# 3D head anthropometric analysis

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## ABSTRACT

Currently, two-dimensional photographs are most commonly used to facilitate visualization, assessment and treatment of facial abnormalities in craniofacial care but are subject to errors because of perspective, projection, lack metric and 3-dimensional information. One can find in the literature a variety of methods to generate 3-dimensional facial images such as laser scans, stereo-photogrammetry, infrared imaging and even CT however each of these methods contain inherent limitations and as such no systems are in common clinical use. In this paper we will focus on development of indirect 3-dimensional landmark location and measurement of facial soft-tissue with light-based techniques. In this paper we will statistically evaluate and validate a current three-dimensional image-based face modeling technique using a plaster head model. We will also develop computer graphics tools for indirect anthropometric measurements in a three-dimensional head model (or polygonal mesh) including linear distances currently used in anthropometry. The measurements will be tested against a validated 3-dimensional digitizer (MicroScribe 3DX).

**Keywords:** anthropometry, face, 3D reconstruction, three-dimensional, digitizer

## 1. INTRODUCTION

Diagnosis and treatment planning of craniofacial anomalies involve the processes of visualization and analysis. In these processes, deviations from the norm, asymmetries and affected structures are realized for comprehensive treatment planning. By enlarge, the majority of this activity is based on visual evaluation, two-dimensional photographs and radiographs, and to a lesser extent CT slice data. Within this system, recording and analysis of facial form are conducted generally in 2-dimensions and constrained to the limitations of the technology. Effective solutions to 3-dimensional facial image acquisition and analyses could have significant benefit[20]. Therefore, the aims of this paper are to develop and refine instrumentation to enable these approaches to clinical care.

In this paper we acquired and validated 3-dimensional images of a plaster head using structured-light image-based techniques and developed computerized methods for indirect measurements based on Farkas' extensive work in the field[9] for assessment of craniofacial form (including facial asymmetries).

Previous reports have demonstrated 3-dimensional facial imaging in a clinical setting however some of the anthropometric measurements were proven to be unreliable (errors higher than 1.5mm)[1; 4]. In addition, recent advances in imaging systems have made 3-dimensional imaging accessible to many healthcare professionals, yet these systems lack validation for specific clinical purposes. Therefore, our goal is to validate a structured-light imaging system using a mannequin head with pre-labeled anthropometric markers.

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## 2. BACKGROUND

### 2.1 Facial imaging technologies in craniofacial care

Imaging modalities for clinical evaluation of the face, such as photographs and two-dimensional radiographic films (used since 1931) were developed decades ago and are still in mainstream clinical use. However, the information they provide is limited in perspective, accuracy, and contains information voids. For these reasons, in the last decades, three-dimensional techniques such as 3D CT, laser surface scanning, photogrammetry (conversion of photographs taken from different views into 3D models), Moire' stripes[18], and Computer Assisted Design (CAD) manipulation of these models have been explored.

**CT Scans:** Computed tomography (CT scan) has much of its history in general medicine while its use in craniofacial assessment is more recent. In this area, the bulk of the research work is focused upon bony cranial landmarks. Previous work reported the use of 3D CT for craniofacial surgical planning[36] and comprehensive assessment of hemifacial microsomia[38]. Richtsmeier and her research group[21] developed mathematical tools such as EDMA (Euclidean Distance Matrix Analysis) to assess asymmetry in human skulls, detection of influencial landmarks[22] and confidence intervals[23]. The authors also assessed the localization error of landmarks in human skulls using CT scans[32] to be less than 0.5mm. This is the repeatability error only. As the authors pointed out the reported localization error of 0.5 mm is in ideal conditions when the soft tissue is removed before digitizing. Later, vitro skull landmark measurements made with a digitizer were compared to the CT data and a mean error of 0.87mm and a maximum error of 2mm was found[4]. The cost and radiation received by the patient during a CT make this technique no suitable for our research.

**Laser facial scanning:** Technologies for generating a 3-dimensional model of a human face with registered texture include laser scanning and visible light techniques. The laser scanners produce a detailed model but the digitization process requires the subject to remain still for a period of several seconds to a minute or more while the scanner head revolves around the subject's head. In addition, the output can be noisy thus requiring additional processing to treat noise, outliers, and holes.
Researchers have explored the use of laser surface scanning for assessment of facial asymmetry[5; 25; 27]. The authors divided the face in different regions and then classified the pre-surgical and post-surgical areas according to different surface type primitives: valley, ridge, saddle surface, etc. The quantitative changes per region are expressed in terms of area size changes and their movement on the face. The reported precision of the laser scanning device is approximately 0.5 mm, and time of exposure is 10 seconds. While the authors claim that these measurements in terms of area regions are more adapted to clinical evaluation of the treatment outcome, anthropometric measurements as described in[9] are more widely used in craniofacial care. Researchers[1] have compared laser scanned anthropometric measurements computed with the same equipment as in[26] with direct physical ones and found out that more than half were unreliable (errors higher than 1.5mm).

The accuracy of lasers (Cyberware) in imaging plastic and plaster heads have also been reported[3] as 0.6mm variance of localization in the three axes when using pre-labeled landmarks. The authors used 22 anthropometric landmarks interactively selected by a user in the image of the plaster's head model. When not using pre-labeled landmarks on the plaster head, the error of localization of the anthropometric landmarks reported is within 2mm.

**Stereo-photogrammetry:** In 1960 dot stereograms and the idea that stereoscopic vision is a cooperative process were introduced[16]. A algorithm for stereo reconstruction followed[24]. The use of stereo in medicine was first reported in a study of facial asymmetry with a dry skull[6]. Stereo-photogrammetry has also been used to find the optimal plane of reference for assessment of craniofacial anomalies such as cleft lip and palate[30] and for quantification and validation of the linear and angular measurements using only eight pairs of landmarks[31]. The absolute value of the reproducibility error for localizing the landmarks reported was 1mm and 1.1 degrees for the angles[31]. Recently, Ferrario et al.[11; 13-15] published their work in stereo-photogrammetry with two CCD cameras working in the infrared fields to automatically locate 22 facial landmarks (retroreflective markers on the face) providing anthropometric information (linear distances, angles and one ratio). The error in reproducibility of a landmark and marker location found was less than 2mm.

**Commercial visible-light imaging systems**: Fixed viewpoint depth maps are created from stereo-photogrammetry systems (Geometrix's Face 200 and 800) and structured-light camera systems (such as Eyetronics, 3DMD and Inspeck requiring a slide projector and one or more cameras). To produce a full face model (from ear to ear) with these systems, two or three depth maps are obtained for a subject from varying view points (e.g., left-side, right-side, and frontal) and stitched together with manual assistance. The only commercially available system that acquires an ear-to-ear model is Face 1200 from Geometrix with 12 cameras. Given the current state, a fast, efficient, reliable, non-invasive solution to 3-D facial image acquisition would be a very significant step forward. A system such as this would eliminate many of the barriers for clinicians to obtain and use such as system. Today, no 3-D systems are in common clinical use, while traditional photography is the standard.

### 2.2 Study of cranial form and asymmetry

Landmarks have been used for over a century by anthropometrists interested in quantifying cranial variation. A new field, morphometrics, has grown around the statistical analysis of shape and size for comparison of biological shapes[2; 33; 35]. Since the 1930's clinical application of facial anthropometry has been reported for cleft lip/palate patients, and to examine children with unilateral facial asymmetry[8]. A recent review of facial anthropometry in cleft patients[37] and applications[20] in other areas of craniofacial care can be found.

A great body of work in craniofacial anthropometry is that of Farkas who established a database of anthropometric norms[9; 10] by measuring and comparing more than 100 dimensions (linear, angular and surface contour's) and proportions in hundreds of people over a period of many years. These measurements include 47 landmark points to describe the face (Figure 1 shows some of the Farkas' landmarks). The anthropometric data include 129 measurements with statistical mean and variance tabulated per age and gender. The measurements are acquired with special equipment used in a consistent fashion (see[20] for the methods used to clinically obtain the measurements).

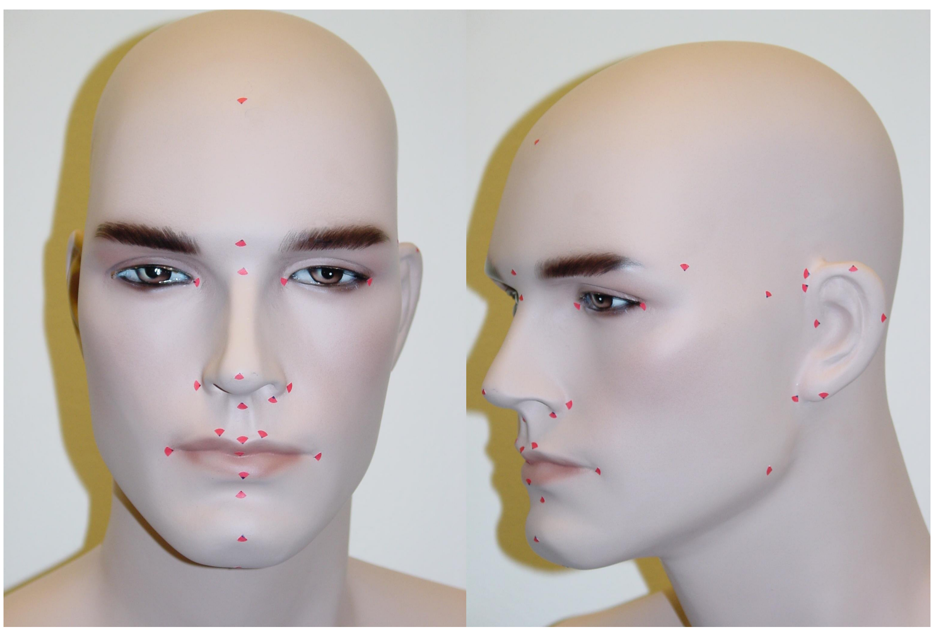

Figure 1: Subset of Farkas's anthropometric landmarks (frontal and side picture of the mannequin).

Clinical application of facial anthropometry has been limited due to the time required to obtain these measurements (45-60 min.) and the difficulty in comprehensively visualizing the problem given the numerical form of the measurements. Our research aims to develop methods to obtain these measurements in an automatic fashion, allowing clinicians to rapidly obtain anthropometric and customized measurements.

### 2.3. Computer-graphics face modeling and anthropometry

Computer modeling of faces dates from the 1970's[29]. Face modeling for artistic and entertainment purposes is now commonplace in the computer graphics community. Farkas's inventory of facial measurements has been used in computer graphics to automatically create new "plausible" computer graphic faces[7]. In very recent work the authors[17] used the anthropometric norms in Farkas studies for aging simulation and facial animation.

## 3. METHODS

### 3.1. Materials and equipment

**Markers:** Retro-reflective markers visible on a photograph (Figure 1) but also accurately digitized by Microscribe's digitizer (Figure 3) will be placed on the mannequin.

**Imaging device: Eyetronics.** The light-based imaging system consists of a regular slide projector, a digital camera and a calibration pattern. ShapeMatcher™ (from Eyetronics**)** software interprets photographs of a pattern projected on the face to build a three-dimensional reconstruction of that view of the face. ShapeSnatcher Suite™ allows the user to stitch more than one view to create one single polygonal mesh and texture image (Figure 2).

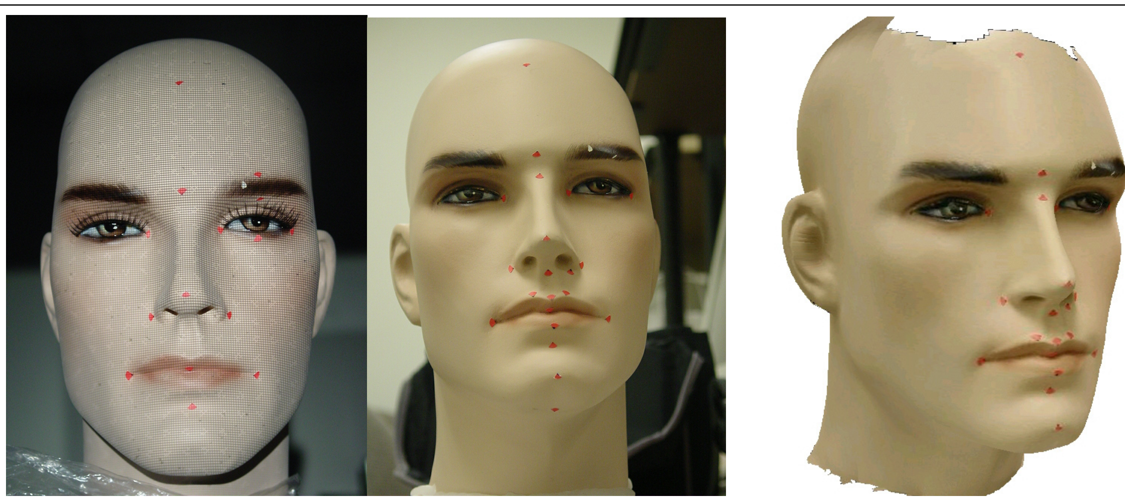

Figure 2. Left: Photograph of the mannequin head with the structured-light pattern projected. Center: Photograph used for texturing the final reconstruction. Right: Scan of the mannequin head obtained with Eyetronics.

**Digitizer for validation:** The Microscribe 3Dx digitizer-probe (Immersion Corp.), our "gold standard", allows continuous scanning up to 90 points per second and point measurements with accuracy of 0.0228 mm (0.009") in a 50" sphere workspace (Figure 3). The reference frame (origin and two axes) and the units (mm) can be established by the user at the beginning of each session. Digitizer coordinates are output for statistical analysis.

### 3.2. Research design

Colored markers were placed in a mannequin head at selected commonly used locations in anthropometric studies[1; 9]. The markers were digitized as in[32] and then the face was scanned with the structured-light imaging system to provide a full three-dimensional polygonal mesh of the face. The user can select the landmarks interactively with the mouse (Figure 4), for comparison of the three-dimensional distances computed with the digitizer.

Figure 3.
Microscribe 3Dx digitizer (Immersion Corporation).

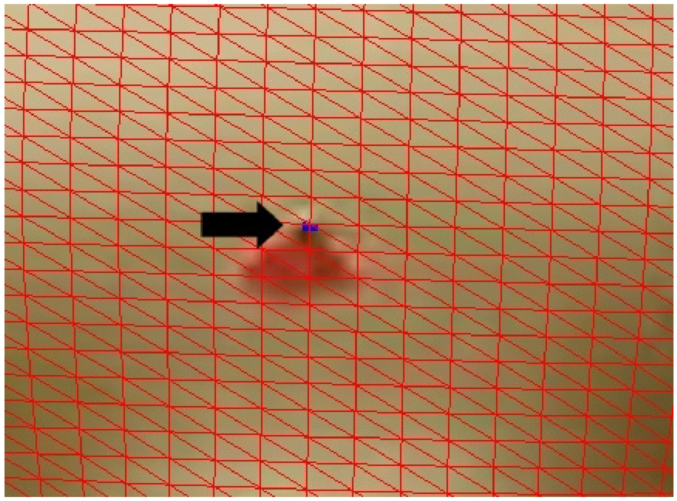

Figure 4. Vertex interactively selected as a landmark (indicated with arrow).

**Mannequin and anthropometric landmarks:** Imaging was performed on the mannequin head (Figure 1-2). The mannequin head was pre-labeled with small red colored papers with a blue dot placed on the following anthropometric landmarks[9]:

- *Head:* g – glabella, tr – trichion, ft – frontotemporale.
- *Face:* zy – zygion, go – gonion, sl – sublabiale, pg– pogonion, gn – gnathion (or menton, not visible), cdl – condylion laterale.
- *Orbits:* en – endocanthion, ex – exocanthion.
- *Nose:* n – nasion, prn – pronasale, sn – subnasale, sbal – sub-alare (sbal'), ac – alar curvature (ac').
- *Lips and mouth:* cph – crista philtri (cph'), ch – cheilion (ch'), sto – stomion, ls – labiale superius, li – labiale inferius.
- *Ears:* obi – otobasion inferius, obs – otobasion superius, sa – superaurale, sba – subaurale, pa – postaurale, pra – preaurale.

**Imaging the mannequin**: The Eyetronics imaging system involves manual and semi-automatic steps: 1) calibration using a calibration target with the structured-light pattern projected onto it, 2) taking multiple photographs under different rotation angles of the mannequin to recover a ear-to-ear model while maintaining the camera and slide projector relative positions static, and 3) semi-automatic alignment of the scans in the computer. The frontal scan is used as a reference and other partial scans are "stitched" to it. The software produces a polygonal triangular mesh with texture coordinates and a combined texture image. The mannequin head modeled with this software using 6 different views is shown in Figure 3. To ensure that the imaging and digitizing systems shared the same origin coordinates and reference frame (XYZ), the calibration target used by Eyetronics was digitized and used as a reference frame for the digitizer. Without moving the calibration target, it was imaged for calibration with Eyetronics system.

**Interactive landmark identification:** Our own software based on OpenGl, C++ and MFC allows for interactive clicking with the mouse of any vertex in a polygonal mesh and highlights it for verification. This interface allows for scaling, rotation and translation of the object for best identification of the landmarks from any viewpoint.

**Indirect anthropometric measurements:** After identification and localization of the anthropometric landmarks (Figure 4) we computed the 3D Euclidian distance between landmarks.

### 3.3. Statistical validation

We followed the research design outlined by Kohn and Cheverud[19] for validation of errors in imaging systems, also used[32] for validation of CT measurements with a digitizer.

**Imaging Research Design:** A digital model of the mannequin head was created. Then two operators in two sessions (*Session 1 and 2)* 24 hours a part twice interactively marked the landmarks in the digital 3D model twice (*L1 and L2*) to test for marking error. This design (Figure 5) will allow us to compute precision and reproducibility of the imaging error from the interactive landmark's marking error.

**Digitization Process:** In a separate process the head's landmark markers were digitized during two sessions (*Session 1 and 2*) by each operator 24 hours apart to compute intraobserver and interobserver error of landmark localization. Each landmark was digitized 10 times twice (*D1 and D2*) for validation of the repeatability of the digitizing process and precision (Figure 6). Precision was defined as the average absolute difference between repeated measures of the same landmark.

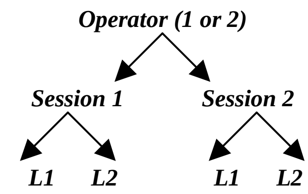


Figure 5. Research design for validation of imaging system.

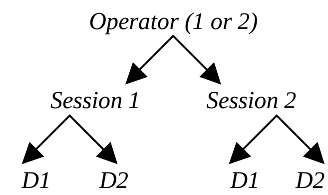


Figure 6. Validation of the Microscribe 3Dx digitizer.

## 4. PRELIMINARY RESULTS

**Precision of the digitizer:** Two operators digitized ten times the two visible corners of a 10 cm ruler in horizontal and vertical positions in two sessions. For the landmark coordinates (X, Y and Z of each corner of the ruler) we found a maximum standard deviation for both sessions combined for the two operators of 0.27mm, and maximum variance of 0.07. We validated the mean length of the ruler as: a) 100.15 mm with standard deviation of 0.22 mm and variance of 0.05 in horizontal position and b) 100.4 mm with standard deviation of 0.32 mm and variance of 0.10 in vertical position.

**Errors in landmark identification in the computer:** To validate the process of landmark localization using the computer, two operators interactively selected the landmarks on the 3-D reconstruction of the mannequin's head. The mean of the difference of the distance between the coordinates selected by the two operators was 0.047 mm with standard deviation of 0.07 mm and variance of 0.006.

**Validation of linear measurements:** The validation consists of comparing the results from imaging (Eyetronics) with those obtained from a physical technique (the digitizer). Because the digitizer is our "gold standard", differences between homologous measurements define the imaging error. Craniofacial landmarks (n=23) described in section 3.2 were digitized and compared with those selected with the mouse on the 3D reconstructions (g, ft, en, ex, zy, go, sl, pg, cdl, n, prn, sn, sbal, sbal', ac, ac', cph, cph', ch, ch', ls, li, obi, obs, pra). The landmarks tr, gn, sto, sa, pa, sba were not visible on the image or the 3D reconstruction was inaccurate.
Twenty-five homologous linear Euclidean distances were compared with the digitizer for validation. In the frontal area, g-n, n-prn, sn-ls, ls-li, sl-pg were found *reliable* with imaging error less than 0.5 mm. The distances en-ex (right eye), cph-cph', ch-ch' and ac-ac' were found between 0.5-1.0 mm imaging error, and the distance ch-ch' had an error of 1.54 mm.

On the left side, we found obs-pra, obs-cdl, obs-obi, zy-go, zy-pra, ft-go and zy-ft with less than 0.5 mm imaging error and ft-obs had an imaging error of 0.55 mm.
On the right side, we found obs-pra, obs-obi, zy-go less than 0.5 mm error, and obs-cdl,, ft-obs and zy-ft between 0.5-1mm, and finally, zy-pra and ft-go with an error between 1.0-1.2mm.

The overall mean absolute error combining frontal, left and right side was of 0.48 mm, with standard deviation of 0.40 mm, variance of 0.16, and maximum absolute error of 1.55 mm.

## 5. CONCLUSIONS

We found the mean absolute error of the light-based imaging system during imaging of twenty-five Euclidian distances of a mannequin head to be 0.48 mm with maximum error of 1.55 mm. Some of the measurements were found unreliable with error higher than 1.5 mm. Further research will involve validation of the system by comparing two different images of the mannequin created by different operators. Although there is great interest and demand amongst the craniofacial healthcare community for the use of 3-dimensional models for treatment planning and visualization[1; 20; 34] and for quantitative assessment of the asymmetry[3; 12; 25; 28; 32], validation of the imaging system is essential for these functions.

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