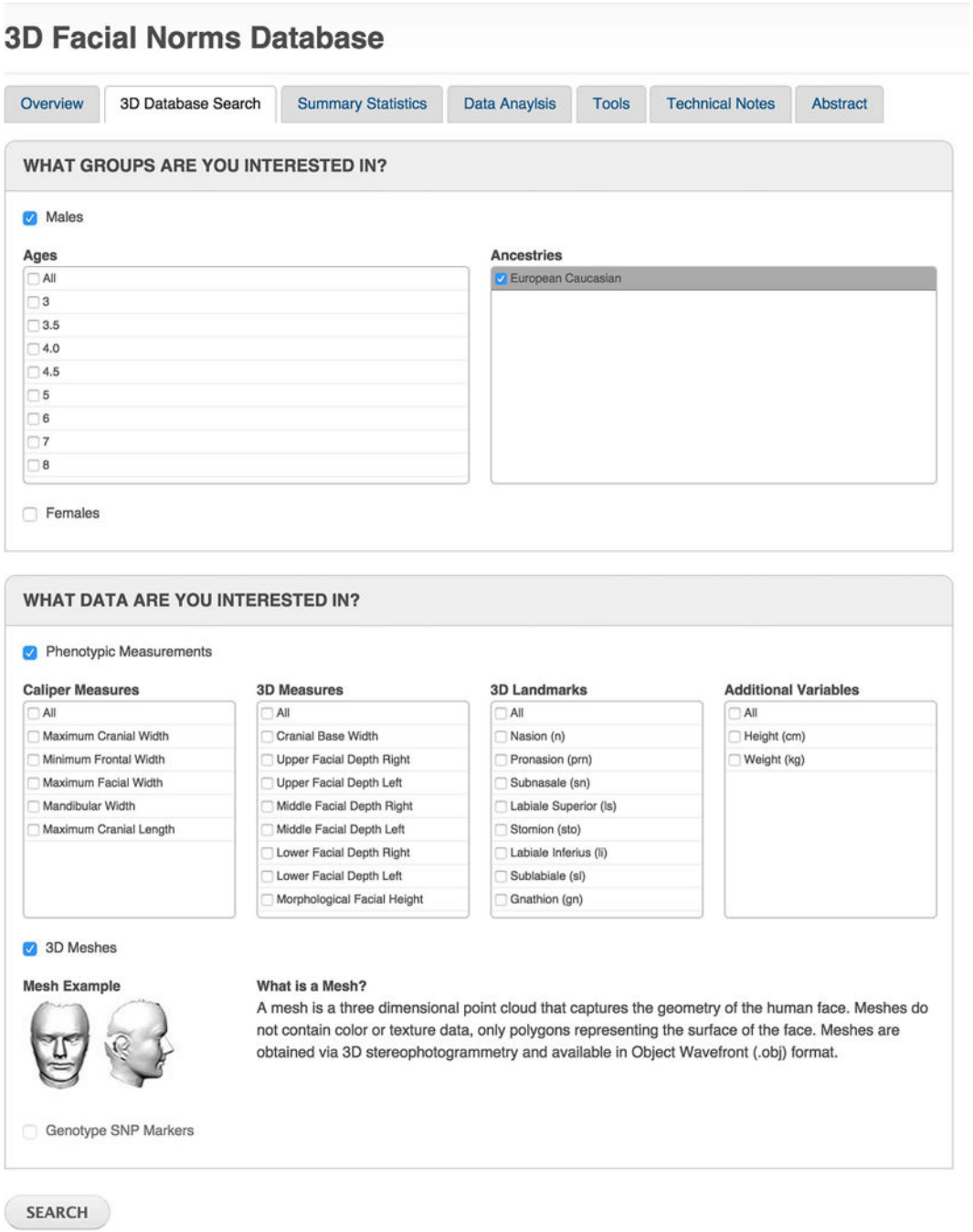


FIGURE 4.

Partial screenshot from the 3D Facial Norms website interface (https://www.facebase.org) showing the database search options. Users can select the sex and age groups and types of data they are interested in querying. The search results show the number of subjects in the database available with the selected search parameters as well as a detailed missing data report.

TABLE 1

3DFN Sample Breakdown by Age and Sex

Age Group*	Male	Female	Total
3	11	13	24
3.5	18	18	36
4	12	13	25
4.5	11	7	18
5	25	21	46
6	21	23	44
7	27	14	41
8	20	16	36
9	17	24	41
10	18	18	36
11	23	22	45
12	24	24	48
13	21	27	48
14	16	14	30
15	16	15	31
16	10	7	17
17	6	10	16
18	30	48	78
19	29	70	99
20	28	72	100
21	41	73	114
22	43	85	128
23	72	105	177
24	48	88	136
25	59	82	141
26	50	64	114
27	37	73	110
28	28	60	88
29	33	39	72
30	37	48	85
31–32	29	88	117
33–34	20	68	88
35–36	25	60	85
37–38	25	52	77
39–40	22	41	63
Totals	952	1502	2454

*Age group 3 = 3.00–3.49 years; 3.5 = 3.50–3.99 years; 4 = 4.00–4.49 years; 4.5 = 4.50–4.99 years; 5 = 5.00–5.99 years; etc.

TABLE 2

Anthropometric Measurements Included in the 3DFN Database

Measurement	Region	Landmarks
Caliper-Based Measurements		
Maximum Cranial Width	Head	Right Euryon (eu_r) - Left Euryon (eu_l)
Minimum Frontal Width	Head	Right Frontotemporale (ft_r) - Left Frontotemporale (ft_l)
Maximum Facial Width	Face	Right Zygion (zy_r) - Left Zygion (zy_l)
Mandibular Width	Face	Right Gonion (go_r) - Left Gonion (go_l)
Maximum Cranial Length	Head	Glabella (g) - Opisthocranion (op)
3D Stereophotogrammetry-Based Measurements		
Cranial Base Width	Head	Right Tragion (t_r) - Left Tragion (t_l)
Upper Facial Depth (Right)	Face	Nasion (n) - Right Tragion (t_r)
Upper Facial Depth (Left)	Face	Nasion (n) - Left Tragion (t_l)
Middle Facial Depth (Right)	Face	Subnasale (sn) - Right Tragion (t_r)
Middle Facial Depth (Left)	Face	Subnasale (sn) - Left Tragion (t_l)
Lower Facial Depth (Right)	Face	Gnathion (gn) - Right Tragion (t_r)
Lower Facial Depth (Left)	Face	Gnathion (gn) - Left Tragion (t_l)
Morphological Facial Height	Face	Nasion (n) - Gnathion (gn)
Upper Facial Height	Face	Nasion (n) - Stomion (sto)
Lower Facial Height	Face	Subnasale (sn) - Gnathion (gn)
Intercanthal Width	Eye	Right Endocanthion (en_r) - Left Endocanthion (en_l)
Outercanthal Width	Eye	Right Exocanthion (ex_r) - Left Exocanthion (ex_l)
Palpebral Fissure Length (Right)	Eye	Right Endocanthion (en_r) - Right Exocanthion (ex_r)
Palpebral Fissure Length (Left)	Eye	Left Endocanthion (en_l) - Left Exocanthion (ex_l)
Nasal Width	Nose	Right Alare (al_r) - Left Alare (al_l):
Subnasal Width	Nose	Right Subalare (sbal_r) - Left Subalare (sbal_l)
Nasal Protrusion	Nose	Subnasale (sn) - Pronasale (prn)
Nasal Ala Length (Right)	Nose	Right Alar Curvature Point (ac_r) - Pronasale (prn)
Nasal Ala Length (Left)	Nose	Left Alar Curvature Point (ac_l) - Pronasale (prn)
Nasal Height	Nose	Nasion (n) - Subnasale (sn)
Nasal Bridge Length	Nose	Nasion (n) - Pronasale (prn)
Labial Fissure Width	Mouth	Right Chelion (ch_r) - Left Chelion (ch_l)
Philtrum Width	Mouth	Right Crista Philtri (cph_r) - Left Crista Philtri (cph_l)
Philtrum Length	Mouth	Subnasale (sn) - Labiale Superius (ls)
Upper Lip Height	Mouth	Subnasale (sn) - Stomion (sto)
Lower Lip Height	Mouth	Stomion (sto) - Sublabiale (sl)
Upper Vermilion Height	Mouth	Labiale Superius (ls) - Stomion (sto)
Lower Vermilion Height	Mouth	Stomion (sto) - Labiale Inferius (li)
Cutaneous Lower Lip Height	Mouth	Labiale Inferius (li) - Sublabiale (sl)