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# 3D Forensic Facial Reconstruction: A Review of the Traditional Sculpting Methods and Recent Computerised Developments

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## Abstract

Forensic facial reconstruction aims at achieving a likeness of the facial outlook of the deceased based on the underlying skull for the purpose of recognition and identification. On encountering a greatly decomposed, mutilated, or skeletonized body, facial reconstruction can be used as a last resort technique to identify the unknown skeletal remains, when the usual methods of investigation fail. This paper focuses mainly on the three-dimensional aspect of facial reconstruction, giving an overview of both the traditional and the computerized techniques. Traditional methods involve physically modeling the clay onto the skull replica to sculpt the face, which tends to be subjective and time-taking. However, with the recent advancement in technology, newer, more rapid and flexible computer-based techniques are underway. Nevertheless, all reconstruction techniques are based on the relationship between the skull and the overlying tissues and thus, the evolution of the various techniques for facial soft tissue depth measurements along with their limitations have also been summarised. One of the major challenges it has to face in the coming future will be to fully explore this relationship between the hard and soft tissues and furthermore increase the accuracy and reliability of the various techniques.

**Keywords:** Forensic Facial Reconstruction; Three-Dimensional; Recognition; Identification; Soft Tissue Depth Measurements

## Introduction

Forensic facial reconstruction is the scientific art of recreating the facial appearance of an individual from the skull for the purpose of personal identification [1]. The work of identifying human remains during a forensic investigation can be strenuous when the remains are highly mutilated, decomposed or skeletonized. In such cases where the usual methods of investigation fail, it can play an important role in establishing the identity of the remains [2-4]. The ultimate aim of facial reconstruction in a forensic context, therefore, is to recreate the appearance that best resembles the original face of the deceased, in an effort to stimulate public recognition that will eventually contribute to personal identification [5,6]. However, it should be noted that facial reconstruction cannot on its own be used for such positive identification but should instead be employed along with other established techniques such as dental records and DNA analysis [6,7]. Outside the forensic scenario, it is also applied in the field of archaeology to restore the faces of the past, where exact accuracy is not a priority. Over the years, several techniques of reconstruction have been developed which are all based on the relationship between the soft facial tissues and the underlying skull. The lack of fully understanding this relationship has been stated as one of the main cause of the various controversy surrounding the techniques [5]. There are currently two basic approaches – two-dimensional and three-dimensional types of reconstruction. Both techniques employ either a manual or a computerized approach. The earliest scientific endeavour towards facial reconstruction began in the late 19$^{th}$ century with various measurements of the facial thickness from cadavers [8-10]. These were later followed by the development of different prominent three-dimensional manual reconstruction techniques including the Anatomical (Russian), Anthropometrical (American) and Combination (Manchester) methods [7,11-13]. These methods involve sculpting the facial tissues over the skull with either clay or plasticine taking into account the information obtained from the skull assessment such as age, sex, height, race, etc. It is a combination of both scientific and artistic skill and hence can have subjective interpretations and can also be time-consuming. Therefore, with the advent of the 20th century, efforts were made to improve the techniques; and with the advancement in technology, new computer-based techniques emerged that claimed to be quicker, more flexible and most importantly, reproducible [2-6,14-17]. This paper mainly focuses on the three-dimensional aspect and intends to summarise the evolution of the techniques over the years, discussing both the traditional as well as the newer computer-based reconstructions. The various methods developed over time for measuring the facial tissue thicknesses, which is a major part of all reconstruction techniques, have also been discussed along with a brief historical review.

### Historical Review of Facial reconstruction

Throughout time, men have always been intrigued with human faces which have led to a significant interest in the faces and appearances of people of the past. The first attempts at building a face on to a skull can be dated back to the Neolithic period where people performed it as a means of ancestor worship [18]. During the Renaissance period, death-mask art was at its peak and people began to take an interest in the anatomy of the human body. Artists such as Verrocchio, Michelangelo, Versalius are known to have used wax models to document their works [18,19]. Towards the end of the 18th century, scientific art became highly popularised and the artists of that time have been considered to be the first sculptors to discover that the skeleton can be used as the ideal frame over which the tissues and muscles can be built up [19]. The credit for developing the theory behind facial reconstruction can, thus, be given to these artists. In the 19th century, many anatomists made efforts to obtain the soft tissue depth measurements of the face from cadavers [8-10]. Facial reconstructions were earlier achieved through the collaboration of scientists and artists. Anatomists depended upon the sculptors to depict their data, as can be seen in the cases of His and Sefner, Kollmann and Buchly [9,10]. In 1895, the German anatomist His made the first attempt at an actual reconstruction where he worked with the artist Sefner to reconstruct a plaster skull cast of Johann Sebastian Bach using the skin depth measurements at nine midline facial points and six lateral points of twenty-four male and four female white cadavers in Leipzig. He further authenticated the reconstruction by comparing it with available portraits of Bach [7,18,19]. A few years later, Kollmann and Buchly also made a facial approximation of Dante in 1898 from the tissue depth measurements taken at ten midline and eight lateral points of twenty-one male and four female cadavers ranged between 17 and 72 years of age, to His's total, thus producing mean measurements for 45 male and eight female European White cadavers [7]. Kollman then went on to reconstruct the face of a stone-age woman from Auvenir, France, which also came to be considered as the first scientific reconstruction, wherein he performed the feat by producing technical drawings from the tissue depth measurements of hundreds of women around that area and finishing touches were carried out by Buchly [18,19].

Many anthropologists further went on to produce various reconstructions of early hominoids. With the advent of the 20th century, facial reconstructions began to be used in museums and also the various manual reconstruction techniques began to spring up. In 1971, the Russian anthropologist Gerasimov developed a technique of modeling the anatomy of the facial muscles and tissues, which came to be known as the Russian or morphoscopic method [12]. Around the same time, another technique, known as the American or morphometric method, which was based on facial tissue thickness was developed in the United States [7]. While in the United Kingdom, Neav incorporated both the Russian and American method to formulate a new technique known as the Manchester and Combination method [7]. With various technical developments, the first ever three-dimensional computer-assisted reconstruction technique for forensic identification was developed [3]. The method utilized a low-power laser scanner and a video camera interfaced to a computer. The current trend in facial reconstructions is to move towards computer-assisted techniques that are considered to be less subjective and more rapid.

## Three-Dimensional Facial Reconstruction Techniques

**Traditional Manual Reconstruction:** Sculpting the face over the unknown skull with clay, wax or plasticine is one of the most common forms of three-dimensional reconstructions. There are a number of ways to go about it. Nonetheless, in any reconstruction technique, the first step is to examine the skull to determine the biological features such as age, gender, race, etc., after which a skull replica is obtained to be worked on. An influential and significant pioneer in this field was the Russian anthropologist, Mikhael Gerasimov who developed the Russian method that relied upon anatomical knowledge and sculptural skills [12]. In this technique, the development of the musculature of the skull and neck is regarded as being of prime importance [18]. Firstly, the main muscles of mastication are modeled over the skull while taking extra care not to exaggerate the bulk of those muscles. Next, the circular muscles around the mouth and eyes are built up. Further details such as the parotid glands or fatty deposits are later added if required. To complete the reconstruction, a layer of skin, which can be textured, is applied to it. Some experts perform the reconstructions only based on the soft tissue thickness of the face [7,20-23]. Such method utilizes tissue depth markers such as dowels or rubber of different lengths depending on the tissue thickness at various anatomical points on the face. The dowels are cut according to the required thickness and glued to the skull. This method is also known as the American or anthropometrical method and was developed from the works of Krogman by the forensic artist Betty Pat Gatliff and the physical anthropologist, Clyde Snow [18,19]. Soft tissues are added in bulk and strips without any regard for the underlying anatomy, all the while making sure that the clay does not exceed the length of the dowels at any point. Others prefer a combination of the two methods above, known as the Manchester or the combination method, which employs the procedure of muscle insertion as in the Russian method to establish a more detailed form of the face, along with the tissue thickness measurements, as in the American method, to reproduce the soft tissue depth [13,18,19].

Figure 1: Three-dimensional Manual Facial Reconstruction. (Image courtesy of Caroline Wilkinson, University of Dundee, UK) [24].

Facial features such as the eyes, nose, ears and mouth cannot be directly determined from the skull and these are added based on some existing guidelines provided through various studies, although, such guidelines have been found to be inaccurate to some extent [12,23,25]. Whilst various successful cases have been reported in the past, the traditional technique is subjective and controversial due to the presence of an artistic aspect. Also, the obtained results always tend to differ between practitioners and also between reconstructions. This point was clearly illustrated in the Green River serial killer cases, in which multiple facial reconstructions of several victims were created by different practitioners. The results were highly variable from practitioner to practitioner and met with little success [26]. Moreover, the manual techniques often tend to be limited to a single reconstruction due to its time-consuming process [17].

**Contemporary Computer-based Reconstruction**

The computer-based reconstructions were found to be more rapid and objective in nature. Unlike the manual techniques, when the same input was given, it would always result in producing the same output. Furthermore, it was possible to generate many faces with little variations from the same skull [17]. The first introduction of the computer-based technique was done by Vanezis and his colleagues [3]. Like every computer-based reconstruction technique, the skull is first digitized. This was done using a laser scanner and a video camera interfaced to a computer, forming a fully shaded 3D surface. An advantage of this system, thus, was that the reconstruction work could be carried out on the image of the actual skull, rather than a replica as in manual reconstructions. Various markers indicating the tissue depths are then placed on different selected sites on the skull. Then a face from a databank of previously scanned face of live subjects is placed over the skull in the form of a mask, allowing it to specifically conform to the skull based on the different tissue depths at various points [27]. Performed both the traditional clay as well as the computer-based technique to make a comparison [3]. After their studies, they concluded that although the manual reconstruction has a number of limitations, yet it can prove to be quite effective when done the right way. The computer-based technique provided greater speed and flexibility but it was still far from perfect. They later improved the technique by upgrading the computer software and added the same tissue markers from the skull on to the face as well [4]. However, live subjects were scanned with their eyes closed and hence, in the last step, eyes and other facial features were added using the police identikit systems to humanize the face. Subsequently, proposed the idea that the individual identity of a face is the direct result of the scale, position, and the ratio of facial features relative to one another [15]. Since the relative positions of facial features are dependent on the skull, even house put forward a hypothesis that an individual's face could actually be formed by substituting an average face onto the skull and formulated an image warping algorithm to create an average face. He merged the facial features of five females to create the average face and with the help of 37 tissue markers, mapped the face onto the skull. He believed that with further research on tissue depth measurements, and a more detailed averaging of the facial features, this technique could be a good tool for the identification process.

A further technique was proposed in 1997 to produce facial reconstructions based on deformable models, instead of tissue depth measurements [16]. They used a CT scanner to obtain the digitized 3D models of two pairs of skulls along with their facial data. The first pair was used as a reference and the other to validate their method. A global parametric transformation algorithm was then used to turn the reference skull into the skull to be reconstructed. This was based on what is known as the crest lines, which are lines of absolute maxima of the largest principal curvature of the skulls. The crest lines of the reference skull were matched to the crest lines of the skull to be reconstructed. The algorithm was then applied to the reference face to obtain the reconstructed unknown face [4,6,27].

Nelson and Michael believed that the lack of fully understanding the relationship between the soft tissues and the underlying skull was one of the main limitations of every reconstruction technique [5,6,27]. Therefore, they introduced a new approach through volume deformation. In the first stage, the unknown skull and a number of reference heads similar to the unknown skull in terms of age, sex, and race are selected which are digitized using a CT scanner. In the next stage, a set of control points are then placed at specific anatomical positions on the heads and the skull. Then a single head is selected for deformation by calculating and comparing the spatial distribution of the control points. Lastly, the selected head is then deformed to the shape of the skull with the help of control points and any adjustments such as the addition of facial features, facial expressions and tissue depth variations are also done by manipulating the control points. This method has one major advantage over surface deformation methods in that all the data representing the facial soft tissues are deformed and not just the surface, thus the face is not merely a mask suspended on a restricted number of reference points.

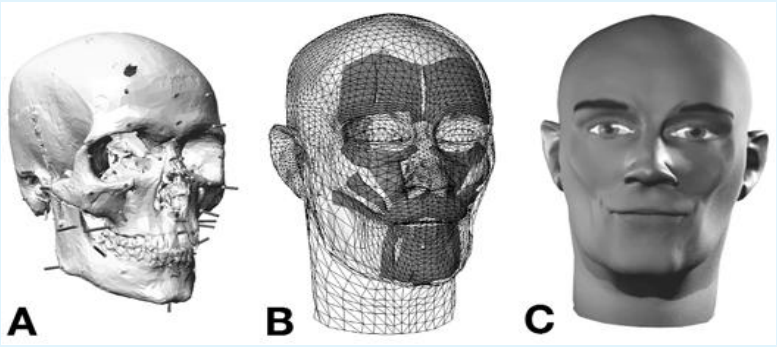


Figure 2: Facial reconstruction using computer software. (Image courtesy of KoljaKähler, MPI Informatik Saarbruecken, Germany.

Several regional methods have recently been proposed, where the face and skull are segmented into regions, and the relationship of each region is then learned independently [28]. After which, the facial regions of a given skull are estimated and finally glued together to generate a face [29].

Have given a summary of the general workflow which has been found to be the same for all current computer-aided techniques [17]. They are basically dependent on the craniofacial model which contains the vital information about the faces and their relationship with the underlying skull and can be deemed to correspond to a person carrying out the manual reconstruction. The process is carried out by first examining the skull to obtain the biological characteristics and digitizing it through the different techniques available. The reconstruction is then performed by calculating the geometrical relationship between the unknown and the craniofacial model. Further details can be added to better represent the face of the individual. The current inclination in facial reconstruction is towards the computerization of the techniques. However, with the ever-changing and advancing technology, it is too soon to designate the best approach or make the comparison between methods. In such instances, the major step to take is to establish reliable standard databases of facial components [2]. However, while the computer technology is advancing at an astounding rate, one of the major problems remain the lack of tissue depth data upon which reconstructions are based on and also the fact that such data are seen as unreliable, and is still the subject of ongoing research.

**Techniques for Tissue Depth Measurement**

A number of studies have gone into quantifying the relationship between the soft facial tissues and the underlying skull, for the purpose of reconstruction. The first of its work, however, can be credited to Welcker, a German physiologist and anatomist in 1883, who documented the average tissue depth thickness of cadavers, by inserting a small surgical blade into various anthropometric landmarks on the face and then measuring the depth of penetration [8]. In the late 1880's and early 1890's, His and Kollman built upon Welcker's work, slightly modifying it by inserting a thin sharp needle which had a small piece of rubber on its tip, instead of using a wider blade, resulting in a more accurate data [9-10]. Subsequently, the anthropologist Kollman along with the sculptor Buchly used a needle that was covered in soot and considered the clean part of the needle to be the tissue depth [6].

However, with the advancement in technology, tissue depth measurements began to be taken using radiographs, MRI images and CT scanners, but more recent measurements were taken using ultrasound, as it had the advantage of measurements being taken in an upright position [30]. But it also came with the difficulty of measuring due to the imperceptibility of the bone underlying the tissue [31].

All computerized reconstruction techniques up to this day use CT scanners for obtaining the virtual copy of the unknown skull. In case of live subjects for the database, CT scanner allowed both the skull and the face surface information to be obtained simultaneously and in the correct spatial relationship to each other. Some major disadvantages of this technique include health hazards caused by the radiation, being taken in a supine position and also its sensitivity to high-density material [30]. A non-harmful alternative to CT scanners were MRI images,

although it had the same problem of being scanned in a horizontal position. Later on, Cone-beam CT (CBCT) scanners were developed and being used in medical practice. In contrast to conventional CT, CBCT scanners acquired images of subjects in an upright position. Moreover, CBCT images could be obtained with a lower absorbed dose at the cost of a slightly reduced image quality [32,33]. Hwang, et al. tested the reproducibility of CBCT scanners by measuring the soft tissue thickness at 31 landmarks on 20 subjects [34]. They then found that thickness was measured with high reproducibility, while also suggesting that certain landmarks should be redefined.

During the twentieth century, various anatomists studied and collected the measurements of tissue depths in different racial and ethnic groups. Birkner (1904) studied Chinese cadavers; Fischer (1903) studied Papuan cadavers; Von Eggeling (1909) studied Herero (Namibian) cadavers; Suzuki (1948) studied Japanese cadavers; Rhine and Campbell (1980) studied American Black cadavers; Rhine, et al. (1982) studied American White cadavers; and Rhine (1983) studied Southwestern Indian cadavers [35].

## Discussion

Facial restoration is a forensic and an archaeological device used by experts to aid in the proof of identity procedure of the unidentified human remains. The last goal of a facial reconstruction, consequently, is to create the best similarity to the original facial position of the unidentifiable remains, also in the background of forensic science, to stimulate community concentration that may finally lead to the recognition and proof of identity the person. Despite some case successes published in the literature since its first introduction years ago, it is difficult to depict the exact accuracy of these methods as it relies on a number of factors. Also, due to the existing limitations, it has not always been possible to get a positive successful result. Reliable accuracy rates of reconstruction techniques can be obtained only when efforts are made to fully explore the true nature of the relationships between the soft facial tissues and the underlying skull. Throughout more current times, certain unseeing studies and estimates have been carried out to increase the consistency of the methods done face pool identification, similarity evaluations or anthropometrical calculation. The renovation methods, whether be it manual or computer-based, can never accomplish an exact demonstration since the human face is a very detailed structure involving of a number of variables such as the eyes, ears, nose, and lips; skin color, hairstyles, occurrence of facial hair in males; surface patterns such as tattoos, scars, moles; ornaments such as rings and glasses, etc. In small, either systems are preferred; the bony frame is unable to give all the clues for the soft- tissue facial reconstruction. It should, though, be noted that the success of a renovation method does not depend only on the skill of the experts and the accuracy of the reconstruction but there are other numerous factors that determine whether a reconstruction is deemed successful or not. How wide the reconstructed image reaches the public may increase or decrease the chances proof of identity that is, the reconstructed image needs to reach those that know the deceased for a likely recognition to occur. Also, on the part of the public, the relatives or friends of the deceased may, at times, not wish to come forward for various personal reasons. The fame of the dead in the community may also have a huge impact on the accomplishment of the case; the identification rate for a secluded person, with no family, relatives or friends is much lesser than that of a individual known by everyone in the public.

## Conclusion

The techniques behind facial reconstruction continue to be more apt, gradually changing from a more artistic method to a scientific one, as the years go by. New and more reliable methods are being studied with the advancement in technology. Nevertheless, it is clear that facial reconstruction methods at present do come with some inaccuracies due to which the techniques are yet to be standardized, and the main challenge in the coming future would undoubtedly be to increase the degree of accuracy and reliability. But despite the limitations and the apparent fact that positive identification could certainly not be allowed to rest on a facial reconstruction alone, there also exist many successful cases that validate the use of reconstruction techniques as a last resort technique. Although it is a long shot, yet, it is worth taking when other attempts fail to identify the unknown remains. Hence, it should not be thrown aside, instead, more research works should be carried out on the lacking elements, for if it can, at the most, narrow down the list of suspects, it will have validated all the research done in this field.

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