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Past, present, and future of craniofacial superimposition: Literature and international surveys

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ABSTRACT

In this manuscript, the past, present and future of the identification of human remains based on craniofacial superimposition is reviewed. An analysis of the different technological approaches developed over time is offered in conjunction with a new classification based on the technology implemented throughout the diverse phases of the process. The state of the art of the technique, in the academic and forensic realms, is reflected in an extensive international survey that includes over one hundred experts worldwide.

The results of the survey indicate the current relative importance of the technique, despite of its controversial nature within the scientific community. Finally, the future challenges to be faced to justify the use of this technique for either profiling, exclusion or identification purposes are discussed.

Contents

1. Introduction

The main focus in forensic anthropology lies on the determination of the identity of human remains when skeletal information becomes the last resort for forensic assessment [1,2]. Craniofacial

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superimposition (CFS) [3] one of the approaches in craniofacial identification [4,5], involves the superimposition of a skull (or a skull model) on a number of antemortem images of a missing person and the analysis of their morphological correspondence.

The first documented cases, in which antemortem images were compared to cranial remains, date to the early decades of the 20th century. In these instances, craniofacial superimposition (CFS) served as supporting evidence to be presented in court, rather than the principal means of identification. Perhaps the most prominent case of this early era is the Ruxton case in 1937, in which two female skulls were compared to photographs of missing women using the superimposition technique [6]. A few years later, an X-ray of a skull was used to make the comparison and supporting identification of the victim in the Baptist Church Cellar Murder [7]. In other instances, the antemortem image was created as a line drawing of the head of the missing person superimposed on the skull [8]. Finally, in the 50s, in South Africa, a case was reported in which photographic superimposition was accepted as a part of evidence for identification [9].

The first instance of positive identification based solely on CFS, accepted in a court of law, took place in 1962 in India [10,11]. In the ensuing decades of the 20th century, several identification cases based on CFS, can be found in the literature. Case reports indicating the effectiveness of craniofacial superimposition for personal identification during the first 50 years of the development of the technique are numerous [10,12–22].

All those identification cases, solved using only photographs of both the skull and the face, belong to the first generation of CFS methods called photographic superimposition. In the ensuing years, a new modality of CFS techniques based on video technology made their way into the scientific realm. Helmer and Gruner [23] were the first researchers that introduced the video superimposition technique. They took advantage of the "live image" of the object (skull and photograph) instead of taking photographs, or making tracings or drawings of the skull and face to superimpose them. These systems present an enormous advantage over the former photographic superimposition technique [17,23–29].

Computer-aided CFS techniques, the next generation of CFS systems, were the result of the popularization, dramatic development and infinite possibilities offered by computers. One of the first documented cases of a superimposition performed using a "computer-enhanced" method was developed by a team of experts from the FBI, led by Ubelaker in 1992. The investigators compared the photograph of the presumed victim and the articulated cranium and mandible with the help of a personal computer. This novel approach was proclaimed "a new, rapid and highly effective method to demonstrate consistency between skeletal features of the head and facial photographs" [30]. Since then, computer-aided superimposition has become a popular identification method among practitioners; while several identifications where supported by a system combining video capabilities with computerized tools [31,32], other systems relied only on the support of commercial software packages such as Corel Draw®™, Rapid Form®™, or Adobe Photoshop®™. In particular, the use of the latter has been reported in identification of victims of mass casualty incidents in Turkey [33], Serbia [34], or during the Indian Ocean tsunami disaster [35]. In the last years, some researchers have used computer methods to simplify the superimposition process by automating the overlay process [36–38]. These are called to be the next generation of CFS systems, although their use in identification cases is still very limited. In fact, only one case, reported by Ghosh and Sinha in which a computerized CFS identification system has been implemented [36,39].

2. Anatomical background supporting CFS

The evaluation of any superimposition is a significant issue that is dependent on the consistency of the anatomical link between the location of the soft tissue surfaces relative to the underlying bone [40].

In order to evaluate this consistency, a full comprehension of the anatomy of the skull and the relationship between the skull and the face are required. In biological organisms structure and function are closely related. The human head, in terms of function, is related to stereoscopic vision (eyes), audition (ears), gustation (-tongue/mouth) and olfaction (nose), along with the protection of the brain. These functions are responsible for the structure of the head and therefore the form of the face and the skull will be directly related to the position of the brain, eyes, ears, mouth and nose.

From an anthropological perspective, craniofacial superimpositions are evaluated mainly on the basis of the consistency between the anatomical structures of the face and skull.

The forensic expert usually relies on the analysis of anatomical criteria such as the soft tissue thickness, outlines and positional relationships between the skull and the face. In the scientific literature, there are several studies conducted to assess the quality/degree of matching in craniofacial superimposition as well as, to examine the criteria used to conduct this assessment. Before reviewing the different studies, Martin and Saller's studies [41] must be considered. They created a treatise in which the fundamental pillars of this discipline were established. They defined an important set of craniometric and somatometric points that are crucial for all anthropological studies.

A correct evaluation of anatomical consistency between facial and cranial structures is of paramount importance for reliable craniofacial superimposition. Generating accurate data on soft tissue thickness and the positioning of facial structures are important steps to improve current practices in craniofacial identification. At the moment, there is a clear lack of consensus in methodological approaches for craniofacial superimposition. The development of standard protocols is necessary to enhance the credibility of the technique making it more readily admissible in judicial processes.

2.1. Anthropometrical relationships

Understanding the relationship between the skull and the facial soft tissue has major relevance for forensic identification. Facial soft tissue thickness, measured as the distance between the skin surface to the most superficial surface of the underlying skeletal tissue at specific landmarks, provides an important criterion for the evaluation of anatomical consistency. This kind of measurement provides general information on the match between the face and the skull, using facial soft tissue thickness as a means to control the outer contour of the face during the superimposition [42,43].

Due to the scientific value of facial soft tissue thickness in craniofacial identification, numerous studies have been conducted since 1883, with a great variation in measuring techniques, sample size, population ancestry, anatomical landmarks and variables analyzed (e.g. sex, age, body composition) [42,43].

Some of the main modalities for soft tissue thickness acquisition mentioned in the literature include [43]: needle puncture, cephaloradiography, ultrasound imaging, computer-assisted tomography (CT), cone-beam CT, and magnetic resonance imaging. None of these methodologies is a perfect solution, as each technique has advantages and disadvantages. For example, needle puncture methods are inexpensive, but cadaveric material is not wholly representative of living subjects; CT scans are accurate and reproducible, but may present gravity effects on the supine face, artefacts and radiation damage; craniographs are inexpensive and the subject is upright, but the images can suffer from magnification and planar issues; ultrasound can be used on upright living subjects, but involves contact and pressure issues. A more extensive list of advantages and disadvantages of the different methodologies used in soft tissue data collection was analyzed in Preedy [44] and in Stephan and Simpson [43].

Recently, Stephan [45] pooled soft tissue depth means from an extensive list of previously published studies. The results, presented in T-tables of three sets of soft tissue depths across the main stages of the human growth and development: birth to 11 years, 12 to 17 years, and 18 years and beyond. In contrast to separate studies that typically include fewer than 40 individuals, each of the T-tables report values for more than 3000 individuals at the more commonly measured craniofacial landmarks. The T-tables have been generated by collapsing prior data using weighted means and standard deviations within the age ranges. The tables are updated annually [46].

Soft tissue thickness depth measurements are usually applied in facial reconstruction, but when applied in craniofacial superimposition, facial expression must also be considered when determining identity. These measurements are usually, but not always, perpendicular to the bony structures, and are most useful if the image shows the soft tissue directly to the point of measurement [47].

2.2. Anatomical relationships

The face is one of the most individualistic and unique parts of the human body. It is important to establish the most commonly utilized morphological features when carrying out an assessment of face and skull correspondence. There are many standards for the prediction of the soft tissue features from skeletal assessment and these standards were established through human dissection, palpation, medical imaging modalities and direct anthropometry of living subjects. The relative limitations of each method when evaluating the reliability of the standards produced should be noted. Human dissection studies offer a unique opportunity to visualize the face and the related skeletal structures, but are limited by the effects of embalming, deformation associated with a cadaver face and dehydration. Palpation studies employ living faces, but are limited by the inability to accurately locate bony landmarks, especially in the areas of the face with the greatest soft tissues. Clinical imaging of living faces enables the visualization of soft and hard tissues simultaneously, but different imaging modalities suffer from gravitational problems (the subject is supine), artifacts (dental flare), bone visibility (MRI) and pressure effects (ultrasound). Direct anthropometry from a living subject is probably the most reliable form of data collection, but although multiple measurements can be collected from the soft tissues, direct measurements of the skull are limited to the teeth. This review will attempt to highlight the published anatomical standards feature by feature.

General face shape: the relationship between the shape of the head and the shape of the cranium is well established. Several classifications of this relationship have been published [48,49]. The relationship between facial measurements and related skull measurements has also been studied and recorded [48].

Eyebrows: eyebrow pattern standards have been developed from a combination of palpation [48] and craniograph studies [49].

Eyes: a number of studies assessing the relationship between the eyeball and the orbit in relation to prominence and frontal position have been conducted. Prominence studies utilizing MRI [50] exophthalmometry [51] and palpation [48,49] all present results indicating a general agreement between current published standards. Studies on the position of the eyeball in the orbit from a frontal view seem to report different results depending on the method of assessment [48,52–55]. The position of the inner (endocanthus) and outer (exocanthus) corners of the eye have been studied in detail, but there is no clear agreement between standards [48,54–60]. There is an agreement that the medial canthus is positioned approximately 2–5 mm lateral to the anterior lacrimal crest [54–56,61], but where exactly on the anterior lacrimal crest this measurement is taken from is unclear middle [48,49,56,62]. The eyelid pattern has been studied using palpation and anthropometry studies (comparison of skulls with ante-mortem images) [48,63].

Nose: is the most studied feature on the face; studies on the relationship between the configuration of the nasal tissue and the bones surrounding the nasal aperture are abundant [64–73]. Studies conducted by Gerasimov [66] show that the soft nose is wider than the bony aperture, as a narrower soft nose would have no supporting structure. Furthermore, he suggested that the bony nasal aperture at its widest point is three-fifths of the overall width of the soft nose. Rynn [74] produced guidelines for nasal shape prediction, utilizing three cranial measurements that can be used to predict six soft nose measurements. These guidelines were tested in a blind study showing a high level of accuracy [75].

Mouth: there are some anatomical standards relating to mouth shape, which have been confirmed in different populations and by a variety of methods of study [48,55,56,72,76]. Scientific literature from orthodontic and anatomical disciplines suggests that the form of the mouth is related to the occlusion of the teeth [77–83], the dental pattern [84] and the facial profile [66].

The cheeks: studies demonstrating the relationship between the zygomatic bones, the canine fossa and the soft cheeks are presented in [48,49].

The ear: although there have been some studies relating ear morphology to skeletal structure [66], this facial feature is understudied and the few existing studies achieved contradictory conclusions [85,86].

The chin: there are some standards relating the mental region of the mandible to chin shape [48].

The facial proportions are an important element to understanding facial geometry. The aim of the facial proportion assessment is to establish the variation from the ideal dimensions of the human form. This, combined with anthropometric norms, gives information about facial features as a symmetrical and balanced pattern, based on statistical means taking into account variations in age, sex and ancestry. In this way, George [70] described facial proportions based on the studies of Farkas and Munro [87] and Powell and Humphreys [88].

2.3. Examination criteria for craniofacial superimposition

Assessment of the quality of the matching and anatomical consistency between the face and skeletal structures for craniofacial superimposition has been carried out following a number of different criteria. The most representative proposal are the following: Helmer [89,90], Chai et al. [91], Austin and Maples [24], Yoshino et al. [29,92], Lan [93], Jayaprakash et al. [94], Ricci et al. [95], Ishii et al. [96] and Gordon et al. [97]. These criteria are presented in detail below.

Helmer [89,90]: this method of assessment includes the use of several soft tissue thickness markers, attached to the skull along a vertical central line. Helmer employed average German soft tissue data collected by ultrasound. These cephalometric landmarks (nasion, rhinion, gonion, gnathion) are then matched to the profile on the ante-mortem photograph. The alignment of these landmarks indicates a positive identification. The skull and the ante-mortem photograph were then superimposed in order to assess whether or not the tissue markers matched with the contours of the face.

Chai et al. [91]: this method is based on a study of 224 Chinese subjects (100 males and 124 females) aged between 18 and 55 years, from X-ray images. The protocol relies on the analysis of positional relationships between homologous facial and skull landmarks, the thickness of soft tissue at specific points and the fit of facial outlines with the cranial structures. 52 indices were established as a standard for craniofacial superimposition and identification.

Austin and Maples [24]: two sets of twelve criteria are employed in this method to analyze skull-face consistency using lateral and frontal view photographs. Relevant soft tissue thickness data is also utilized along with the anatomical criteria. The authors suggest that with anterior dentition, skull/photograph superimposition is reliable when two or more photographs are used in the identification.

Yoshino et al. [29,92]: this method evaluates the anatomical consistency between skull and face by means of video superimposition. The anatomical relationships and soft tissue thickness data is based on Ogawa's data [98]. The exact thicknesses of soft tissue at the anthropometrical points of the skull are measured on the superimposed transparent films by using a sliding caliper. Eighteen assessment criteria are used for the evaluation of the anatomical consistency between the face and the skull. The criteria used are divided into three types: outlines, soft tissue thickness and positional relationships. The authors suggest a positive identification can be achieved if 13 or more criteria demonstrate concordance between the skull and the face.

Lan [93]: this method is based on a study of 3123 subjects from 15 nationalities (1554 males and 1569 females), with one front view and one profile photograph of each subject. The method includes anthropometry from photographs and X-rays. A total of 69 indices are established for identification. The authors noted that some indices showed significant differences between different nationalities: the distance between the vertical line of ectocanthion, and gonion; the distance between gonions, and the thickness of the soft tissue at the trichion, opisthocranion and sellion.

Jayaprakash et al. [94]: this is a craniofacial morpho-analytical approach, based on the shape correlation between the skull and face photograph. This approach relies on previous work developed by Fedosyutkin and Nainys [49], İşcan [99], Farkas [87], Gatliff [100], Rhine [101] and George [70,102] and special attention is placed on the nasal region.

Ricci et al. [95]: the authors presented an algorithm for identification using craniofacial superimposition. Fourteen subjects and their matching facial photographs and skull radiographs were selected. The algorithm calculated the distance of each transferred cross (anatomical points) and the corresponding average. Their results indicate that the smaller the mean value, the greater the index of similarity between the face and the skull. A total of 196 cross-comparisons were carried out.

Ishii et al. [96]: this method was based on a study of three subjects, a young man (23 years old), a man with an edentulous upper jaw (36 years old) and a woman (40 years old), using 3D CT data for craniofacial superimposition. Miyasaka [103], Suzuki [104], and Ichiwaka [105] studies were used for the morphological assessment technique.

Gordon et al. [97]: the authors studied three methods: basic morphological matching [24], landmark matching, and a combination of both approaches. The bony and soft tissue landmarks used were based on Martin and Saller [41] and Farkas [87]. They proposed three different sets of landmarks for orientation and evaluation purposes for CFS.

3. Technical review of craniofacial superimposition

The diverse CFS technical approaches evolved as new technologies became available on previously laid foundations [40,106]. Although several authors had made different classifications of the technique, all of them recognize three different categories: photographic superimposition (developed in the mid 1930s), video superimposition (widely used since the second half of the 1970s) and computer-aided superimposition (introduced in the second half of the 1980s) [3,4,38]. Moreover, Yoshino et al. [107] classified some of the computer-aided craniofacial superimposition methods into two categories based on the identification strategy i.e. morphological and morphometrical examinations. Damas et al. [108] suggested a classification for computer assisted CFS techniques based on the stage in which computers play a part on the technique; (a) face enhancement and skull modelling, (b) skull face overlay, and/or (c) decision making. This characterization of the superimposition process will be considered all along the current paper.

3.1. Craniofacial photo superimposition

In craniofacial photo superimposition the first steps comprised in the "face enhancement and skull modelling" phase are intended to select and/or obtain clear and measurable images. The knowledge of all the technical details of the photographic equipment, the focal-length, the distance to the camera, need to be considered in this step. In this case, the quality of the photographs is related to the quality of the photographic equipment used during acquisition [109]. Furthermore, different approaches to obtain measurable images like objects depicted on the antemortem image, distance among anatomical landmarks, coupled with anthropometric measures [6–8,16,110]. Additionally, many authors draw tracings of the face and/or skull to ease the superimposition process [8,18,111].

During the acquisition stage, when photographing the skull, it is necessary to determine not only its correct life-size but to be able to replicate the orientation of the face in the photograph. To perform these tasks, a diverse set of elements (X-ray, negative and positive photographs, outlines and transparencies), apparatus (light stand, optical bench) and methodologies (measurable objects, distance among landmarks or anthropometric measures, triangulation based in the landmarks and transparencies, asymmetrical features of the facial skeleton) are employed tasks [17,111–114].

The evaluation of the correspondence between the face and the skull is the result of the comparison between anatomical landmarks, morphological features and anthropometric measurements. In photographic CFS techniques, this crucial stage relies on the visual observation of the expert without any technological support.

The scientific literature on the implementation of photographic craniofacial superimposition is presented in Table 1. Only the methodology followed within the stages of face enhancement and skull modelling and skull face overlay is summarized, since no significant contributions were made on the decision making stage of the process.

3.2. Craniofacial video superimposition

The common components of almost all video superimposition systems include two video cameras, an electronic mixing device and a TV monitor. These systems present a great advantage over the former photographic superimposition procedure by minimizing several problems associated with the photographic systems. Nevertheless, the processes of skull orientation and sizing the antemortem photograph and the skull in video superimposition remain troublesome.

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Table 1
Review of the literature on photographic superimposition methods.

Stage	Authors
Face enhancement and skull modelling	
Location of anthropometric measurements	[7,17–19,110,115,116]
Location of measurable objects	[6,8,16,19,113]
Location of anatomical landmarks	[112–117]
Location of special characteristics	[115]
Draw tracings or outlines of the face and skull	[6,8,9,18,118]
Reconstruct fragmented skulls	[111]
Replicate the exact photographic conditions	[109]
Skull face overlay	
Size replication using measurable objects	[6,8,16,19]
Size replication using anthropometric measurements	[7,18,19,115]
Size replication using anatomical landmarks	[117]
Use of pivoting head, skull holding, phantom-head or pan-and-tilt device	[17,19,115,117]
Geometrical method to calculate projections of anthropometric distances, angles of rotation and inclination of the head	[114]
Distance calculation between skull and camera	[113,117]
Use of asymmetrical features of the facial skeleton to assess the matching	[9]
Landmark matching	[6,18]
Match of the tracings, outlines, negatives, transparencies or X-ray of the face and skull	[6,8,18,112,113,115,118]
Triangulation system based on landmarks	[111]
Importance to photographic perspective	[119]
Furue's methodology validation	[109]

Table 2
Review of the literature on video superimposition methods.

Stage	Authors
Face enhancement and skull modelling	
Location of anthropometric measurements	[13,94,120]
Location of anatomical landmarks	[13,24,25,117,121,122]
Location of useful morphological characteristics	[123]
Location of tissue thickness markers	[24,25]
Skull face overlay	
Replication of the exact photographic conditions	[124]
Size replication using anthropometric measurements	[13,94,120]
Size replication using tissue thickness markers	[24]
Size replication using anatomical landmarks	[13,121,122]
Size replication using zoom	[28,124]
Size replication using focal length and the focusing of video camera	[27]
Orientation using landmarks	[28]
Orientation by trial and error manipulation	[24]
Dynamic orientation process	[25]
Use of pivoting head, skull holding, phantom-head or pan-and-tilt device	[26,94,120,125]
Distance calculation between skull and camera	[117]
Tracings, outlines, negatives or transparencies matching	[23,27,117,121,124]
Landmark matching	[13,27,122,124]
Morphological matching	[24,25,94,120,123]
Decision making	
Fade-in/fade-out and sweep	[13,23,121]
Video mixing unit device	[13,23,24,27,28,94,120,123,124]
Special effects generator	[26,122,125]

The face enhancement and skull modelling stage in this modality, is very similar to the one in the photographic superimposition technique. Measurable images using anatomical landmarks and anthropometrical measurements of the skull and the face, are used to ascertain the object-subject distance, to know all technical data of the equipment and filter the image to produce as much useful image information as possible.

Skull orientation can be performed in the same manner as in photographic superimposition, however, the correct size of the skull is easier to achieve by adjusting the size of the skull using the zoom mechanism of the video camera [92]. The orientation of the skull has varied with the incorporation of new tools, apparatus, and mechanisms (see Table 2).

The main tools involved in the decision making stage include fade-in/out, video mixing, or special effect generators. Nevertheless, the experience of the forensic anthropologist continues to be of paramount importance in the determination of identity.

3.3. Computer-aided craniofacial superimposition

The role of the computerized systems in CFS is very important at the present time. In most reviews on CFS, the classification of the systems do not differentiates clearly between computer-aided methods and the other techniques [92]. The confusion arises when computers are used in combination with either photo superimposition or video superimposition techniques.

Whenever a computer is employed as part of the CFS system, the method should be considered a computer-aided technique. The following classification better reflects the state of the art regarding the use of computers in one or all stages of the process

Table 3
Overview of computer-aided video superimposition systems.

Stage	Authors
Face enhancement and skull modelling	
Manual anatomical landmarks location on a plastic slide taped on the monitor	[30]
Manual landmark location using specific software	[29,31,107,126–132]
Manual contouring using specific software	[29,107,126,127]
Automatic contrast enhancement, equalization and filtering using specific software	[126,127]
Manual tissue markers location on the real skull	[31]
X-rays acquisition in seven pitch angles and ten reflection angles (research method for living individuals)	[131]
Skull face overlay	
Manual manipulation of the skull for replication and orientation using landmarks	[30,128–132]
Manual skull replication and orientation using anthropometric measurements	[128,129]
Face and skull visualization at the same time using specific software	[29,31,107]
Manual skull replication and orientation using a pulse motor-driven mechanism, fade-out and wipe mode	[29,107]
Decision making	
Manual assessment using soft tissue markers	[31]
Fade-in and fade-out	[29,30,107]
Semi-automatic landmark distances measurement	[29,107,133]
Semi-automatic measurement of anthropometrical indexes using specific software	[128,129]
Automatic assessment of skull and the face outlines using specific software	[29,107,126,127]

and the interaction between various technological approaches: (a) computer-aided craniofacial photo superimposition, (b) computer-aided craniofacial video superimposition and (c) computer-aided craniofacial 3D–2D superimposition.

Additionally, the classification should differentiate between non-automatic and automatic methods. While automatic methods use computer programs to accomplish a CFS sub-task, i.e. face enhancement and skull modelling, skull-face overlay or decision making, the non-automatic methods use some kind of digital infrastructure to support the CFS process, i.e. computers are used for storing and/or visualizing the data. These non-automatic techniques are characterized by the fact that their computational capacity to automate human tasks is not considered.

In automatic methods, the face enhancement and skull modelling phase deals with the restoration of the photograph by means of digital image processing techniques, or with achieving an accurate 3D model of the skull.

Computer-aided non-automatic methods use computers to support the overlay procedure and/or to visualize the skull, the face, and the obtained superimposition. In these techniques, the size and orientation of the skull are changed manually to by physically moving the skull, while the image is visualized on the computer monitor, or by moving the digital image on the screen until a good match is found. These methods should be distinguished from automatic skull face overlay techniques which find the optimal superimposition between the 3D model of the skull and the 2D image of the face using computer programs.

Finally, a crucial difference between automatic and non-automatic CFS systems, pertains to the decision making stage. While automatic systems assist the forensic expert to evaluate the match using objective and numerical data, in the non-automatic systems the identification decision relies only on the human expert who visually evaluates the skull face overlay obtained in the previous stage.

3.3.1. Computer-aided craniofacial video superimposition

This group of methods combine the use of a video superimposition system with computer capabilities to enhance and visualize images, draw points or contours, measure distances, make mathematical operations, etc. Table 3 summarizes the existing systems and provides their main features according to the three CFS stages.

3.3.2. Computer-aided craniofacial photo superimposition

These methods employ computer software to carry out all the CFS process. However, they rely on a series of photographs of the skull trying to mimic the photographic conditions of the available antemorten facial photographs. Table 4 summarizes the existing approaches and provides their main features according to the three CFS stages.

3.3.3. Computer-aided craniofacial 3D–2D superimposition

These methods are the most novel ones and represent the future of the technique. They provide the basis to automate the most tedious and error prone tasks within CFS by using a 3D model of the skull. Contrary to most of the previous approaches, a multidisciplinary team of computer scientists and forensic anthropologists were involved in developing these techniques. In the scientific literature there are a number of publications describing approaches aiming to solve one of the three CFS stages. Table 5, summarizes the main 3D–2D approaches dealing with the facial enhancement and skull modeling (FESM) and the skull face overlay (SFO) stages. While the former mainly focused on acquiring a unique 3D model of the complete skull (a step already included in all the recent scanners), the latter are all SFO automatic methods that make use of evolutionary computation [134] to apply iteratively a projective transformation over the 3D skull aimed to minimize the distance between craniometric and cephalometric landmarks.

4. State of the art

A thorough analysis of the scientific literature concerning cases resolved with CFS was conducted to ascertain the prevalence of craniofacial superimposition among forensic scientists. However, since many experts working with CFS might have not published their activity in the field, in order to present a truly comprehensive state of the art a survey among anthropologists was launched by the MEPROCS (methodologies and protocols of forensic identification by craniofacial superimposition); a project aimed to propose a common EU framework to allow the extensive application of the CS technique in practical forensic identification scenarios, commonly tackled by the European scientific police units.

The questionnaire was prepared by the European Center for Soft Computing (Spain), based on the requirements and scientific experience of forensic investigators from the University of Granada (Spain), Coimbra University (Portugal), Guardia Civil (Spain) and Israel Police. This survey was sent to approximately 600 forensic scientists worldwide, over a period of three months. The data was provided by forensic investigators from universities and law enforcement agencies from 32 countries in North, Central and South America, Europe, Asia and Africa. A total of 97 responses

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Table 4
Overview of computer-aided photo superimposition systems.

Stage	Authors
Face enhancement and skull modelling	
Acquisition of photographs of the skull in different angles	[35]
Acquisition of frontal photographs of the skull	[8,39]
Skull face overlay	
Manual scaling with Adobe Photoshop™ "free transform" tool	[33,35,95,109]
Face and skull visualization at the same time with Adobe Photoshop™ "semi-transparent" utility	[33–35,95,109]
Automatic overlay using artificial neural networks (only frontal images)	[8,39]
Decision making	
Morphological validation with Adobe Photoshop™ "semi-transparent" utility	[33,34,109]
Automatic calculation of Index of similarity based on distances	[95]
Automatic objective assessment of the symmetry	[8,39]

Table 5
Overview of computer-aided 3D–2D approaches.

Stage	Authors
Face enhancement and skull modelling	
Manual alignment of skull range images	[27,135,136]
Automatic alignment of skull range images	[137–139]
Automatic and faster alignment of skull range images	[140,141]
Holography for 3D recording of forensic objects	[142]
Computed tomography vs laser range scanner	[143]
Fuzzy location of cephalometric landmarks	[138,144–146]
Skull face overlay	
Automatic overlay by matching pairs of landmarks and genetic algorithms	[37,38,147,148]

Table 6
Use of CFS reported by 45 investigators.

Scenario result	Positive identification	Exclusion	Undetermined	Not classified	Total
PIOI	451 (11.7%)	33 (0.9%)	61 (1.6%)	–	545 (14.1%)
PICL	309 (8.0%)	4 (0.1%)	19 (0.5%)	–	332 (8.6%)
UICL	336 (8.7)	–	2 (0.1%)	–	338 (8.8%)
UIOL	150 (3.9%)	–	–	–	150 (3.9%)
CNC	–	–	–	2489 (64.6%)	2489 (64.6%)
Total	1246 (32.3%)	37 (1.0%)	82 (2.1%)	2489 (64.6%)	3854 (100.0%)

*Remarks on scenarios result: (PIOI) presumed identity of only one individual candidate, (PICL) presumed identity of an individual within a closed list of possible candidates, (UICL) unknown identity of an individual within a closed list of possible candidates, (UIOL) unknown identity of an individual within an open list and (CNC) cases not classified by the responders.

were received. Of these, over 50% investigators answered that they have used CFS as a method of identification in diverse investigations.

The survey was composed of 16 questions addressing issues related to the number of cases in the last 30 years, classified according to different identification scenarios (mass graves, terrorism, etc.), the number of hours employed for CFS, identification results, whether the results were presented in court, the materials, tools and technique used, set of landmarks employed and the main problems found in the application of CFS.

The investigators were first asked "Does/Did your laboratory perform craniofacial superimposition?". The results of the survey showed that out of the 97 responses, 56% were positive, i.e. the investigator reported using CFS in a regular basis or of having used CFS in the past. If the investigator reported on the affirmative, the questionnaire preceded to inquire about the number of cases and the identification scenario in which the technique was implemented by asking "How many cases?" and "classify them according to the identification scenario" i.e. presumed identity of only one candidate (PIOI), the presumed identity of an individual within a closed list of possible candidates, PICL or the unknown identity of an individual within a closed list of possible candidates, UICL. The last category is the unknown identity of an individual within an open list (UIOL). A closed list depicts the situation where a known group of identifiable people died in one incident, while an open list is considered an event that results in the death of an undetermined number of unknown individuals for whom no data or records are available. Finally, CNC denoted those cases not classified by the responders.

As Table 6 shows, the most common scenario is the presumed identity of only one individual candidate (545 cases). The two different categories considering a closed list includes 670 cases while the open list was applied in at least 150 cases.

The comparison between the results of the survey to the reports in the scientific literature reviewed during the project, covering the years 1937 to 2014, indicates that the vast majority of the cases in which craniofacial superimposition was attempted, are instances in which the presumed identity of an individual (PIOI) needed to be confirmed, from these cases the reports in the literature are, as expected, almost all positive identifications (Table 7).

The next issue addressed by the questionnaire was the nature of the investigation. The table to be filled by the practitioners included the possible scenarios in which the technique has been implemented. The survey defined four main categories in which CFS was implemented by the investigators; Terrorist attack, Miss-

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Table 7
Review of case reports classified according to the nature of investigation, identification scenario and result.

Authors	Nature of investigation					Identification scenario				Result		
	TA	MP	MCI	MG	O	PIOC	PICL	UICL	UIOL	PI	E	U
[6]					x		x				x	
[7]					x	x				x		
[8]					x	x				x		
[9]					x	x				x		
[10]					x	x						
[13]					x	x				x		
[18]					x	x				x		
[27]					x	x				x		
[28]					x	x				x		
[30]					x	x				x		
[31]					x	x				x		
[32]					x	x				x		
[33]					x	x				x		
[35]			x						x	x		
[39]					x	x				x		
[90]					x	x				x		
[91]		x					x			x	x	x
[112]					x	x				x		
[113]					x		x			x		
[123]					x	x				x		
[149]					x		x				x	
[150]	x						x			x		
[151]		x							x		x	
[152]					x	x				x		
[153]		x				x				x		
[154]					x	x				x		

*Remarks on nature of investigation: terrorism attack (TA), missing person (MP), mass casualty incident (MCI), mass grave (MG), other (O); identification scenarios: presumed identity of only one candidate individual (PIOI), presumed identity within a closed list of possible individuals (PICL), unknown identity within a closed list of possible individuals (UIOL), unknown identity within an open list of possible individuals (UIOL); and result: positive (PI), exclusion (E), undetermined (U).

Table 8
Classification of results obtained in the survey according to the nature of investigation.

Nature of the investigation	Cases
Terrorist attack	15 (0.4%)
Missing persons	458 (11.9%)
Mass casualty	130 (3.4%)
Mass grave	87 (2.3%)
Other	3164 (82.1%)
Total	3854 (100.0%)

ing person, Mass casualty incident, Mass Grave or Others and weather the resolved cases were presented in a Court of Law. Table 8 shows the distribution of the solved cases among these scenarios.

A total of 3854 cases of CFS were reported in the survey, of these, 2744 (71.2%) were presented in a court of law, and 1246 (32.3%) of them resulted in positive identification. Most cases (2489–82.1%) were not classified by the responders in any of the survey categories. In the scientific literature, the majority of the articles were classified within a general category "others" which, in most cases include single case identification of cadavers in diverse taphonomical conditions, or the identification of historical figures such as Mozart [152] thus; comparing the results to the survey to the scientific literature was irrelevant.

The literature reviewed revealed that 26 articles addressed the nature of the investigation in which CFS was implemented and later on, had undergone judicial scrutiny. It should be noted that a lot of the cases based on superimposition, cited in the literature as referred to the judicial authorities, were corroborated by other identification techniques, i.e. comparison of DNA profiles. When no corroboration could be obtained, the superimposition, together with the anthropological profile, was used as the identification method.

The final set of questions presented in the survey, addressed the technology implemented to achieve the superimposition and the set of landmarks used. The investigators were asked to report on the method used (Photo, video or computer-aided CFS) and on the nature of the process followed (manual, semi-automatic or fully automatic). The results of the survey seem to present some inconsistencies which can be explained by the lack of proper differentiation between the three CFS methods in the literature. While only 23% of the investigators answered that they use a computer-aided method, at least 61% of them reported that they use computer software (Photoshop) to perform CFS. Eleven investigators claimed to have used automatic photo superimposition, when in fact, these types of systems do not exist.

The statistics obtained in the survey were similar to the data found in the literature. Tables 1–5 summarize the technological development of CFS reported in the literature as described in section X of this review.

With regard to the question of set of landmarks used in CFS, a total of 26 responses were obtained. For a given set of possible landmarks, taken from different sources but mainly Martin and Saller [41] and George [70], the most commonly employed landmarks resulted to be Gonion, Gablella, Nasion, and Gnathion in more than the 30% of the cases. In addition, 65% of the participants indicated "other" landmarks a part from the set provided. This latter category includes anatomical features as the tragus or the Whitnall's tubercle, upper anterior teeth, dental patterns, the shape of the skull, contour of face and skull vault, position of auditory meatuses, position and shape of orbits, eye width, nose, position of lips, chin and mandibular angles, chin lip fold, the individual features (bifid nose, cleft chin), jawline and chin shape, vertical and horizontal proportions. Table 9 shows the set of landmarks analyzed in the survey and the percentages of responses in each case.

The survey conducted during the MEPROCS project supplied complementary information on the popularity of CFS among forensic practitioners, which otherwise would have remained

Table 9
Use of landmarks in CFS by 26 investigators.

Landmarks	Percentage of responses	Number of responses
Glabella-Glabella	31	8
Nasion-Nasion	31	8
Rhinion-Rhinion	12	3
Nasospinale-Subnasale	19	5
Alare-Alare	23	6
Subspinale-Superior labial sulcus	23	6
Prosthion-Upper lip border (Labiale superius)	27	7
Infradentale superius-Lower lip border	12	3
Incisor superius-Stomion	4	1
Supramentale-Labiomental	12	3
Gonion-Gonion	35	9
Zygion-Zygion	27	7
Orbitale-Infraorbital	12	3
Supraorbital-Supraorbital	8	2
Porion-Porion	8	2
Supraglenoide-Supraglenoide	8	2
Dacryon-Endocanthion	27	7
Gnathion-Menton	15	4
Gnathion-Gnathion	31	8
Pogonion-Mental	12	3
Pogonion-Pogonion	8	2
Prosthion-Prosthion	19	5
Ectoconchion-Ectocanthion	31	8
Frontozygomatic suture-Ectocanthion	19	5
Other	65	17
Total responses		26

unpublished. The great number of cases reported by investigators from developing countries in Latin America and Asia probably reflects a reduced availability of other antemortem information like dental or radiological data, for comparison with the skeletonized remains, or reduced funds to perform DNA profiles comparison (Table 10). Nevertheless, the responses of the survey are found in agreement with the scientific literature as far as the various technological approaches and scenarios are concerned.

5. Discussion and future challenges

The reliability of a scientific method is of paramount importance in a medico-legal investigation. The application of inaccurate techniques could lead to significant biases, compromising the identification process carrying serious consequences.

Table 10
CFS cases grouped by country.

Continent/country	Cases	Percentage
Central and North America	147	3.8
Mexico	105	2.7
USA	42	1.1
South America	1164	30.2
Brazil	6	0.2
Chile	2	0.1
Peru	980	25.4
Uruguay	176	4.6
Asia	2367	61.4
China	600	15.6
Japan	15	0.4
Jordan	5	0.1
India	1471	38.2
Russia	217	5.6
Turkey	58	1.5
United Arab Emirates	1	0.0
Europe	176	4.6
Spain	31	0.8
Denmark	10	0.3
Italy	20	0.5
Lithuania	80	2.1
Netherland	8	0.2
UK	7	0.2
Romania	20	0.5
Total cases	3854	100.0

While some authors classify CFS as a 'useful', 'powerful' and 'very successful' method for positive identification [124,149,155] others [1,25,27] agree that this technique should be used only for excluding identity, rather than for positive identification. A third group of authors contend that CFS cannot claim to qualify for the definite identification of an individual, but the combination of two methods can help to reduce mismatch and eliminate the chance of false identification [94,95].

Thus, CFS although existing for one century, is still a controversial technique within the scientific community. That is demonstrated by the small number of publications in the last decades. The evolution on the use of craniofacial superimposition highly depended on the kind of country and the frequency of potential cases to apply it and the available means to apply alternative identification techniques. In developed countries, the few number of cases and the boom in the application of alternative and more expensive techniques for identification led to a progressive reduction on the application of craniofacial superimposition. On the contrary, the important number of cases in developing countries is typically related to high criminal rates. Also, the funds for identification are usually limited in these regions. This situation led to a very frequent application of the technique in such countries.

Since the technique is used for identification purposes in many countries, the main concern related to its reliability is to demonstrate that a match is specific to one and only one person. Several experimental studies developed to evaluate reliability of the technique are cited in the literature.

The reliability of craniofacial superimposition in human identification was assessed by Chai et al. [91] thru the analysis of 52 indexes. The results demonstrated that the rate of false identification varied with the number of judging criteria, achieving a 0% error rate over 10,000 cross-comparisons, when 8 marking lines and profile curves were analyzed conjointly. Austin-Smith and Maples [24] conducted a total of 585 skull face overlays (SFO) from 3 identified male human skulls and a set of 100 mug shot (lateral and frontal view). The authors demonstrated that a match can obtained during the overlay process with the skull and the face of two different persons. The results of the study also showed that CFS can be an accurate technique, with less than 1% probability of false positives, when two or more photograph with different angles is used. Similarly, Yoshino et al. [29] examined 52 Japanese cases. They proposed that special attention should be paid to the analysis of outlines, the soft tissue thickness at various landmarks and positional relationships. They recommended both frontal and oblique or lateral face photographs to be used in craniofacial superimposition. Their examination indicates that a person can be positively identified if 13 or more matching criteria are observed. The investigation conducted by Jayaprakash et al. [94] on 30 cases, showed that the combination of CFS and craniofacial morpho-analysis minimized the probability of a mismatch to zero when considering the nasal traits alone. Ricci et al. [95] developed an algorithm that attained 100% precision in a sample composed of 14 individuals from whom a frontal photograph and an anterior X-ray were collected. Finally, in the study conducted by Gordon and Steyn [97] the reliability of craniofacial superimposition was evaluated in a sample of 40 male skulls and a postmortem frontal view photographs. The authors performed a 400 superimposition, achieving a positive match rate of circa 80% and a higher false negative rate ~20%.

The diverse support received within the forensic community, coupled with the different uses given to the technique in different countries, and the significant differences obtained in the reliability studies developed so far, emphasize three main challenges in craniofacial superimposition.

- The need of a common methodology, standards and best practices:

The survey conducted by MEPROCS showed that each expert tends to apply his/her own approach to the problem, based on the technology available at the time and on his/her knowledge on human craniofacial anatomy, soft tissues and their relationships. Establishing a common methodology to perform CFS, despite the technological means available, is required. Establishing standards concerning the quantity and quality of the materials, the criteria and the decision making process, in order to assure a reliable CFS is also very much in need. For these purposes, the MEPROCS[1] project, with more than twenty institutions active in the forensic realm work together, worked on defining a "best practices" document, identifying sources of errors and uncertainties, requirements of the equipment employed, and detailing procedures that should be followed and those that must be avoided.

- The need of objective assessment and automatization:

Knowledge exchange and the possibility to improve existing approaches and propose new methods to solve problems are the main forces behind the evolution of science. The guarantee of objective procedures to evaluate the performance of those proposals is essential.

To compare the performance of newly developed CFS methods, a common forensic dataset of known case studies should be available. In this way, the validation of the methods proposed, could be applied to solved cases and compare the results with the identification previously determined by forensic anthropologists.

The absence of a common repository of solved CFS cases has limited the development of automatic methods that could solve some of the most tedious CFS tasks in a fast, accurate, reproducible and objective way. To date, few automatic CFS tasks are used in practical applications despite the high number of cases examined and the large amount of time that the forensic expert invests in performing the examination [11]. In particular, skull-face overlay has been stated as a very challenging and time-consuming part of the craniofacial superimposition technique [25]. Despite the existence of promising works in this direction, automatic techniques are not implemented due to the inability to test their behavior in an objective manner [37,38,145].

- The need of a significantly large reliability study that takes into consideration the two previous points:

The reliability studies reported in the literature are fraught with limitations. The absence of an objective measure of the skull face overlay match, technical limitations of the equipment, disregard for accurate landmarks location while performing landmark based methods, absence of soft tissue data for the tested population, insufficient quality of the 3D cranial models, postmortem photographs, reduced samples, absence of appropriate statistical analysis, the absence of inter and intra observer studies are but a few. Statistically significant reliability studies that tackle the challenges identified in this manuscript are required to obtain a more solid picture on the reliability of craniofacial superimposition.

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References

[1] Cattaneo C. Forensic anthropology: developments of a classical discipline in the new millennium. Forensic Sci Int 2007;165:185–93.
[2] Burns KR, Wallington J. Forensic anthropology training manual. Saddle River, New Jersey: Prentice Hall; 1999.
[3] Yoshino M, Seta S. Skull-photo superimposition. Enc Forensic Sci 2000;2:807–15.
[4] Aulsebrook W, İşcan MY, Slabbert J, et al. Superimposition and reconstruction in forensic facial identification: a survey. Forensic Sci Int 1995;75:101–20.
[5] Stephan CN. Craniofacial identification: techniques of facial approximation and craniofacial superimposition. In: Blau S, Ubelaker DH, editors. Handbook of forensic anthropology and archaeology. California: Left Coast Press; 2009. p. 304–21.
[6] Glaister J, Brash JC. Medico-legal aspects of the Ruxton case. Edinburgh: Livingstone; 1937.
[7] Simpson K, Dobkin Rex v. The Baptist Church cellar murder. Med Legal Soc Trans 1943;11:132–45.
[8] Gordon I, Drennan M. Medico-legal aspects of the Wolkersdorfer case. S Afr Med J 1948;22:543–9.
[9] Prinsloo I. The identification of skeletal remains in Regina versus K and another: The Howick Falls murder case. J Forensic Med 1953;1:11–7.
[10] Sen N. Identification by superimposed photographs. Int Crim Police Rev 1962;162:284–6.
[11] Ubelaker DH. A history of Smithsonian-FBI collaboration in forensic anthropology, especially in regard to facial imagery. Forensic Sci Commun 2000:2.
[12] Basauri C. A body identified by forensic odontology and superimposed photographs. Int Crim Police Rev 1967;204:37–43.
[13] Bastiaan RJ, Dalitz GD, Woodward C. Video superimposition of skulls and photographic portraits—a new aid to identification. J Forensic Sci 1986;31:1373–9.
[14] Brown KA. The identification of Linda Agostini: the significance of dental evidence in the Albury Pyjama Girl case. Am J Forensic Med Pathol 1982;3:131–42.
[15] Gejvall N. Superimposition plus SEM-comparison of hair cuticle for identification purpose. Int J Skeletal Res 1974;1:99–103.
[16] Janssens P, Hansch C, Voorhamme L. Identity determination by superimposition with anthropological cranium adjustment. Int J Skeletal Res 1978;5:109–22.
[17] McKenna JJ, Jablonski NG, Fearnhead RW. A method of matching skulls with photographic portraits using landmarks and measurements of the dentition. J Forensic Sci 1984;29:787–97.
[18] Reddy K. Identification of dismembered parts: the medicolegal aspects of the Nagaraju case. Forensic Sci 1973;2:351–74.
[19] Sekharan PC. A revised superimposition technique for identification of the individual from the skull and photograph. J Crim L Criminol 1971:107–13.
[20] Sivaram S, Wadhera C. Identity from skeleton—a case study. Forensic Sci 1975;5:166.
[21] Vogel G. Zur Identifizierung unbekannter Toter. Kriminalistik 1968;4:187–9.
[22] Webster WP, Murray WK, Brinkhous W, Hudson P. Identification of human remains using photographic reconstruction. In: Reichs JK, Bass WM, editors. Forensic osteology: advanced in the identification of human remains using photographic reconstruction. Charles C. Thomas: Springfield; 1986. p. 256–89.
[23] Helmer RP, Grüner O. Vereinfachte Schädelidentifizierung nach dem Superprojektionsverfahren mit Hilfe einer Video-Anlage. Z Rechtsmed 1977;80:183–7.
[24] Austin-Smith D, Maples WR. The reliability of skull/photograph superimposition in individual identification. J Forensic Sci 1994;39:446–55.
[25] Fenton TW, Heard AN, Sauer NJ. Skull-photo superimposition and border deaths: identification through exclusion and the failure to exclude*. J Forensic Sci 2008;53:34–40.
[26] Sekharan, P.C. Video superimposition technology practised. Proceedings of the advances in skull identification via video superimposition: An international symposium and workshop. Kiel, West Germany, 1998, p. 3.
[27] Shahrom A, Vanezis P, Chapman R, et al. Techniques in facial identification: computer-aided facial reconstruction using a laser scanner and video superimposition. Int J Legal Med 1996;108:194–200.
[28] Solla H, Iscan MY. Skeletal remains of Dr. Eugenio Antonio Berrios Sagredo. Forensic Sci Int 2001;116:201–11.
[29] Yoshino M, Imaizumi K, Miyasaka S, et al. Evaluation of anatomical consistency in craniofacial superimposition images. Forensic Sci Int 1995;74:125–34.
[30] Ubelaker DH, Bubniak E, O'Donnell G. Computer-assisted photographic superimposition. J Forensic Sci 1992;37:750–62.
[31] Birngruber CG, Kreutz K, Ramsthaler F, et al. Superimposition technique for skull identification with Afloat® software. Int J Legal Med 2010;124:471–5.

[32] Pushparani C. Radiography superimposition in personal identification–a case study involving surgical implants. J Forensic Res 2011;3:2.
[33] Bilge Y, Kedici PS, Alakoç YD, et al. The identification of a dismembered human body: a multidisciplinary approach. Forensic Sci Int 2003;137:141–6.
[34] Takač Š, Pilija V. Exclusion of identification by negative superposition. Glas Antropol druš Srb 2012:311–6.
[35] Al-Amad S, McCullough M, Graham J, et al. Craniofacial identification by computer-mediated superimposition. J Forensic Odontostomatol 2006;24: 47–52.
[36] Ghosh A, Sinha P. An economised craniofacial identification system. Forensic Sci Int 2001;117:109–19.
[37] Ibáñez O, Cordón O, Damas S, et al. Multimodal genetic algorithms for craniofacial superimposition. In: Chiong R, editor. Nature-inspired informatics for intelligent applications and knowledge discovery: implications in business, science, and engineering. Hersey: IGI Global; 2009.
[38] Nickerson BA, Fitzhorn PA, Koch SK, et al. A methodology for near-optimal computational superimposition of two-dimensional digital facial photographs and three-dimensional cranial surface meshes. J Forensic Sci 1991;36:480–500.
[39] Ghosh A, Sinha P. An unusual case of cranial image recognition. Forensic Sci Int 2005;148:93–100.
[40] Taylor J, Brown K. Superimposition techniques. In: Clement JG, Ranson D, editors. Craniofacial identification in forensic medicine. London: Arnold; 1998. p. 151–64.
[41] Martin R, Saller K. Lehrbuch der Anthropologie. 3rd ed. Stuttgart: Gustav Fischer Verlag; 1957.
[42] Codinha SCF. Facing the dead: prediction of facial soft tissue depths from craniometric dimensions for forensic craniofacial identification [Ph.D. dissertation]. University of Coimbra; 2010.
[43] Stephan CN, Simpson EK. Facial soft tissue depths in craniofacial identification (Part I): an analytical review of the published adult data*. J Forensic Sci 2008;53:1257–72.
[44] Preedy VR. Handbook of anthropometry: physical measures of human form in health and disease. Springer; 2012.
[45] Stephan CN. The application of the central limit theorem and the law of large numbers to facial soft tissue depths: T-table robustness and trends since 2008. J Forensic Sci 2014;59:454–62.
[46] Stephan CN. Craniofacialidentification.com [Online] [cited 2014 Oct 29]. Available at: http://craniofacialidentification.com/.
[47] Clement JG, Ranson D. Craniofacial identification in forensic medicine. London: Arnold; 1998.
[48] Balueva T, Veselovskaya E, Valencia-Caballero L, et al. Nuevos estudios en el área de reconstrucción facial a partir de datos craneológicos. Rev Esp de Antropol Fís 2009:11–22.
[49] Fedosyutkin BA, Nainys JV. The relationship of skull morphology to facial features. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Wiley-Liss; 1993. p. 199–213.
[50] Wilkinson CM, Mautner SA. Measurement of eyeball protrusion and its application in facial reconstruction. J Forensic Sci 2003;48:12–6.
[51] Stephan CN. Facial approximation: globe projection guideline falsified by exophthalmometry literature. J Forensic Sci 2002;47:730–5.
[52] Whitnall SE. Anatomy of the orbit. London: Oxford Medical Publication; 1921.
[53] Stephan CN, Davidson PL. The placement of the human eyeball and canthi in craniofacial identification. J Forensic Sci 2008;53:612–9.
[54] Stephan CN. Craniofacial identification: techniques of facial approximation and craniofacial superimposition. In: Blau S, Ubelaker DH, editors. Handbook of forensic anthropology and archaeology. Walnut Creek: Left Coast Press; 2010. p. 304–21.
[55] Krogman WM, Iscan MY. The human skeleton in forensic medicine. Springfield: Charles C Thomas; 1986.
[56] Angel J. Anonymous Restoration of head and face for identification. Proceedings of meetings of American academy of forensic science. St. Louis, MO; 1978.
[57] Wolff E, Warwick R. Eugene Wolff's Anatomy of the eye and orbit: including the central connexions, development, and comparative anatomy of the visual apparatus. London: Lewis; 1976.
[58] Rosenstein T, Talebzadeh N, Pogrel MA. Anatomy of the lateral canthal tendon. Oral Sur Oral Med Oral Pathol Oral Radiol Endod 2000;89:24–8.
[59] Couly G, Hureau J, Tessier P. The anatomy of the external palpebral ligament in man. J Maxillofac Surg 1976;4:195–7.
[60] Anastassov GE, van Damme PA. Evaluation of the anatomical position of the lateral canthal ligament: clinical implications and guidelines. J Craniofac Surg 1996;7:429–36.
[61] Yoshino M, Seta S. Personal identification of human skull: superimposition and radiographic techniques. Forensic Sci Rev 1989;1:23–42.
[62] Stewart TD. The points of attachment of the palpebral ligaments: their use in facial reconstructions on the skull. J Forensic Sci 1983;28:858–63.
[63] Rynn C, Balueva T, Veselovskaya E. Relationships between the skull and face. In: Wilkinson CM, Rynn C, editors. Craniofacial identification. Cambridge: University Press; 2012. p. 193.
[64] Tandler J. Über den Schädel Haydns. Mitteilungen der Anthropologie Gesellschaft Wien 1909;39:260–80.
[65] Virchow H. Die anthropologische untersuchung der nase. Z Ethnol 1912:289–337.
[66] Gerasimov MM. The reconstruction of the face from the basic structure of the skull. Russia: Publisher Unknown; 1955.
[67] Glanville EV. Nasal shape, prognathism and adaptation in man. Am J Phys Anthropol 1969;30:29–37.
[68] Macho GA. An appraisal of plastic reconstruction of the external nose. J Forensic Sci 1986;31:1391–403.
[69] Robison JM, Rinchuse DJ, Zullo TG. Relationship of skeletal pattern and nasal form. Am J Orthod 1986;89:499–506.
[70] George RM. Anatomical and artistic guidelines for forensic facial reconstruction. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Willey-Liss; 1993. p. 215–27.
[71] Prokopec M, Ubelaker DH. Reconstructing the shape of the nose according to the skull. Forensic Sci Commun 2002:4.
[72] Stephan CN, Henneberg M, Sampson W. Predicting nose projection and pronasale position in facial approximation: a test of published methods and proposal of new guidelines. Am J Phys Anthropol 2003;122:240–50.
[73] Schultz AH. Relation of the external nose to the bony nose and nasal cartilages in whites and negroes. Am J Phys Anthropol 1918;1:329–38.
[74] Rynn C. Craniofacial approximation and reconstruction: tissue depth patterning and the prediction of the nose [Ph.D. dissertation]. University of Dundee; 2006.
[75] Rynn C, Wilkinson CM, Peters HL. Prediction of nasal morphology from the skull. Forensic Sci Med Pathol 2010;6:20–34.
[76] Stephan CN, Murphy S. Mouth width prediction in craniofacial identification: cadaver tests of four recent methods, including two techniques for edentulous skulls. J Forensic Odontostomatol 2008;27:2–7.
[77] Rudee DA. Proportional profile changes concurrent with orthodontic therapy. Am J Orthod 1964;50:421–34.
[78] Roos N. Soft-tissue profile changes in Class II treatment. Am J Orthod 1977;72:165–75.
[79] Koch R, Gonzales A, Witt E. Profile and soft tissue changes during and after orthodontic treatment. Eur J Orthod 1979;1:193–9.
[80] Waldman BH. Change in lip contour with maxillary incisor retraction. Angle Orthod 1982;52:129–34.
[81] Holdaway RA. A soft-tissue cephalometric analysis and its use in orthodontic treatment planning. Part I. Am J Orthod 1983;84:1–28.
[82] Denis KL, Speidel TM. Comparison of three methods of profile change prediction in the adult orthodontic patient. Am J Orthod Dentofacial Orthop 1987;92:396–402.
[83] Faysal Talass M, Tollaae L, Baker RC. Soft-tissue profile changes resulting from retraction of maxillary incisors. Am J Orthod Dentofacial Orthop 1987;91:385–94.
[84] Subtelny JD. A longitudinal study of soft tissue facial structures and their profile characteristics, defined in relation to underlying skeletal structures. Am J Orthod Dentofacial Orthop 1959;45:481–507.
[85] Renwick N. Ear lobe morphology and its relationship to the mastoid process. Centre for Anatomy and Human Identification, University of Dundee, Dundee. AXIS: Online J CAHID, 12; 2012.
[86] Guyomarch P, Stephan CN. The validity of ear prediction guidelines used in facial approximation. J Forensic Sci 2012;57:1427–41.
[87] Farkas LG. Anthropometry of the head and face in medicine. New York: Elsevier Norlh Holland; 1981.
[88] Powell N, Humphreys B. Proportions of the aesthetic face. New York: Thieme-Stratton; 1984.
[89] Helmer RP. Schädelidentifizierung durch elektronische Bildmischung: zugleich ein Beitrag zur Konstitutionsbiometrie und Dickenmessung der Gesichtsweichteile. Heidelberg: Kriminalistik Verlag; 1984.
[90] Helmer RP. Identification of the cadaver remains of Josef Mengele. J Forensic Sci 1987;32:1622–44.
[91] Chai DS, Lan YW, Tao C, et al. A study on the standard for forensic anthropologic identification of skull-image superimposition. J Forensic Sci 1989;34:1343–56.
[92] Yoshino M. Craniofacial superimposition. In: Wilkinson CM, Rynn C, editors. Craniofacial identification. Cambridge: University Press; 2012. p. 238–53.
[93] Lan Y. A study on national differences in identification standards for Chinese skull-image superimposition. Forensic Sci Int 1995;74:135–53.
[94] Jayaprakash P, Srinivasan G, Amravaneswaran M. Cranio-facial morphanalysis: a new method for enhancing reliability while identifying skulls by photo superimposition. Forensic Sci Int 2001;117:121–43.
[95] Ricci A, Marella GL, Apostol MA. A new experimental approach to computer-aided face/skull identification in forensic anthropology. Am J Forensic Med Pathol 2006;27:46–9.
[96] Ishii M, Yayama K, Motani H, et al. Application of superimposition based personal identification using skull computed tomography images. J Forensic Sci 2011;56:960–6.
[97] Gordon GM, Steyn M. An investigation into the accuracy and reliability of skull-photo superimposition in a South African sample. Forensic Sci Int 2012;216:198. e1–198. e6.
[98] Ogawa H. Anatomical study on the Japanese head by the X-ray cephalometry. Shika Gakuho 1960;60:17–34.
[99] İşcan MY. Introduction of techniques for photographic comparison: potential and problems. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Willey-Liss; 1993. p. 57–70.
[100] Gatliff BP. Facial sculpture on the skull for identification. Am J Forensic Med Pathol 1984;5:327–32.
[101] Rhine JS, Campbell HR. Thickness of facial tissues in American blacks. J Forensic Sci 1980;25:847–58.

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[102] George RM. The lateral craniographic method of facial reconstruction. J Forensic Sci 1987;32:1305–30.
[103] Miyasaka S. Progress in facial reconstruction technology. Forensic Sci Rev 1999;11:51–90.
[104] Suzuki H. Thickness of Japanese facial skin. Anthropol Sci 1948;60:7–11.
[105] Ichikawa K. Morphological relationships between nose breadth and aperture piriformis on the view point of face type. Rep Nat Inst Police Sci 1975;28:133–6.
[106] Iscan MY. Introduction of techniques for photographic comparison: potential and problems. In: Iscan MY, Helmer RP, editors. Forensic analysis of skull. New York: Wiley-Liss; 1993. p. 57–90.
[107] Yoshino M, Matsuda H, Kubota S, et al. Computer-assisted skull identification system using video superimposition. Forensic Sci Int 1997;90:231–44.
[108] Damas S, Cordón O, Ibáñez O, et al. Forensic identification by computer-aided craniofacial superimposition: a survey. ACM Comput Surv 2011;43:27.
[109] Scully B, Nambiar P. Determining the validity of Furue's method of craniofacial superimposition for identification. Malay J Comput Sci 2002;9:17–22.
[110] Sognnaes RF. Hitler and Bormann identifications compared by postmortem craniofacial and dental characteristics. Am J Forensic Med Pathol 1980;1:105–16.
[111] Cocks F. Barkly highway murder. Criminologist 1971;6:41–53.
[112] Webster G. Photography as an aid in identification: the Plumbago Pit case. Police J. 1955;28:185.
[113] Gruner O, Reinhard R. A photographical procedure for cranial identification. Dtsch Z Gesamte Gerichtl Med 1959;48:247–56.
[114] Maat G. The positioning and magnification of faces and skulls for photographic superimposition. Forensic Sci Int 1989;41:225–35.
[115] Brocklebank LM, Holmgren CJ. Development of equipment for the standardization of skull photographs in personal identifications by photographic superimposition. J Forensic Sci 1989;34:1214–21.
[116] Lan Y. Development and current status of skull-image superimposition-methodology and instrumentation. Forensic Sci Rev 1992;4:125–36.
[117] Dorion RB. Photographic superimposition. J Forensic Sci 1983;28:724–34.
[118] Pearson K, Morant G. The Wilkinson head of Oliver Cromwell and its relationship to busts, masks and painted portraits. Biometrika 1934;26:1–116.
[119] Klonaris NS, Furue T. Photographic superimposition in dental identification. Is a picture worth a thousand words? J Forensic Sci 1980;25:859–65.
[120] Jayaprakash P, Singhb B, Yusopc Ridzuan Abd, Mohd Aziz, et al. Skull-photo superimposition: a remedy to the problem of unidentified dead in Malaysia. Health Environ J 2010;1:65–74.
[121] Koelmeyer TD. Videocamera superimposition and facial reconstruction as an aid to identification. Am J Forensic Med Pathol 1982;3:45–8.
[122] McKenna JJ. A method of orientation of skull and camera for use in forensic photographic investigation. J Forensic Sci 1988;33:751–5.
[123] Austin D. Video superimposition at the C.A. Pound Laboratory 1987 to 1992. J Forensic Sci 1987;1999(44):695–9.
[124] Iten PX. Identification of skulls by video superimposition. J Forensic Sci 1987;32:173–88.
[125] Sekharan PC. Positioning the skull for superimposition. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Willey-Liss; 1993. p. 105–18.
[126] Delfino PV, Vacca E, Potente F, et al. Shape analytical morphometry in computer-aided skull identification via video superimposition. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Willey-Liss; 1993. p. 131–59.
[127] Delfino PV, Colonna M, Vacca E, et al. Computer-aided skull/face superimposition. Am J Forensic Med Pathol 1986;7:201–12.
[128] Lan Y. Research report on model TLGA-213 image superimposition identification system. Special Issue on Criminal Technology Supplement. The Fifth Bureau of the National Public Security Department. Beijing, China 1990;13.
[129] Lan Y, Cai D. A new technology in skull identification. In: Helmer RP, editor. Advances in skull identification via video superimposition. Germany: Kiel; 1988. p. 3.
[130] Lan Y, Cai D. Study on model TLGA-1 skull identification apparatus. Special Issue on Criminal Technology Supplement. The Fifth Bureau of the National Public Security Department. Beijing, China 1985;3.
[131] Lan Y, Cai D. Technical advances in skull-to-photo superimposition. In: Iscan MY, Helmer RP, editors. Forensic analysis of the skull. New York: Willey-Liss; 1993. p. 119–29.
[132] Tao C. Report on computer programming for model TLGA-1 skull identification. Special Issue on Criminal Technology Supplement. The Fifth Bureau of the National Public Security Department. Beijing, China 1986;41.
[133] Bajnoczky I, Kiralyfalvi L. A new approach to computer-aided comparison of skull and photograph. Int J Legal Med 1995;108:157–61.
[134] Bäck T, Fogel DB, Michalewicz Z. Handbook of Evolutionary Computation. Bristol: IOP and Oxford University Press; 1997.
[135] Benazzi S, Fantini M, De Crescenzio F, et al. The face of the poet Dante Alighieri reconstructed by virtual modelling and forensic anthropology techniques. J Archeol Sci 2009;36:278–83.
[136] Fantini M, de Crescenzio F, Persiani F, et al. 3D restitution, restoration and prototyping of a medieval damaged skull. Rapid Prototyping J 2008;14:318–24.
[137] Santamaría J, Cordón O, Damas S, et al. A scatter search-based technique for pair-wise 3D range image registration in forensic anthropology. Soft Comput 2007;11:819–28.
[138] Santamaría J, Cordón O, Damas S, et al. Tackling the coplanarity problem in 3D camera calibration by means of fuzzy landmarks: a performance study in forensic craniofacial superimposition. In: Proc IEEE 12th Int Conf Comput Vision. IEEE Comput Soc, 2009b. p. 1686–1693.
[139] Santamaría J, Cordón O, Damas S, et al. Performance evaluation of memetic approaches in 3D reconstruction of forensic objects. Soft Comput 2009;13:883–904.
[140] Ballerini L, Calisti M, Cordón O, et al. Automatic feature extraction from 3D range images of skulls. In: Srihari SN, Franke K, editors. IWCF 2008. LNCS 5158. Berlin: Springer; 2008. p. 58–69.
[141] Ballerini L, Cordón O, Damas S, et al. Automatic 3D modeling of skulls by scatter search and heuristic features. Appl Soft Comput 2009;52:149–58.
[142] Biwasaka H, Saigusa K, Aoki Y. The applicability of holography in forensic identification: a fusion of the traditional optical technique and digital technique. J Forensic Sci 2005;50:393–9.
[143] Galantucci L, Percoco G, Angelelli G, et al. Reverse engineering techniques applied to a human skull, for CAD 3D reconstruction and physical replication by rapid prototyping. J Med Eng Technol 2006;30:102–11.
[144] Ibáñez O, Ballerini L, Cordón O, et al. An experimental study on the applicability of evolutionary algorithms to craniofacial superimposition in forensic identification. Inf Sci 2009;179:3998–4028.
[145] Ibánez O, Cordón O, Damas S, et al. Modeling the skull–face overlay uncertainty using fuzzy sets. IEEE Trans Fuzzy Syst 2011;19:946–59.
[146] Ibáñez O, Cordón O, Damas S, et al. Craniofacial superimposition based on genetic algorithms and fuzzy location of cephalometric landmarks. In: Hybrid artificial intelligence systems. Springer; 2008. p. 599–607.
[147] Ballerini L, Cordon O, Santamaria J, et al. Anonymous Craniofacial superimposition in forensic identification using genetic algorithms. In: Proc IEEE Int Workshop Comput Forensics. Springer 2007. p. 429–434.
[148] Ibáñez O, Cordón O, Damas S, et al. An advanced scatter search design for skull-face overlay in craniofacial superimposition. Expert Syst Appl 2012;39:1459–73.
[149] Furuhata T, Yamamoto K. Forensic odontology. Sprinfield: Thomas; 1967.
[150] Indriati E. Historical perspectives on forensic anthropology in Indonesia. In: Blau S, Ubelaker DH, editors. Handbook of forensic anthropology. California: Left Coast Press; 2009. p. 115–25.
[151] Iscan MY. Forensic anthropology of sex and body size. Forensic Sci Int 2005;147:107–12.
[152] Puech P, Puech B, Tichy G. Identification of the cranium of WA Mozart. Forensic Sci Int 1989;41:101–10.
[153] Ross AH. Use of digital imaging in the identification of fragmentary human skeletal remains: a case from the Republic of Panama. Forensic Sci Commun 2004;6:4.
[154] Teixeira WRG. The Mengele report. Am J Forensic Med Pathol 1985;6:279–83.
[155] Kamijo Y, Sakai K. Basic study on superimposition with application of roentgencephalometry. Report II: Postural relationship between soft and hard tissues of the human head and face, a study of special camera for superimposition. Nat Res Institute Police Sci Rep 1970;23:10–7.

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