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The use of craniofacial superimposition for disaster victim identification

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Abstract: Skull-to-face comparison is utilised for human identification where there is a suspected identity and the usual methods of identification, such as DNA or dental comparison, are not possible or practical. This research aimed to accurately compare manual and computerised craniofacial superimposition techniques and to establish the application of these techniques for disaster victim identification, where there may be a large database of passport-style images, such as the MPUB Interpol database. Twenty skulls (10 female; 10 male) were utilised from the William Bass Skeletal Collection at the University of Tennessee and compared to face pools of 20 face photographs of similar sex, age and ethnic group. A traditional manual photographic method and a new 3D computer-based method were studied. The results suggested that profile and three-quarter views of the ante-mortem face were the most valuable for craniofacial superimposition. However, the poor identification rate achieved using images in frontal view suggests that the MPUB Interpol database would not be optimal for disaster victim identification, and passport-style images do not provide enough distinguishing facial detail. This suggests that multiple ante-mortem images with a variety of facial expression should be utilised for identification purposes. There was no significant difference in success between the manual and computer methods.
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Dear Editor  

We submit a paper to be considered for publication in the Forensic Science International as a research paper.  

The research has not been presented at any conference, nor published in any publication, nor submitted for publication to any other journal or publication.  

There are no conflicts of interest or publication problems, or additional information appropriate to the publication.  

Thank you very much for your attention.  

Yours sincerely  

Prof Caroline Wilkinson
THE USE OF CRANIOFACIAL SUPERIMPOSITION FOR DISASTER VICTIM IDENTIFICATION

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- Comparison of manual and computerised craniofacial superimposition for DVI
- Twenty skulls compared to face pools
- Profile and three-quarter views were the most valuable facial images
- Poor identification rate suggests MPUB database images would not be optimal
- Multiple ante-mortem images with a variety of facial expression should be utilised
THE USE OF CRANIOFACIAL SUPERIMPOSITION FOR DISASTER VICTIM IDENTIFICATION

ABSTRACT

Skull-to-face comparison is utilised for human identification where there is a suspected identity and the usual methods of identification, such as DNA or dental comparison, are not possible or practical. This research aimed to compare the reliability of manual and computerised craniofacial superimposition techniques and to establish the application of these techniques for disaster victim identification, where there may be a large database of passport-style images, such as the MPUB Interpol database. Twenty skulls (10 female; 10 male) were utilised from the William Bass Skeletal Collection at the University of Tennessee and compared to face pools of 20 face photographs of similar sex, age and ethnic group. A traditional manual photographic method and a new 3D computer-based method were studied. The results suggested that profile and three-quarter views of the ante-mortem face were the most valuable for craniofacial superimposition. However, the poor identification rate achieved using images in frontal view suggests that the MPUB Interpol database would not be optimal for disaster victim identification, and passport-style images do not provide enough distinguishing facial detail. This suggests that multiple ante-mortem images with a variety of facial expression should be utilised for identification purposes. There was no significant difference in success between the manual and computer methods.

KEYWORDS

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INTRODUCTION

Facial anthropology involves biological analysis and interpretation of the skull and/or the face and can be applied to identification of the living (biometrics, image analysis) and the dead (facial depiction, craniofacial superimposition, osteology, anatomy)[1]. Craniofacial analysis of the dead can be utilised for single unidentified human remains, multiple victims of disasters and mass graves. In the majority of forensic investigations there will be a suspect in relation to identity; in single forensic cases there may be a missing persons list, in mass disasters there may be a closed list (such as a passenger list for a transport system) or an open list (reported missing by families and/or employers) and for mass graves there may be whole missing populations. In these circumstances there may be ante-mortem data available relating to the suspects and this might include biological profiles (age, sex, stature, ethnic group), personal information (body modifications, identifying marks, clothing, jewellery, hair style etc.), photographs (ID cards, passport images, family albums or snapshots), hair samples (collected from a hairbrush etc.), dental records, clinical images and/or medical records [2].
However, much of this ante-mortem data may not be available, for example where the individual did not have a history of dental or medical treatment, or the available data may not be useful, for example where multiple members of the same family are missing (such as in a mass grave or mass disaster) and DNA analysis cannot separate family members. This may be significant in areas/countries with high levels of poverty, low socio-economic status and poor medical/dental practise.

Where ante-mortem images are present craniofacial superimposition may be effective as it does not require expensive or invasive techniques and is cost and time efficient. Craniofacial superimposition is the process where ante-mortem images are aligned and matched to the skull in order to assess the relationship between the hard and soft tissues of the face. This analysis may allow positive identification, especially where multiple ante-mortem images are available and this has been accepted in international courts as a method of identification [3-8].

Traditionally craniofacial superimposition has been carried out by forensic anthropologists or anatomists [5, 7, 9] and the techniques incorporate similar anatomical principles [10] and anthropological standards [11] as utilised in facial depiction. Numerous computerised systems have been developed for skull-to-face alignment [8, 12-15].

The first documented use of craniofacial superimposition for identification in a medico-legal investigation was in 1935 [3], with a particular case involving a Lancastrian GP and the mysterious disappearance of his wife. Dr Ruxton claimed that his wife had left him for another man, but two weeks later two dismembered bodies were found in Glasgow. Police recovered two human heads and over seventy body parts wrapped in newspaper. The newspaper was from a special edition that was distributed only in the area where the Ruxtons lived. Dr Buck Ruxton had killed his wife and her maid and removed the eyes, noses, lips, skin and teeth to avoid identification of the bodies. The police suspected that the maid and the wife were the victims and a craniofacial superimposition was carried out using ante-mortem images of the two women and photographs of the skulls [16]. The method used in this case was photographic; employing enlargement, measurable objects, anatomical landmarks and craniophore orientation [17]. Known objects in the photographs (e.g. a tiara and a picket fence) were used to enlarge the faces to life size in order to identify Mary Rogers and Isabella Ruxton.

There have been other significant forensic cases where craniofacial superimposition has been utilised for identification of human remains, including the identification of the remains of Josef Mengele [7, 18] and the identification of the victims of the serial killers, Fred and Rosemary West, in the UK [19]. Other significant cases are the Dobkin case [4], the Warkstersdorfer case [5] and the Howick Falls murder case [6]. Detailed reviews of the techniques can be found in the literature [17, 20-27] and many case studies have also been published [8, 13, 28-42].

Craniofacial superimposition development has passed through three technological phases: photographic, video and computer-assisted [17, 25]. The photographic technique was pioneered in the 1930s [3-5], the video technique was developed in the 1970s [43-45] and the computer-assisted technique was introduced in the 1980s [12, 36, 46].

It is professionally agreed that craniofacial superimposition is of greater value for exclusion than positive identification [17] and a single facial image of a different person may also appear consistent with the skull in question. Therefore, forensic practitioners must be well trained in anatomy and anthropology for the effective utilization of craniofacial superimposition and multiple ante-mortem images of the suspect should be analysed. When evaluating anatomical consistency special attention is paid to the cranial outline, the soft tissue thickness at various anthropometric landmarks on the skull and feature relationships between the skull and the face [47].

It is vitally important to practitioners and law enforcement agencies to establish the level of accuracy of these craniofacial techniques, especially in the case of craniofacial superimposition where this may be utilised in court for positive identification. The credibility of craniofacial
Superimposition was first established in a study using a database of 52 skulls from the Smithsonian collection [8]. An unknown skull was shown to match an ante-mortem facial photograph, while the four most similar skulls from the collection showed distinct differences to the facial photograph. Another blind study [48] used three skulls and compared them to 97 lateral view and 98 frontal view photographs of subjects (including the targets); in total 585 superimpositions. False matches were recorded for 9.6% of the lateral view and 8.5% of the frontal view superimpositions and all 3 targets were correctly matched. The incidence of false matches was reduced to 0.6% when both frontal and lateral view photographs of the same individual were used, suggesting that multiple photographs are optimal to prove or disprove identity by craniofacial superimposition. A further study [17] found that the outline from trichion to gonion in the lateral or oblique view was the optimal portion for personal identification.

Technological advances in the field of facial imaging over the past 20 years have produced new opportunities for research in facial morphology and facial growth assessment [49]. Surface scanning technologies such as laser scanners, photogrammetry cameras and other three-dimensional systems (including three-dimensional digitizers and structured light systems) have advanced craniofacial landmark location [50-52] and facial anthropometry in both adults and juveniles [53-58]. These systems have benefited the field of orthodontic and plastic surgery with the ability to record subtle changes in surface morphology, especially important in the monitoring orthodontic treatment, facial growth and maxillofacial intervention [59, 60].

Numerous accuracy studies have been conducted on different laser scanners with regard to the accuracy from three-dimensional capture of faces of the resulting scan measurements when compared with anthropometric measurements from the face [52, 60-62]. These studies all found that laser scanners are a reliable and fast means of capturing a three-dimensional reproduction of a facial surface whilst maintaining high levels of accuracy with regard to the difference in resulting measurements between the scan and the subject. However, Aung et al. [52] did indicate that accurate location of landmarks and operator skill are important factors in achieving reliable results.

The ability of a forensic practitioner to reliably cite the accuracy of a particular method employed in forensic human identification is highly desirable. The reason for this is not simply for legal reasons but also as a moral and ethical obligation to the victim and their family. This will ensure that if the practitioner is required to provide an expert witness report to the court (with regard to the identification they have assigned to the deceased) the evidence provided is valid with the support of scientific research.

In order to improve craniofacial analysis techniques further rigorous quantitative accuracy studies need to be conducted especially with regard to the scientific method. Improving the accuracy of these techniques and increasing publication of the findings of accuracy studies will allow the use of craniofacial analysis techniques more widely in the field of forensic human identification, especially with regard to disaster victim identification and also increase the acceptance of these methods in a medico-legal investigation.

The aim of this research was to accurately compare manual and computerised craniofacial superimposition techniques and to establish the application of these techniques for disaster victim identification, where there may be a large database of passport-style images, such as the MPUB Interpol database.

**METHOD**

This study utilised a three-dimensional laser scanning system (FastSCAN™ Polhemus Scorpion™ handheld laser scanner) [63] for collection of 3D skull models for use in craniofacial analysis.
Data collection was conducted on the William Bass donated skeletal collection from the University of Tennessee, USA, following the approval of the University of Tennessee Ethics Board. This collection consists of skeletal material and related ante-mortem images. Twenty (10 male and 10 female) crania and their associated mandibles were scanned using a glass platform and wooden mounting pole to enable 360 degree scanning ability. The crania were scanned separately from the associated mandibles to ensure as much detail was captured as possible. The mandibles were scanned using a glass platform that enabled scanning from all views. Before scanning of the crania and mandible commenced, photographic images were captured of the skeletal remains from numerous angles to display any features that the laser scanner may not be able to acquire. The related ante-mortem images were collected and employed as the target images.

Three male face pools and three female face pools were created using the target images in addition to a large number of other ante-mortem images collected from unrelated cases in the William Bass Collection. This enabled the creation of the face pools with consistent demographic profiles. The following face pools were created:

- Female Face Pool 1 - FFP1 (20 faces – 3 targets, 17 foils)
- Female Face Pool 2 - FFP2 (20 faces – 3 targets, 17 foils)
- Female Face Pool 3 - FFP3 (20 faces – 4 targets, 16 foils)
- Male Face Pool 1 - MFP1 (20 faces – 3 targets, 17 foils)
- Male Face Pool 2 - MFP2 (20 faces – 3 targets, 17 foils)
- Male Face Pool 3 - MFP3 (20 faces – 4 targets, 16 foils)

Within each face pool there were a variety of images, ranging from candid shots to professional portraits. The image quality ranged from poor quality (i.e. photocopies of original documents and low resolution photographic shots – small pixel count) to high quality (i.e. higher resolution photographic shots – large pixel count) and the angle of the faces in the photographs varied from frontal to profile images. The age of the images also varied (with some from the 1960s) although the age of the subjects in the images was similar. The individuals in the face pools also displayed a variety of facial hair and clothing, some of which caused areas of the face to be distorted or obscured. This variation in the face pools represented a typical DVI scenario where photographs would originate from a variety of sources.

The twenty skulls were equally divided between the two methods with 10 skulls per method (with 5 female and 5 male in each group). The craniofacial superimposition guidelines used to determine a successful or unsuccessful CFS were based upon the morphology of the skull and the closeness of the match between the skull and the ante-mortem (AM) image (no measurements were taken). The researcher created a set of 3 stages to aid with determination of a match (for both manual and computerised), these were as follows:

- **Stage 1**: Individuals were eliminated if the skull did not fit within the facial outline of the AM image.
- **Stage 2**: Individuals were eliminated if skeletal features did not match in position or morphology to the AM image.
- **Stage 3**: Additional AM images were requested for further analysis and elimination. Not all individuals had additional photographs to reflect a real life DVI scenario. The remaining individuals were then classified as a match or no match to the skull based on all available material.

The two methods of craniofacial superimposition (CFS) included:

1. The Manual method was an updated version of a pre-existing method described by Seta and Yoshino [64] for craniofacial analysis that utilises a remote guided motor driven machine to orientate the skull for image capture.
The manual method required physical skulls for use with the skull orientation machine. However the original skulls were not available and replicas of the 10 skulls were created by stereolithography (rapid prototyping) [65]. The mandibles were then temporarily fixed to the crania with modelling putty (based upon guidelines produced in [66]). The skull orientation machine was set up in front of a high resolution digital web camera which recorded the movement of the skull model and transmitted the live feed to a PC (see Figure 1). Current literature states that the optimum objective length for photographic superimposition is at 1 metre [23, 24]. Craniofacial superimposition can be conducted with the aid of free online software called Glass 2K (Chime Software Ltd) [67] which enables the user to change the opacity of computer windows. The user can set up the web camera feed and then overlay an image and change the opacity of the image file window to enable the web camera feed to be visualised through the image (see Figure 1). Two hundred manual craniofacial superimpositions were conducted utilising this method for the ten skull models with each skull model undergoing a separate craniofacial superimposition for each face in the face pool.

The Computer Method was a newly developed and utilised a combination of specialist computer hardware (haptic device) and 3D modelling software to orientate a digital skull model in virtual space for image capture. The computer method also utilised the same procedure, except that it did not require a physical skull model as the entire process was conducted in a virtual space. The laser scan models were used (in an .obj format) and were imported into a 3D modelling software package (Geomagic’s Freeform Modelling®) [68] where the mandible was fixed to the cranium in a relaxed resting position (in the same position as for manual). This modelling package allows a 3D model to be orientated in a virtual space when used in combination with a piece of computer hardware called a Phantom® Desktop™ Haptic Device [69], which enables the user to rotate and orientate a 3D model using an arm-like tool. The computer method allows the user to position a 3D skull model file in virtual space (see Figure 2) and then position an AM image (on a virtual plane) anterior to the skull model. The opacity of the ante-mortem image can be altered to allow better visibility of the 3D skull model. The user can then use the haptic device to orientate the skull model to match in scale and position to the face in the AM image (See Figure 2). A screen shot can then be captured and imported into Adobe Photoshop © CS3 [70] for final analysis and demonstration. Two hundred computer craniofacial superimpositions were conducted utilising this method for the ten skull models with each skull model undergoing a separate craniofacial superimposition for each face in the face pool.

RESULTS

The CFS methods correctly matched the target to the skull at stage 3 in 40% manually and 50% by computer. It was observed that the overall correct match rate at stage 3 was 45% (see Tables 1 & 2). The false match rate at stage 3 was 15% manually and 8% by computer, giving an overall false match rate of 12%. The manual method matched 17% and the computer method matched 11% of the total faces to the skull at stage 3.

Ten (50%) of the targets were falsely rejected at stage 1 and a further one (5%) falsely rejected at stage 2. The manual method rejected more targets (60%) at stage 1 than the computer method (40%) and the computer method rejected more targets (10%) at stage 2 than the manual method (0%) (see Tables 1 & 2).

Thirty-six per cent of foil images were of low, 47% medium and 18% high quality. Fifty per cent were colour and 50% were black & white images, with 68% in frontal, 19% three-quarter and 14% profile views. The majority (76%) of images displayed a smiling face with 40% open mouth smile and 34% closed mouth smile. Twenty-three per cent of images displayed an individual not smiling with a closed mouth and relatively few individuals displayed no smile and an open mouth (5%). The majority of foil images displayed no facial distractions (eg. glasses,
hats, facial hair) of any kind (57%), however 18% of individuals were observed to wear spectacles, 18% of individuals wore facial hair and relatively few individuals displayed a mixture of spectacles, facial hair and clothing. Visible photographic distortion was recorded in a relatively small number of images (11%).

Forty per cent of target images were of low, 30% medium and 30% high quality. Sixty per cent were colour and 40% black & white images, with 50% in frontal, 25% three-quarter and 25% profile views. The majority (70%) displayed a smiling target with 45% of images displaying an open mouth smile and 25% displaying a closed mouth smile. Twenty-five per cent of images displayed the target not smiling with a closed mouth and only 5% displayed the target not smiling with an open mouth. The majority of targets displayed no facial distractions of any kind (80%), however 5% were observed to wear spectacles, 10% wore facial hair and 5% wore both spectacles and facial hair. Visible photographic distortion was only recorded in 5% of target images.

Most of the targets (67%) that reached stage 3 had non-frontal view images, whereas most of the targets (60%) that were eliminated at stage 1 had frontal view images (see Figure 3). This would suggest that CFS was more successful where the target was seen in profile or ¾ views. These views enable observation of the profile of the face and the jaw line, which can result in optimal assessment due to the relatively thin soft tissue thicknesses over the gonial, nasal and orbital areas.

Eighty-nine per cent of the targets that reached stage 3 did not have any facial distractions, and 30% of the targets eliminated at stage 1 displayed facial distractions (see Figure 4). This would suggest that facial distractions had a small effect on CFS success.

Forty-four per cent of the targets that reached stage 3 displayed an open mouth expression and 60% of the targets that were eliminated at stage 1 displayed an open mouth expression (see Figure 5). This would suggest that CFS was less successful when the AM image depicted an open mouth expression.

There was no observable difference between colour and black and white target images in relation to successful match rates, and there was no significant difference in match rates in relation to visible photographic distortion or hair thickness.

**DISCUSSION**

These results are similar to previous accuracy tests. Austin-Smith and Maples [48] recorded a 9.5% false match rate, which is similar to the 12% false match rate in this study. Yoshino and colleagues (47) also found that the profile and three-quarter views were the most valuable for craniofacial superimposition. However, the poor identification rate achieved using images in frontal view suggests that the MPUB Interpol database would not be optimal for disaster victim identification, and passport images do not provide enough distinguishing facial detail. Gordon and Steyn [71] carried out a craniofacial superimposition study using forty frontal face images of cadavers, ten skulls for comparison with each face (400 comparisons in total) and morphological and landmark superimposition techniques. They also found that frontal images have limited use for identification and recommended corroborative evidence.

This study suggests that to improve the chance of a successful CFS in a DVI scenario the following standardised protocols should be followed:

1. The ante-mortem images should be of a high quality and without facial distractions or visible distortion.
2. Ideally at least two images should be utilised; neutral facial expression with a closed mouth and slightly open mouth showing the upper teeth.
3. Multiple views including profile and ¾ views are ideal. Frontal views alone are not optimal.

There was no significant difference in success between the manual and computer methods, and this suggests that digital technology is as reliable as traditional methods. However, neither method in this study utilised the physical remains, and the detail provided by the laser scans was consistent with the stereolithographic replicas.

This study concludes that craniofacial superimposition could be a useful tool in disaster victim identification for narrowing the possible identifications of individuals in a large scale closed disaster (such as a commercial aeroplane crash where the manifest of passengers is known) and when used in combination with other disaster victim identification techniques, such as DNA and dental analysis, craniofacial superimposition can result in a fairly reliable and accurate outcome for the identification of individuals.

Following the success of the computer method, further studies should focus on decreasing the amount of expensive equipment and computer software and the development of a bespoke craniofacial superimposition software system. The researcher noted that although the haptic device was a useful tool for the orientation of the skull, it was the least portable aspect of the CFS equipment and also the most expensive piece of equipment used. Any bespoke computer software would require an ability to position three-dimensional models in virtual space in combination with a two-dimensional plane to support an AM image. This software should also include a sliding scale option for perspective views enabling the user to adjust the scale in response to any photographic distortion observed within the AM image.

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65. [http://pdronline.info/](http://pdronline.info/) Accessed last at 22.10 on 02/02/2014
Figure 1: The manual craniofacial superimposition set up with webcam, lap top and skull orientation machine

Figure 2: An example of craniofacial superimposition (left) using the computer method (right)

Table 1: Results of the manual craniofacial superimposition test (F = female; M = male)

Table 2: Results of the computer-based craniofacial superimposition test (F = female; M = male)

Figure 3: Survival graph in relation to the angle of view for the target images

Figure 4: Survival graph in relation to the facial distractions for the target images

Figure 5: Survival graph in relation to the expression for the target images
THE USE OF CRANIOFACIAL SUPERIMPOSITION FOR DISASTER VICTIM IDENTIFICATION

ABSTRACT

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INTRODUCTION

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Technological advances in the field of facial imaging over the past 20 years have produced new opportunities for research in facial morphology and facial growth assessment [49]. Surface scanning technologies such as laser scanners, photogrammetry cameras and other three-dimensional systems (including three-dimensional digitizers and structured light systems) have advanced craniofacial landmark location [50-52] and facial anthropometry in both adults and juveniles [53-58]. These systems have benefited the field of orthodontic and plastic surgery with the ability to record subtle changes in surface morphology, especially important in the monitoring orthodontic treatment, facial growth and maxillofacial intervention [59, 60].

Numerous accuracy studies have been conducted on different laser scanners with regard to the accuracy from three-dimensional capture of faces of the resulting scan measurements when compared with anthropometric measurements from the face [52, 60-62]. These studies all found that laser scanners are a reliable and fast means of capturing a three-dimensional reproduction of a facial surface whilst maintaining high levels of accuracy with regard to the difference in resulting measurements between the scan and the subject. However, Aung et al, [52] did indicate that accurate location of landmarks and operator skill are important factors in achieving reliable results.

The ability of a forensic practitioner to reliably cite the accuracy of a particular method employed in forensic human identification is highly desirable. The reason for this is not simply for legal reasons but also as a moral and ethical obligation to the victim and their family. This will ensure that if the practitioner is required to provide an expert witness report to the court (with regard to the identification they have assigned to the deceased) the evidence provided is valid with the support of scientific research.

In order to improve craniofacial analysis techniques further rigorous quantitative accuracy studies need to be conducted especially with regard to the scientific method. Improving the accuracy of these techniques and increasing publication of the findings of accuracy studies will allow the use of craniofacial analysis techniques more widely in the field of forensic human identification, especially with regard to disaster victim identification and also increase the acceptance of these methods in a medico-legal investigation.

The aim of this research was to accurately compare manual and computerised craniofacial superimposition techniques and to establish the application of these techniques for disaster victim identification, where there may be a large database of passport-style images, such as the MPUB Interpol database.

**METHOD**

This study utilised a three-dimensional laser scanning system (FastSCAN™ Polhemus Scorpion™ handheld laser scanner) [63] for collection of 3D skull models for use in craniofacial analysis.
Data collection was conducted on the William Bass donated skeletal collection from the University of Tennessee, USA, following the approval of the University of Tennessee Ethics Board. This collection consists of skeletal material and related ante-mortem images. Twenty (10 male and 10 female) crania and their associated mandibles were scanned using a glass platform and wooden mounting pole to enable 360 degree scanning ability. The crania were scanned separately from the associated mandibles to ensure as much detail was captured as possible. The mandibles were scanned using a glass platform that enabled scanning from all views. Before scanning of the crania and mandible commenced, photographic images were captured of the skeletal remains from numerous angles to display any features that the laser scanner may not be able to acquire. The related ante-mortem images were collected and employed as the target images.

Three male face pools and three female face pools were created using the target images in addition to a large number of other ante-mortem images collected from unrelated cases in the William Bass Collection. This enabled the creation of the face pools with consistent demographic profiles. The following face pools were created:

- Female Face Pool 1 - FFP1 (20 faces – 3 targets, 17 foils)
- Female Face Pool 2 - FFP2 (20 faces – 3 targets, 17 foils)
- Female Face Pool 3 - FFP3 (20 faces – 4 targets, 16 foils)
- Male Face Pool 1 - MFP1 (20 faces – 3 targets, 17 foils)
- Male Face Pool 2 - MFP2 (20 faces – 3 targets, 17 foils)
- Male Face Pool 3 - MFP3 (20 faces – 4 targets, 16 foils)

Within each face pool there were a variety of images, ranging from candid shots to professional portraits. The image quality ranged from poor quality (i.e. photocopies of original documents and low resolution photographic shots – small pixel count) to high quality (i.e. higher resolution photographic shots – large pixel count) and the angle of the faces in the photographs varied from frontal to profile images. The age of the images also varied (with some from the 1960s) although the age of the subjects in the images was similar. The individuals in the face pools also displayed a variety of facial hair and clothing, some of which caused areas of the face to be distorted or obscured. This variation in the face pools represented a typical DVI scenario where photographs would originate from a variety of sources.

The twenty skulls were equally divided between the two methods with 10 skulls per method (with 5 female and 5 male in each group). The craniofacial superimposition guidelines used to determine a successful or unsuccessful CFS were based upon the morphology of the skull and the closeness of the match between the skull and the ante-mortem (AM) image (no measurements were taken). The researcher created a set of 3 stages to aid with determination of a match (for both manual and computerised), these were as follows:

- **Stage 1**: Individuals were eliminated if the skull did not fit within the facial outline of the AM image.
- **Stage 2**: Individuals were eliminated if skeletal features did not match in position or morphology to the AM image.
- **Stage 3**: Additional AM images were requested for further analysis and elimination. Not all individuals had additional photographs to reflect a real life DVI scenario. The remaining individuals were then classified as a match or no match to the skull based on all available material.

The two methods of craniofacial superimposition (CFS) included:

1. **The Manual method** was an updated version of a pre-existing method described by Seta and Yoshino [64] for craniofacial analysis that utilises a remote guided motor driven machine to orientate the skull for image capture.
The manual method required physical skulls for use with the skull orientation machine. However, the original skulls were not available and replicas of the 10 skulls were created by stereolithography (rapid prototyping) [65]. The mandibles were then temporarily fixed to the crania with modelling putty (based upon guidelines produced in [66]). The skull orientation machine was set up in front of a high resolution digital web camera which recorded the movement of the skull model and transmitted the live feed to a PC (see Figure 1). Current literature states that the optimum objective length for photographic superimposition is at 1 metre [23, 24]. Craniofacial superimposition can be conducted with the aid of free online software called Glass 2K (Chime Software Ltd) [67] which enables the user to change the opacity of computer windows. The user can set up the web camera feed and then overlay an image and change the opacity of the image file window to enable the web camera feed to be visualised through the image (see Figure 1). Two hundred manual craniofacial superimpositions were conducted utilising this method for the ten skull models with each skull model undergoing a separate craniofacial superimposition for each face in the face pool.

2. The Computer Method was a newly developed and utilised a combination of specialist computer hardware (haptic device) and 3D modelling software to orientate a digital skull model in virtual space for image capture.

The computer method also utilised the same procedure, except that it did not require a physical skull model as the entire process was conducted in a virtual space. The laser scan models were used (in an .obj format) and were imported into a 3D modelling software package (Geomagic’s Freeform Modelling®) [68] where the mandible was fixed to the cranium in a relaxed resting position (in the same position as for manual). This modelling package allows a 3D model to be orientated in a virtual space when used in combination with a piece of computer hardware called a Phantom® Desktop™ Haptic Device [69], which enables the user to rotate and orientate a 3D model using an arm-like tool. The computer method allows the user to position a 3D skull model file in virtual space (see Figure 2) and then position an AM image (on a virtual plane) anterior to the skull model. The opacity of the ante-mortem image can be altered to allow better visibility of the 3D skull model. The user can then use the haptic device to orientate the skull model to match in scale and position to the face in the AM image (See Figure 2). A screen shot can then be captured and imported into Adobe Photoshop © CS3 [70] or final analysis and demonstration. Two hundred computer craniofacial superimpositions were conducted utilising this method for the ten skull models with each skull model undergoing a separate craniofacial superimposition for each face in the face pool.

RESULTS

The CFS methods correctly matched the target to the skull at stage 3 in 40% manually and 50% by computer. It was observed that the overall correct match rate at stage 3 was 45% (see Tables 1 & 2). The false match rate at stage 3 was 15% manually and 8% by computer, giving an overall false match rate of 12%. The manual method matched 17% and the computer method matched 11% of the total faces to the skull at stage 3.

Ten (50%) of the targets were falsely rejected at stage 1 and a further one (5%) falsely rejected at stage 2. The manual method rejected more targets (60%) at stage 1 than the computer method (40%) and the computer method rejected more targets (10%) at stage 2 than the manual method (0%) (see Tables 1 & 2).

Thirty-six per cent of foil images were of low, 47% medium and 18% high quality. Fifty per cent were colour and 50% were black & white images, with 68% in frontal, 19% three-quarter and 14% profile views. The majority (76%) of images displayed a smiling face with 40% open mouth smile and 34% closed mouth smile. Twenty-three per cent of images displayed an individual not smiling with a closed mouth and relatively few individuals displayed no smile and an open mouth (5%). The majority of foil images displayed no facial distractions of any kind
(57%), however 18% of individuals were observed to wear spectacles, 18% of individuals wore facial hair and relatively few individuals displayed a mixture of spectacles, facial hair and clothing. Visible photographic distortion was recorded in a relatively small number of images (11%).

Forty per cent of target images were of low, 30% medium and 30% high quality. Sixty per cent were colour and 40% black & white images, with 50% in frontal, 25% three-quarter and 25% profile views. The majority (70%) displayed a smiling target with 45% of images displaying an open mouth smile and 25% displaying a closed mouth smile. Twenty-five per cent of images displayed the target not smiling with a closed mouth and only 5% displayed the target not smiling with an open mouth. The majority of targets displayed no facial distractions of any kind (80%), however 5% were observed to wear spectacles, 10% wore facial hair and 5% wore both spectacles and facial hair. Visible photographic distortion was only recorded in 5% of target images.

Most of the targets (67%) that reached stage 3 had non-frontal view images, whereas most of the targets (60%) that were eliminated at stage 1 had frontal view images (see Figure 3). This would suggest that CFS was more successful where the target was seen in profile or ¾ views. These views enable observation of the profile of the face and the jaw line, which can result in optimal assessment due to the relatively thin soft tissue thicknesses over the gonial, nasal and orbital areas.

Eighty-nine per cent of the targets that reached stage 3 did not have any facial distractions, and 30% of the targets eliminated at stage 1 displayed facial distractions (see Figure 4). This would suggest that facial distractions had a small effect on CFS success.

Forty-four per cent of the targets that reached stage 3 displayed an open mouth expression and 60% of the targets that were eliminated at stage 1 displayed an open mouth expression (see Figure 5). This would suggest that CFS was less successful when the AM image depicted an open mouth expression.

There was no observable difference between colour and black and white target images in relation to successful match rates, and there was no significant difference in match rates in relation to visible photographic distortion or hair thickness.

**DISCUSSION**

These results are similar to previous accuracy tests. Austin-Smith and Maples [48] recorded a 9.5% false match rate, which is similar to the 12% false match rate in this study. Yoshino and colleagues (47) also found that the profile and three-quarter views were the most valuable for craniofacial superimposition. However, the poor identification rate achieved using images in frontal view suggests that the MPUB Interpol database would not be optimal for disaster victim identification, and passport images do not provide enough distinguishing facial detail.

This study suggests that to improve the chance of a successful CFS in a DVI scenario the following standardised protocols should be followed:

1. The ante-mortem images should be of a high quality and without facial distractions or visible distortion.
2. Ideally at least two images should be utilised; neutral facial expression with a closed mouth and slightly open mouth showing the upper teeth.
3. Multiple views including profile and ¾ views are ideal. Frontal views alone are not optimal.

There was no significant difference in success between the manual and computer methods, and this suggests that digital technology is as reliable as traditional methods. However, neither
method in this study utilised the physical remains and the detail provided by the laser scans was consistent with the stereolithographic replicas.

This study concludes that craniofacial superimposition could be a useful tool in disaster victim identification for narrowing the possible identifications of individuals in a large scale closed disaster (such as a commercial aeroplane crash where the manifest of passengers is known) and when used in combination with other disaster victim identification techniques, such as DNA and dental analysis, craniofacial superimposition can result in a more reliable and accurate outcome for the identification of individuals.

Following the success of the computer method, further studies should focus on decreasing the amount of expensive equipment and computer software and the development of a bespoke craniofacial superimposition software system. The researcher noted that although the haptic device was a useful tool for the orientation of the skull, it was the least portable aspect of the CFS equipment and also the most expensive piece of equipment used. Any bespoke computer software would require an ability to position three-dimensional models in virtual space in combination with a two-dimensional plane to support an AM image. This software should also include a sliding scale option for perspective views enabling the user to adjust the scale in response to any photographic distortion observed within the AM image.

REFERENCES


65. http://pdronline.info/ Accessed last at 22.10 on 02/02/2014


70. Adobe Photoshop © CS8.0 (Adobe) Systems, San Jose, CA; http://www.adobe.com/ Accessed last at 22.15 on 02/02/2014
Figure 4: Survival graph in relation to the angle of view for the target images

Figure 5: Survival graph in relation to the facial distractions for the target images
Figure 6: Survival graph in relation to the expression for the target images
<table>
<thead>
<tr>
<th>N = 20</th>
<th>Skull</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of matches</strong></td>
<td>F2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>False matches</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Correct match</strong></td>
<td>x</td>
</tr>
<tr>
<td><strong>Stage target eliminated</strong></td>
<td>S1</td>
</tr>
</tbody>
</table>

Table 1: Results of the manual craniofacial superimposition test (F = female; M = male)

<table>
<thead>
<tr>
<th>N = 20</th>
<th>Skull</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of matches</strong></td>
<td>F1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>False matches</strong></td>
<td>0</td>
</tr>
<tr>
<td><strong>Correct match</strong></td>
<td>yes</td>
</tr>
<tr>
<td><strong>Stage target eliminated</strong></td>
<td>x</td>
</tr>
</tbody>
</table>

Table 2: Results of the computer-based craniofacial superimposition test (F = female; M = male)
Revision List:

1. In the Introduction, first para - change "gender" to "sex" as we are dealing with biological characteristics
   CHANGED

2. Where the word "distractions" (facial distractions) is used for the first time, just explain briefly what is meant by this
   ADDED ON PAGE 5

3. P. 5, 4th last line before Results - should read "].. Adobe Photoshop FOR final analysis.." (not OR)
   CORRECTED

4. Discussion: last sentence of the second last paragraph, change to read :"]..craniofacial superimposition can result in a FAIRLY reliable and accurate ..."- instead of "more reliable"
   CHANGED

5. I also think the authors should, in the Discussion, correlate their results with those of Gordon & Steyn (2012), Forensic Science International, who found similar poor results with frontal view superimpositions
   ADDED TO DISCUSSION AND REFERENCE LIST

Many thanks to the reviewer for comments and corrections.
Revision List:

1. The paper is very long for the data it presents - the paper has been shortened as much as is possible. All remaining text is now considered essential.

2. Both Vancouver and Harvard referencing styles are used throughout the manuscript - corrected to all Vancouver style.

3. Manufacturer and city details are not provided for software or equipment – corrected.

4. Empty bullet points follow the list on P4 – corrected.

5. Numbers are not spelled out at the beginning of sentences – corrected.

6. Title case has not been used for all journal names in the reference list – corrected.

7. Some references are wrong (e.g., ref [24] is a book chapter and needs to be fully described as such with the title and editors of the book given) – corrected.

8. There were also no figure legends attached to my review version of the paper – provided.

9. Line graphs should be presented as column or bar plots so as not to imply change across time – these changed DO occur over time and have been left as line graphs.

10. Character case should be consistent across Tables 1 & 2 (see use of "yes" and "Yes", and "x" and "X") – corrected.

Many thanks to the reviewer for comments and corrections.