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Three-dimensional Cranio-Facial Reconstruction in Forensic Identification: *Latest Progress and New Tendencies in the 21st Century*

ABSTRACT: Three-dimensional (3D) cranio-facial reconstruction can be useful in the identification of an unknown body. The progress in computer science and the improvement of medical imaging technologies during recent years had significant repercussions on this domain. New facial soft tissue depth data for children and adults have been obtained using ultrasound, CT-scans and radiographies. New guidelines for facial feature properties such as nose projection, eye protrusion or mouth width, have been suggested, but also older theories and "rules of thumbs" have been critically evaluated based on digital technology. New fast, flexible and objective 3D reconstruction computer programs are in full development. The research on craniofacial reconstruction since the beginning of the 21st century is presented, highlighting computer-aided 3D facial reconstruction. Employing the newer technologies and permanently evaluating and (re)questioning the obtained results will hopefully lead to more accurate reconstructions.

KEYWORDS: forensic science, human anthropology, human identification, three-dimensional facial reconstruction, facial soft tissue depths, facial soft tissue features, computer-aided

In optimal conditions, the identification of human remains can be restricted to a comparison of ante- and postmortem records. Unfortunately, when confronted with a corpse that is unrecognisable due to its state of decomposition, skeletonisation, mutilation or calcination, simple identification by comparison becomes impossible. Confronting the public with an image of the victim's face before death could in such cases lead to new evidence and finally to a likely candidate to be identified with the remains in conjunction with other corroborative methods as radiographic- and dental comparisons or DNA-analysis. Depending on the available evidence different 2D and 3D techniques of recreating the face of the victim exist. This survey concerns the 3D cranio-facial reconstruction. The roots of cranio-facial reconstruction are situated in the late 19th century in Europe (1–4). The pioneers built the facial soft tissue thickness in bulk, based on the placement of soft tissue depth markers and this without much regard to the rest of the underlying anatomy. In the middle of the 20th century in the United States, this method was revised by Snow et al. (6) and the name American or morphometric method was attributed to it. Around the same period, Gerasimov developed a 3D technique of cranio-facial reconstruction based on the facial muscles, modelled one by one on the skull (5). This technique is referred to as the Russian, morphoscopic or anatomical technique. In the United Kingdom, Neave (7) developed the combined sculpting method, a combination technique, incorporating the Russian and American methods.

Since the first reconstruction attempts in the late 19th century, the subject has been excessively commented in the literature. Complete books have been devoted to the different methods (5,7–13) as well as comprehensive reviews providing an extensive bibliography dealing with the issue (14–19). The recent literature on this extensive subject is, therefore, reviewed and categorised under the following headings: skull anthropology, efficacy of craniofacial reconstruction techniques, soft tissue depth data, facial soft tissue features and computer-aided 3D cranio-facial reconstruction.

Skull Anthropology

Before attempting any facial reconstruction, a correct anthropological evaluation of the skull to determine sex, age and race is of decisive importance (20,21). In this context, Lynnerup (22) studied the thickness of cranial vault bone biopsies taken from four sites on 64 autopsied Danish individuals. He did not find any statistical correlation between the cranial bone thickness and age, sex nor body build. Schywi-Bochat (23) studied the roughness of the supranasal region on a total of 80 skulls and although it was helpful in categorising the skull as hyperfeminity, feminity, masculinity or hypermasculinity, it was found to be unreliable for sexing a skull. Gülekon and Turhut (24) investigated the type of external occipital protuberance according to a modified classification system from Broca (25,26), but found it was not a decisive criterion in determination of sex. Next to gender, age, and race, it has recently been demonstrated (27,28) that individualizing traits of a skull such as bony scars appear to be very helpful in the reconstruction process.

Efficacy of Cranio-facial Reconstruction Techniques

Recently Stephan and Henneberg (29) reported on the efficacy of four commonly used reconstruction methods. Of each of four dry skulls, four different facial reconstructions were made. Two 2-D (drawing American method, computer "FACE" assisted American method) and two 3-D techniques (American and combined sculpting methods) were used. Each reconstruction was executed following the published methods. No additional individualising treats were provided. The accuracy of the reconstructions was tested by having 37 assessors attempt to identify the target out of a face pool. Each face pool was made up of ten photographs of people of similar

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age, sex and population of origin as the target individual and did not all include the target individual. The authors concluded that facial approximation in the strict sense of a reconstruction of a face based on a skull with no additional individual information is an inaccurate and unreliable technique.

In the past, several studies assessing the accuracy of the facial reconstruction methods used resemblance ratings (7,9,30) or face pool comparisons (6,31). Stephan (32) reported a discrepancy between the accuracy of facial reconstruction as measured by face pool comparison and direct comparison methods. Analyzing the assessor's questionnaires of the Stephan and Henneberg (29) study, regarding the resemblance between their target face and reconstructed face and their confidence in the identification, he concluded that resemblance ratings (i.e., direct comparison) of a facial reconstruction to a target individual did not indicate a facial reconstruction's accuracy. It only measures the similarity between the reconstruction and the target individual and does not necessarily indicate the ability for the target individual to be recognized from a group of faces. This suggests that previous studies using resemblance ratings should be approached with caution and that future studies assessing the accuracy of facial reconstruction should use face pool comparisons.

Wilkinson and Whittaker (33) produced a detailed evaluation of facial reconstruction. Using British juvenile tissue depth data (34) and the combination technique (7), five 3D juvenile facial reconstructions were performed. All five reconstructions were correctly identified by face pool assessment, and further resemblance rating assessments suggested that all the reconstructions showed close similarity to the identified individuals.

Soft Tissue Depth Data

As today, most facial reconstruction techniques employ sets of average tissue depths, which either act as guides (7) or as the main basis (6), it is not surprising that more research needs to be done on facial soft tissue depths.

Especially the group of the children, a subgroup that was considered to be under-documented in the past, saw their tissue thickness database grow. Smith and Buschang (35) like Garlie and Sanders (36) studied the changes in soft tissue thicknesses during growth and development on lateral cephalographs of French-Canadian children and adolescents. They observed nine soft tissue thicknesses, three measures of nasal projection and two hard tissue distances to allow comparison between hard and soft tissue growth in the same individual. The greatest average change per year was found in the hard tissue measure nasion-menton but much of the variations in soft tissue thicknesses remain unexplained by changes with age or differences between sexes. They hope that future use of 3D ultrasound technology might allow better understanding and quantification of the three dimensional relationships between bony surface and the soft tissues covering them.

Williamson et al. (37) added data for the African-American children to the literature based on lateral craniographs, concluding that age being the primary factor contributing to significant variation in facial tissue thickness. In general their results where in agreement with previously published data regarding children (36,38,39).

Ultrasound is an effective diagnostic tool used in the medical field as well as for soft tissue depth measurements. Manhein et al. (40) were the first to use a "B-mode" scan, which provides simultaneous visualisation of soft tissue and the underlying bone, on 807 White, Black and Hispanic American children and adults on 19 unilateral facial points in upright position. They found significant variations in tissue depth means between the two sexes in children. For adults their standards were comparable to those developed by Rhine and Moore (41) with the exception of the cheek region where their measurements were larger. This concurs with the observation of some facial artists (40) that the classic data reproduce a rather gaunt face. Manhein et al. (40) concluded that sex, race and age strongly influence facial soft tissue thickness. Wilkinson (34) scanned 200 British children bilaterally on 21 anatomical landmarks using Helmer's. A-mode ultrasound scanner (42) and confirmed the overall findings of Manhein et al. (40). El-Mehallawi & Soliman (43) also confirmed these same findings based on soft tissue thickness measurements at the 17 Aulsebrook et al. (44) landmarks in a very small segment of the Egyptian adult population (20–35 years).

Providing simultaneous location of landmarks and visualization of overlaying structures, CT- and MRI scanning were found to be useful in the acquisition of tissue depths and the identification process in general. After Phillips and Smuts (45) also Vignal and Schuliar (46) reported to use a dataset of soft tissue thicknesses coming from CT-scans made on living people for their 2D computer-assisted facial reconstruction technique.

Dos Santos Rocha et al. (47) demonstrated that 3D CT imaging using the volume rendering technique by computer graphics made it possible to determine craniofacial measurements with adequate precision. This was tested by scanning five cadaver heads and having two examiners independently determine 10 craniometric measurements.

Wilkinson et al. (48) reported, in the conference proceedings of the Tenth Meeting of the International Association for Craniofacial Identification, an unpublished study, on the importance of tissue depth data with respect to racial origin in the combined facial reconstruction technique. Six identical casts of a white male were reconstructed using the same methodology and charts of tissue depths of different ethnic groups (White European (42), Black American (49), Korean (50), Japanese (51), Mixed race (45), Southwestern Indian (52)). The reconstructions were rated by 247 volunteers as a resemblance to the target individual. They concluded that, in craniofacial reconstruction techniques where the primary source of information is the skeletal detail, it appears possible to recreate a "reasonable" recognisable face even with charts of the incorrect ethnic group.

Studying 50 cadavers, Simpson and Henneberg (53) obtained regression equations to calculate the soft-tissue thickness at a given point of the face, by measuring the craniometric dimension of a particular skull. The authors admit that while clearly of significance, other research on the relationship between the cranial dimensions and the facial soft tissue thicknesses is required.

Facial Soft Tissue Features

Since the beginning of the 21st century, progress in computer science and the improvement of medical imaging technologies have been used to study new facial feature prediction guidelines and systematically evaluate traditional guidelines in an objective way using empirical methods.

Stephan (54), based on opthalmologic literature and dissection, and Wilkinson and Mautner (55) using MRI imaging showed a highly statistically significant differences around 4 mm between reality and the traditional eye protrusion guideline (Wolff's theory (56)).

Stephan (57) demonstrated using digital photography that the guideline, locating the superciliare directly above the most lateral point of the iris, is unreliable.

Wilkinson et al. (58) using calliper measurements and digital photography showed the interlimbus to be the most reliable and accurate guide for mouth width, disagreeing with the rules of thumb quoted by other facial reconstruction artists (59,60,9) who suggested the best indicator is the interpupillary distance. Stephan (61) performed an even more extensive study on mouth width investigating more variables and came with an improved guideline "mouth width equals canine width plus 57% of the cumulative distance between the lateral aspect of the canines and the pupil centers on each side of the face". Later Stephan and Henneberg (62), based on a highly standardized photogrammetric method, suggested using a simpler prediction rule "the inter-canine width being 75% of actual mouth width". This later guideline, unlike all other, has a complementary advantage that it relies solely upon hard tissue landmarks instead of soft tissue features like the limbus or eye pupil/center.

Stephan et al. (63) examined the accuracy of four commonly used soft-tissue prediction guidelines for estimating nose projection and/or pronasale position on cephalogram tracings. The method of Gerasimov (5) was found highly unreliable and overestimated the nose projection. Krogmans' method (20) also appeared to perform poorly. The Prokopec and Ubelaker technique (64) performed rather well but the George (65) technique generated the best results of the four methods.

Computer-aided Cranio-facial Reconstruction

3D computer-aided cranio-facial reconstruction was originally considered to provide an answer to fundamental shortcomings of the classic cranio-facial reconstruction methods using clay, such as being time-consuming, highly subjective and requiring artistic talent. The goal was to create a flexible, repeatable and accurate process.

The first to present a method for facial reconstruction using 3D computer graphics were Vanezis et al. (66). As in all other computer-aided facial reconstruction systems, the unknown skull had to be digitized by collecting a large number of surface coordinates. They developed two techniques: a manual semi-automated technique that was still time consuming and a fully automated technique. The former was based on the tracing of a skull in 3-D space converting the analogue coordinates into a digital form (67). The latter consists of the direct digitization of a specific skull based on a projected laser line and a video camera interfaced to a computer. Finally after transformation of the digitally recorded video signals, the skull is displayed as a fully shaded 3D surface. Similar to placing the tissue depth markers in the manual method, facial thicknesses are indicated on a number of sites by the operator. A featureless mask of the face, obtained by smoothening the surface between the thickness markers, gives the fundamental facial shape. Out of a databank, a previously digitized facial surface is "transplanted" on the simple facemask. The computer program maps various facial features by scaling them and adjusting them on to their anatomically correct positions of the skull. The obtained facial profiles are stored in a database suitable for 3D graphic display, which allows viewing the head from different angles. At this stage of their research, methods are being developed to allow merging in three dimensions of a library of key facial features as mouth, eyes, ears, and lips with the basic facial form in order to produce a recognisable face.

Comparing the classic and computer-aided techniques of reconstruction, Vanezis et al. concluded that highly sophisticated equipment is not required for the manual method but it is time consuming and not simply to provide variations. The computer method for reconstruction seems feasible but the technique is far from perfect. To humanize the face problems related to the accurate assessment of the nose, ears, eyes and hair have to be overcome. Nevertheless, more anatomical data could and should be incorporated and within a matter of minutes several faces, compatible with the underlying skull, can be generated.

Research on facial perception had suggested that the individual identity of a face is a function of the scale, position and ratio of facial features relative to each other. Evenhouse et al. (68) based their work on the supposition that if an "average" face were to be mapped to a specific skull, the resulting face would take on the identity of the possessor of that skull. Thirty-seven soft tissue and corresponding bony landmarks, referred to as "control points," were connected to obtain a polygonal mesh. This mesh defines the metric relationship of the facial features and is used to warp an average face on the unknown skull. Although originally developed for 2D, the principle was tested for three-dimensional reconstruction. Evenhouse et al. conclude that although their 3D project is far from complete their methodology is a valuable tool in computer-aided three-dimensional facial reconstruction. They insist on the collection of additional bony landmarks and their corresponding tissue thicknesses to provide sufficient control points over which to generate a more complete, smooth soft tissue surface.

Shahrom et al. (69) describe a 3D computer graphics system for reconstructing a face on the skull. To produce a 3D skull image they use a 3D laser scanning system (66). After selecting the facial thickness tissue type between normal, thin or fat, 44 landmarks (peg markers) are entered on the skull image. An "average face" corresponding with the anthropological properties of the victim is selected from a database of scanned faces and provided with 44 similar markers. After alignment of the skull and facial image with respect to orientation, position and scale, they are superimposed. Automatic reconstruction of the face on the 3D skull image is done by the computer after manual matching of the peg markers between the two 3D images. Speed in creating a face as well as in mastering the technique and the ability of selecting the 'average face' out of a databank are advantages of this method. However, the technique also shares similar problems to the sculpting technique using the same tissue depth charts and manually positioning the landmarks.

Quatrehomme et al. (70) proposed a different method, not based on specific landmarks and average facial tissue thickness, but on the principle of deformable models. They assumed that "if skulls have similar forms, the corresponding faces should have main characteristics in common." So, after digitizing the datasets with a CT-scanner, a global parametric transformation is calculated to match an unknown skull to a reference skull with same anthropologic characteristics. The computation of the transformation is based on the crest lines, which are lines of absolute maxima of the largest principal curvature of the skulls. The same transformation is then applied to the face of the reference skull in order to provide the reconstructed unknown face. In their article, the authors present promising preliminary results of a test case.

In order to free 3D craniofacial reconstruction from the constraints and problems attached to the use of a limited number of average soft tissue depth values, Nelson and Michael (71) developed a method based on volume deformation. A CT-scan is used to digitize a database of reference heads (skull and overlying tissue) and the unidentified skull. Out of the database a number of reference heads with similar sex and age range as the unknown skull are selected. In a next stage, every closely matching reference head and the unknown skull are provided with a set of control points. The placement of these control points at a number of known anatomical positions around the skulls is achieved with a volume-based correspondence algorithm. The reference head with the closest matching spatial distribution of the control points to the unknown skull's control points is used for the deformation. The deformation of the reference head to the shape of the unknown skull is then done using the same control point sets. Finally through manipulation of one or more control points the reconstruction can be adjusted simply and quickly, either during or after the initial deformation process. Also this paper presents only one preliminary test.

In the labs of Vanezis et al. (72), using 3D computer graphics for facial reconstruction has become a routine procedure. After anthropological assessment of the skull, data acquisition of the unknown skull is done with a laser scanning system (73). On the digitised 3D skull image landmarks ($n = 40$) are located and corresponding soft tissue depth are represented as lines projecting from these landmarks, very much like the pegs used in classic manual facial reconstruction. The recently developed facial reconstruction software allows the operator to easily adapt the tissue depth values, landmark position and orientation. After selection of a facial template based on anthropological properties, landmarks are placed on the face that corresponds in location to those of the skull. A "final" warp is calculated based on the transfer of the facial landmarks to the new location determined by the tissue depth lines on the skull, after which this warp is applied in a point wise fashion to the other points on the face. Individual facial features as eyes, ears, lips and nose can be added after exporting the result of the facial warp in a 2D digital file. The present system uses the same principles of reconstruction presented as in 1989 but allows a more precise and easier placement and adjustment of the facial template on the skull.

Instead of using depths at limited locations, Jones (74) proposes a new method in which he uses depths at all points on the skull. With a CT-scanner, the unidentified skull and a reference head of same sex, age and race are scanned. Automatic feature detection then identifies regions of similarity between the scanned discovered skull and the reference skull. Thirty-four common feature points are located and the warp is calculated within a few seconds. For each point in the discovered skull, the warp defines a corresponding point in the reference skull. Based on previous work on distance fields for volumetric data, an algorithm defines the tissue depth at these points. Mapping these depths onto the discovered skull should give the unknown face. Jones work is still in full development but progress has been made in particular within the areas of automatic detection of feature points, the closure of the skull surface for mapping and the warping process.

Based on the fact that the 3-D reconstruction methods bear many resemblances with surface fitting techniques used in computer graphics, Kähler et al. (75) designed a computer reconstruction program. First they implemented the manual "peg placement" in the classic technique as an interactive procedure. Once the skull is tagged with landmarks ($n = 40$), a head model, consisting of the skin surface represented as a triangle mesh, virtual muscles ($n = 24$) to control the facial expression, a mass-spring system connecting skin, muscles and skull, and landmarks defined on the skin surface, was warped on the skull. This initial warp function is calculated based on the 40 hard and soft tissue landmark pairs and extra landmarks pairs in areas as the mandibula where tissue thickness is near constant. These additional landmark pairs are computed automatically by interpolation between existing ones. In the skull landmark editor, five extra rules for estimating nose and mouth shape, expressed by the placement of vertical and horizontal guides in the frontal view of the skull were incorporated. After repositioning the concerned landmarks based on these rules, a second deformation is executed. The resulting mesh can then be colored, corresponding additional information. The overall reconstruction is reported to require approximately an hour of interactive work, excluding time for data acquisition.

To reduce this data acquisition time, Hering (76) created a system to capture the facial surface of a person with high accuracy in an extremely short acquisition time. His method is based on the shooting of a hologram portrait with an eye-safe pulsed laser. In a second step, which is independent from the shooting of the hologram, the real image is generated from the hologram and sections of this image are projected onto a diffuser. These sectional views are digitised with a digital camera and are numerically converted into a surface model.

Conclusion

Research on the human face is moving from hit and miss case studies in a more scientifically sound direction (77). Today the progress in computer and medical image technology makes it possible to obtain more and accurate facial soft tissue depth charts, to test older facial reconstruction guidelines and to develop new guidelines, based on objective systematic empirical evidence. Also computerised 3D cranio-facial reconstruction programs are improving and start to integrate, next to the tissue depths, facial anatomy and facial feature guidelines.

Nevertheless as shown in this review and other articles (78), several studies have demonstrated that facial reconstruction methods and their traditional guidelines present some inaccuracies. The challenge of the coming years will be to increase the degree of accuracy of the facial reconstruction especially by (re)questioning and ameliorating our knowledge of the facial details that can be extrapolated from the bony skull.

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