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THE USE OF THREE DIMENSIONAL LASER IMAGING FOR FACIAL RECONSTRUCTION

A Thesis Presented for the
Master of Arts Degree
The University of Tennessee, Knoxville

Susannah M. Addyman
December 1994

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DEDICATION

This thesis is dedicated to my parents
Dr. Peter V. Addyman
and
Mrs. Shelton O. Addyman
who are best research assistants anyone could ask for
and who have provided me with constant support and encouragement
throughout my life and educational career.

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ABSTRACT

This thesis outlines the examination and test of a method developed by the University College, London, Department of Medical Physics and Bioengineering for facial reconstruction using the latest technology in three dimensional laser imaging. The University College technique involves a skull on a rotating platform as the focal point of a laser beam fanned out into a straight line. A video camera placed obliquely to the skull records the distortions in the laser beam created by the surface contours. These distortions are recorded from two directions through the use of four surface-silvered mirrors which allows for the triangulation of all the points along the laser beam. As the skull rotates numerous points are measured in order to create a three dimensional computer image of the skull. In the second phase of the process, a living individual of comparable age, race, sex, and stature to the skull under examination is scanned using the same process. The two separate images are then combined to form a third which is assumed to represent a reconstructed image of the skeletal material.

Although the results of the faces that have been created by this method have thus far been successful, University College has not been able to conduct adequate testing of this process. This is largely due to the mainly historic nature of the subjects, and an inability to gain access to modern remains. This lack constitutes a possible flaw in what would otherwise be a highly beneficial system.

In order to conduct such tests, five skulls were used from the Anthropological Research Facility at the University of Tennessee, Knoxville that had been photographed prior to decomposition. A blind test of the system with a comparison of the final computer generated image to the individual's photograph would provide results that can confirm or reject the validity of the technique. The skepticism voiced over the use of the data taken from live individuals, specifically its combination with the remains to create the final image, has been shown to have grounds for concern.

Preliminary results indicate that both the use of older living subjects, with more prominent facial features (necessary due to the aged nature of the skeletal remains), and an over-weight subject provide problems with which the system has difficulty in coping. Also the use of a living subject with a facial expression creates a further feature for which the computer is unable to compensate. However, it is possible to instruct the system to produce a result using the more traditional skin depth measurement tables, as well as adding a program to enable the computer to 'average out' any distinct features of the living subject used. These aspects provide further avenues for experimentation and testing.

The implications of this system could be far reaching. If the accuracy of the technique can be enhanced then the potential for the method to provide a quick, realistic, and affordable image of a set of skeletal remains can be realized. In addition, this technique could provide a reliable and beneficial service to many law enforcement agencies. The somewhat negative results offer valuable information on which aspects of the system need to be revised. This factor is especially important because this technique is growing in popularity, and the accuracy of its methodology must continue to be assessed and improved.

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I. INTRODUCTION

Through the nineteenth and twentieth centuries facial reconstruction has evolved from a two dimensional artist generated product to a three dimensional reproduction generated by computer software. In recent years, the use of laser imaging as developed by the Department of Medical Physics and Bioengineering, at the University College, London has been utilized to generate facial reproductions.

This technique involves scanning a set of skeletal cranial remains in conjunction with the face of a living individual and then utilizing computer software to recreate the face of the skeletal remains incorporating the living individual's face data. The eventual goal of such a method is to provide an accurate, affordable, and time saving service for law enforcement agencies and museums who would otherwise have to look towards other methods of reconstruction. As with other facial reconstruction techniques, this technique recognizes that the basis of an individual's facial identity is the skeletal structure of the skull. However, instead of using clay to reconstruct the skin depths over the skull, the computer uses the skull data as the basis of the reconstruction and the data from the living individual's face as a surface structure to spread over the remains.

Skepticism has been voiced over the use of data taken from live individuals; specifically its combination with the remains to create the final image. However, it is possible to instruct the system to alter the skin depth measurement tables it uses, and thereby possibly alter the final result. This aspect provides a further avenue for experimentation and a need for more in-depth testing.

The implications of this proposal are extremely exciting. Provided that this study is able to demonstrate the accuracy of this technique then the potential for this method to generate a quick, realistic, and affordable image of skeletal remains can be realized. In addition, this technique would provide a reliable and beneficial service to many law enforcement agencies. However, if the results are negative this would also provide valuable information on which aspects of the system need to be revised. This factor is especially important in the light of the fact that this technique is growing in popularity, and the accuracy of its methodology must assessed.

II. FACIAL DEVELOPMENT AND GROWTH

The human brain is able to recognize thousands of faces as well as remember the names, backgrounds, and personalities that go along with them. Facial features and head shapes are a means by which the brain categorize and subsequently is capable of distinguishing between individuals. Recognition, however, is in part dependent on memory which can be affected by time and events that occur at the point of initial input. Furthermore, as found by Tooley et al. (1987) subjects demonstrate a greater likelihood of recognizing individuals of the same race as opposed to individuals of other races. The brain, however, is able to compensate for alterations and variations of a face such as makeup, hair styles, and ageing. The brain tends to categorize five main qualitative features as a means of discriminating between different faces, those being the eyes, hair, nose, face shape and chin which are used for retrieval and screening (Heafner, 1990; Kamel et al., 1993). Because these factors are directly related to recognition, great care must be taken in reconstructing these features, and where no evidence for the reconstruction of a factor is available, such as eye colour and hair type, then a generic representation must be presented in the hopes that it will not hamper recognition.

The development and growth of the face is an ever continuing process from conception until death. As holds true for age, the genetic make-up, environment, and sex of the individual are all significant factors in the development of facial features. As a baby develops into a child its face looks globular, this is due to the brain and its development which causes the face to be relatively wide but short in a vertical plane. The growth of the neurocranium happens earlier and at a greater rate than that of the facial complex. The basicranium serves to pace the early width of the face dictating the position of the facial-cranial sutures of the nasomaxillary complex of the face, and the fossae of the mandible. However, the length of the face remains short due to the size of the nasal aspect of the face, the development and establishment of the primary and secondary dentition, and to the lack of development of all the lower face bones which have yet to grow vertically in order to support the dentition as well as muscles and the airway (Enlow, 1990; y'Edynak and Iscan, 1993).

The typical infant face regardless of sex has a short rounded nose, the bridge of which is low and has a concave profile. The face is flat though the forehead is bulbous and upright. The eyes appear to protrude and are wide-set with prominent cheek bones. The nasal aspect of the face will develop and affect the other facial features, directly influencing forehead slope, the prominence of the cheekbones, nasal height configuration, and in turn affecting the prominence of the face (Enlow, 1990).

During the formative years, the facial characteristics of both sexes are highly similar. However, the onset of puberty heralds dramatic changes. The sex specific development that characterizes the adolescent growth period also affects facial morphology. Female growth begins to slow after approximately 13 years of age, but occurs somewhat later in males. The facial superstructure of both sexes continues to mature throughout adolescence and into adulthood, which can effect facial appearance in a significant manner (Burke and Hughes-Lawson, 1989; Enlow, 1990; y'Edynak and Iscan, 1993).

During middle age, lines and wrinkles develop in specific locations on the face. The nasolabial furrows or 'smile lines', running from the outside of the nasal ala to the corners of the mouth, are one of the first to appear. They can be seen when an individual smiles, though the lines become fixed in most individuals between the late 30's and through the 40's. However, this age progression is varies depending on environmental, biological, and genetic factors which can also determine whether individuals will look older or younger than their age. Other typical lines include 'crows feet' at the lateral corners of the eyes and 'frown lines' running horizontally across the forehead. As the age process continues, the constant development of lines include vertical lines between the eyebrows over the glabella, small lines running vertically up from the top lip, vertical lines running downwards from the corners of the mouth lateral to the chin, and lines running horizontally across the chin. Numerous environmental factors can increase the aged appearance of an individual including sun damage which accelerates these aging processes, alcoholism, which can promote skin sagging due to the dehydrating and anesthetizing nature of alcohol affecting both skin and muscle tone, and smoking tobacco which also increases wrinkling due to its nature as a peripheral vasoconstrictor (Enlow, 1990).

Once through middle age the skin then starts to sag due to the changes of the physical and biochemical makeup of the hypodermis and dermis that cause the connections between the bone and muscle to weaken. Any weight loss at this point will also result in sagging of excess skin as its natural elasticity is lost. This process can make a younger face seem older, and can be seen in severely malnourished children. Adipose resorption around the orbits leads to the eyes looking shrunken as well as darkening under the eyes as the venus plexus becomes more visible with 'bags' forming as the skin sags. Aging also causes the skin cells to decline in activity which in turn leads to subcutaneous dehydration and shrunken facial volume, skin surplus, and wrinkling. 'Jowls' begin to droop over the sides of the mandible and eventually a bag of skin sags from the chin and over the neck producing the 'turkey gobbler' effect (Enlow, 1990).

A second characterization of the ageing process is change in the distribution, nature and size of the collagenous fiber matrix of the face, especially relevant in advancing age groups. Unlike bone, cartilage is not hard but rather it is a ridged and firm, yet flexible tissue that is located in specific skeletal areas to aid the growth process and provide flexible support. It is present in the end of the nose and ear lobe. During adulthood the ears grow longer, broader, and thicker and similarly the nose grows broader, longer, and the tip grows downward. (Enlow, 1990; Macho, 1986). Edentulism or even minor tooth loss can cause noticeable changes in both facial topography and structure. Whereas edentulism tends to be more prominent in an elderly population, it is not solely related to advanced age. Furthermore, changes in the skin are a constant process beginning in childhood when it is pink, soft, resilient, and firm; as the years pass it becomes blemished, leathery, wrinkled, limp, and open-pored. Although some skeletal change and remodeling does occur during adulthood, the changes in the soft tissue are more dramatic and noticeable, which is especially relevant when reconstructing a likeness (Enlow, 1990).

All these various ageing and environmental factors must be taken into consideration when attempting to reconstruct a face. Not only will age, sex, and ethnic background be significant factors in how to reconstruct the face but socioeconomic status, life style and build can also provide useful indicators for reconstruction. Artifacts such as clothing and other personal items recovered at a crime scene may provide valuable information about an individual (Gatliff and Snow, 1979).

III. THE EVOLUTION OF FACIAL RECONSTRUCTION

The various techniques of facial reconstruction can be placed under the heading of forensic art, a multi-media discipline in which the primary function is to present visual information within a legal context (Stewart and Richlin, 1989). Forensic art encompasses a wide range of legal services which include composite drawing, illustration of evidence, courtroom sketches, and facial reconstructions. The area of facial reconstruction comes into play when all other avenues of inquiry have failed to identify a set of remains. It should be remembered that facial reconstruction is not a method of identification but is rather a means of generating leads in an investigation. The reconstruction is not a portrait of the unidentified individual but rather is the best possible approximation of the facial features utilizing bony structure and soft tissue depth information. The process is used as a means of jogging the memory of the public in order to generate information that can lead to a positive identification (George, 1987). Although artistic skill is essential for facial reconstruction, measurements play a fundamental role in the basic foundations of this technique.

The skin depth tables provide measurements for twenty one specific anatomical and anthropometric points, ten of which are on the mid-line of the face and eleven bilateral providing a total of thirty two points over the complete face. The data for the original set of skin depth tables was created in 1883 by Welcker with further research conducted by His in 1895, and Kollman and Buchly in 1898 (Gruner, 1993; Dumont, 1986). All of these researchers strove to develop the method of facial reconstruction in order to recreate the faces of historical individuals for whom they had skeletal remains. Collectively, they can be considered as the fathers of modern facial reconstruction (Gruner, 1993). The tables developed by Kollman and Buchly are still used today. The method of data collection consisted of inserting a rubber-collared calibrated needle into the facial tissue of cadavers at specific anatomical and anthropometric points, taking a reading when the bone was reached (Dumont, 1986; Hodson et al., 1985). Although this technique has provided results accurate enough to reconstruct a face, other techniques for measuring skin depth are being developed using radiographic and ultrasound information.

Two dimensional facial reconstruction is a method that recreates the appearance of the soft tissues over the skeletal features of the remains. This can be drawn over a radiograph or a scale photograph of the remains, utilizing the same measurements and principles of three dimensional methods but a two dimensional format. This method can provide a similarly reliable end result in a faster period of time (Stewart and Richlin, 1989).

An extension of the two dimensional facial reconstruction technique is lateral craniographics, which can provide a reconstructed profile of an unidentified skull using a lateral radiograph of the skull. The first step requires a cephalometric analysis of the cranium to determine the type and proportions of the skull. The tissue thickness data points on the mid-line of the face are then plotted in accordance with available skin depth data. Particular attention is given to the shape of the nose due to its prominence in a profile reconstruction and the fact that it is one of the most distinguishing features of the face. Finally tone, an eye, hair, and age lines, are added in order to make the image more lifelike, and thus more recognizable. Though this technique does require less artistic skill in order to produce a result, problems with this method include the fact that only a few cranial points are taken in to account for the reconstruction and that the two dimensional nature of the technique means only the lateral angle can be viewed. Therefore this method is perhaps best utilized in conjunction with clay three dimensional reconstructions acting as a blue print to help provide a more accurate reconstruction (George, 1987).

Perhaps the most well known and intriguing method of facial reconstruction utilizes the application of clay to the cranial remains or a cast of the remains. This method has been utilized to recreate the visage of many well known individuals in history, including Johann Sebastian Bach, Immanuel Kant, Josef Haydn, and King Philip II of Macedon, as well as some not so well known historical individuals including the Lindow bog man, three ancient Egyptian mummies, and a Neanderthal. To date, this method, when executed by an experienced professional, can provide accurate results. However, the basic steps are the same regardless of who creates the facial image.

In the first step the mandible has to be positioned and taped to the calvarium in the original position it would have occupied during life (Charney, 1989). Positioning is important because the different positions of the mandible may significantly alter the appearance of the face. Once the alignment of the mandible is correct peg markers are then glued to the cranium. The markers are cut from cylindrical erasers a quarter of an inch in diameter. Each marker is cut to the average skin depth thickness of the anatomical point it is going to occupy. The height of the peg is measured on pre-determined race and sex skin depth tables. Because individuals of different races, sexes, and builds all have different skin depth measurements it is essential to know at least the first two and preferably the third criterion before any reconstruction can be begun (Gatliff and Snow, 1979). Build can significantly alter appearance because the thicker the soft tissues that cover the face, the less effect the underlying bone will have on the appearance of those tissues (Bartlett et al., 1991). An estimation of age at death is also required for reconstruction as is knowledge of antemortem injuries which affect the facial features (Gatliff and Snow, 1979). The initial studies of these problems were conducted nearly a century ago and although the methodologies utilized are still the same, recently there has been an effort to apply new techniques in order to provide more accurate data from which to reconstruct a face.

Radiographic facial thickness data has several advantages over the traditionally collected data. Images of living individuals can be utilized (the soft tissue of cadavers may be distorted due to embalming or drying of the skin), the soft tissues measured in radiographs are not distorted by the insertion of a needle, and large and diverse data bases can be gathered due to the wide availability of radiographs (Dumont, 1986). Ultrasound is a method that uses electricity which is converted into sound waves that travel through the soft tissue and are reflected off the bone, providing a distance recorded on an oscilloscope. Ultrasound provides a non invasive method of gathering skin thickness data that is comparable to radiographic techniques in its accuracy. However, the method does require an understanding and proficiency in scanning and film interpretation. At the present, this technique is being used to gain a greater understanding of the growth process involved in childhood development and to provide information that will aid the reconstruction and identification of unknown children (Hodson et al., 1985).

Even though these new techniques may provide more accurate information, all the methods measure the depths to at least the nearest hundredth of a millimeter. However, it is hard to get this level of accuracy cutting erasers. Consequently the measurements used for reconstructions are taken from the nearest tenth of a millimeter. Once they are cut to length, the markers are glued to their respective landmarks on the skull (Charney, 1989; Gatliff and Snow, 1979).

The eyes, usually surgical glass eyes, need to be positioned in the orbits of the remains, either before or after the pegging process. The positioning of the eyes is critical and care must be taken to center the pupil and to place the eyes flush with the edges of the orbital bones in order to prevent them from looking crossed, sunken, or bulging.

The pupil should be centered on a cross created by horizontal and vertical lines which bisect the medial edge and lateral margin, and the superior and inferior margins of the orbit respectively (Krogman, 1978; Charney, 1989).

The next step is to place strips of clay, up to half an inch wide on the skull, connecting the pegged landmark points together, while following the contours of the bone underneath. The spaces in-between these strips can then be filled in taking care to smooth the clay out and to maintain the height of the peg points (Charney, 1989). A second method of applying the clay requires a greater knowledge of anatomical structures, as the muscles of the face are recreated on the reconstruction first, then a fat layer is applied and finally the skin, while also taking in to account the peg data. Though there is some controversy as to which method is more accurate, both have been utilized to provide positive results and the differences between the two methods may not be significant (Hodson et al., 1985). As important as the data from soft tissue measurement tables is, the skill and experience of the artist creating the reconstruction is also essential (Bartlett et al., 1991; Dumont, 1985). One particular problem with clay reconstruction is that different forensic artists may provide a different countenance for the same set of remains and only through the development of scientific standardization will a check be held on variances in artistic style and skill (George, 1987).

The areas of the face that are comprised primarily of soft tissue, such as the eye lids, lower nose, ears, and mouth can be determined partly through anatomical knowledge and partly through the experience of the artist (Gatliff and Snow, 1979). The shape of the nose is determined to a large extent by the size and shape of the nasal bones. The curve of the bones at the top and base of the nasal aperture will help to dictate the shape of the nose. The width of the nasal aperture provides the width of the fleshy nose. The aperture is approximately three fifths the width of the nose measured from each side of the alae. The projection of the nose measures roughly three times the length of the nasal spine (Krogman, 1978).

The length of the ear is approximately the same length as the nose. The bony external auditory meatus is positioned 5 millimeters (mm) below, 2.6 mm in front, and 9.6 mm medial to the cartilaginous portion of the auditory meatus (Krogman, 1978). However, the shape of ears are unique to the individual so a generalized ear shape should be created in order not to be misleading in the reconstruction (Charney, 1989). The width of the mouth is approximately the same as the width between the pupils, the placement of which have been discused earlier, so their proper placement are extremely important. The width of the mouth also approximates the distance between the junctions of the canine and the first premolar, which may in turn also aid the placement of the eyes (Krogman, 1978). Clearly, the artist must have an understanding of the basic structure of the face so as to accurately enhance and age the face without masking the features of the individual.

Through the use of computer simulation, it is possible to add, subtract, and alter various hair styles, facial hair styles, eye colour, and glasses on a clay reconstruction. By providing several alternate images of a reconstruction, it is possible to increase the likelihood of gaining a positive identification. A change in these variables can significantly alter the manner in which a face is perceived, and in cases where a hair sample cannot be found at the crime scene (which would indicate hair colour and length) providing multiple images may reduce this problem.

A technical progression from the methods utilized by the clay reconstructions is provided through photographic technology. However, as with facial reconstruction the use of photographic superimposition tends to be a last resort method of identification of skeletal remains, and may only be necessary when all other avenues of enquiry have been exhausted. One of the first successful applications of this technique can be found as early as 1935 in the Ruxton Case (Glaister and Brash, 1937) The technique is especially useful when conventional identification techniques cannot be used, for example as a result of a lack of dental treatment of the remains or due to the incomplete nature or absence of any type of dental or radiographic records or the remains themselves (Brocklebank and Holmgren, 1989; McKenna et al., 1984).

Photographic superimposition is a technique of identifying skeletal material by superimposing a photograph of post mortem remains over an antemortem photograph. However, the technique can only be utilized in cases where the identity of the individual is suspected. The method also requires that the remains and the photograph are compatible, in that they must be orientated in the same position (Brocklebank and Holmgren, 1989; McKenna et al., 1984). Problems arise in the selection of the photograph to be used in the identification. For optimal results, the photograph should be sharply focused; it should also show as many anterior teeth as possible, specifically the maxillary anterior teeth. However, the successful use of this technique is to an extent dependent upon the recovery of teeth (McKenna et al., 1984).

Once the photograph has been selected, the skull then must be mechanically manipulated into the exact position of the individual depicted in the antemortem photograph. The tilt and rotation of the photograph must also be emulated by the skull. The size of the skull can be altered by adjusting the skull-to-camera distance, while a scale is added to the image to enable it to be enlarged to life size (Brocklebank and Holmgren, 1989).

The size of the photographic image is then also enlarged to life size through the use of other objects or structures in the photograph for which the dimensions are known. However, this can be difficult using the structures in the photograph; the best objects to utilize are those that occupy the same plane as the subject, for example jewelry and clothing. This process can also be done by using anatomical landmarks and anthropometric measurements made on the skull combined with soft tissue data or by a shared feature visible on the picture and the skull, for example, any anterior dentition. The feature utilized as the scale for enlarging the photograph to life size naturally should not be utilized as an identifying feature (McKenna et al., 1984; McKenna, 1988; Bastiaan et al., 1986).

Both photographs, of the skeletal material and the antemortem image, are assessed to determine the degree of positive superimposition. Tracings are made of all the clearly defined features in the photographs in order to provide an objective assessment of the degree of positive match-up. Once the transparencies have been drawn, they are then superimposed on each other. At this point dental landmarks can then be verified and all the corresponding features of the cranium and face are noted. Suitable features for this process include any and all dental features that correspond, outlines of bone margins such as nasal spine, zygomatic processes, orbits and mandibular body and angles, corresponding soft tissue (taking into account skin depth), interpupillary and mid orbital lines, and mid-line of the face and the skull. Criticisms have been raised regarding the use of interpupillary distance as a non dental landmark due to the problems inherent in locating the pupils in the antemortem photograph, and subsequently in the placing of the pupil within the orbit margins. This method has been criticized due to of the problematic nature of enlarging the antemortem photograph to life-size, and due to the difficulty of positioning the cranial remains accurately with the position of the subject in the antemortem photograph. Recent studies suggest the technique can provide a positive identification with an error rate of one percent when more than one set of images are utilized in conjunction with each other (Austin-Smith and Maples, 1994). Critics, though, accept the use of this method as a means of excluding possible subjects from an investigation rather than a means of positive identification of individuals.

Several of the problems associated with photographic superimposition can be reduced by the use of video superimposition, a video mixing unit can help to provide a visual match (Brocklebank and Holmgren, 1989). Image mixing is a method of superimposing the photographic images on recordings made of the mounted cranial remains as a means to achieve the best possible fit. As with photographic superimposition, an antemortem photograph showing the teeth of the individual is the best image for this method. The skeletal remains are mounted on a support that allows for their movement in three planes. Two video cameras are then set up, one in front of the photograph and the other in front of the cranium. The two video images are then combined through a vision mixer. The skull is then orientated to the best possible match with that of the photograph, the photograph is then enlarged using points of reference, such as the teeth. The benefits of this system are that it provides a greater flexibility in the alignment of the skull and the photograph, as well as providing immediate results that do not need to be processed. The video allows for landmarks to be highlighted and the images to be faded in order to see the remains or photograph more clearly. Sweeping the images over each other allows one to be superimposed on the other in a horizontal or vertical plane (Bastiaan et al., 1986; Iten, 1987; Lan, 1992). However, a slow 'wipe' of one image over the other can provide the illusion of a positive match as the discrepancies between the skull and photograph are not able to be determined (Iscan, 1993). Another disadvantage of the system is that the photograph is not enlarged through the use of objects contained in the picture, but rather is determined visually by the examiner. This aspect automatically opens the method up to criticism (Brocklebank and Holmgren, 1989; Bastiaan et al., 1986).

As new technology develops and progresses so does the methodology and complexities of facial identification and reconstruction. The increasing sophistication and intricacy of computer technology heralds the creation of new techniques of facial reconstruction. Various methods are in the process of being developed such as digitization, contour reconstruction from Computerized Axial Tomography (CAT) scans, and three dimensional laser imaging. The laser imaging system is designed to provide a three dimensional surface scan of a skull or a face while reducing manual involvement and subsequent human errors.

The three dimensional laser imaging technique generates a reconstruction through the manipulation of living face data onto skeletal material.

> "The system consists of a computer-controlled rotating platform, a projected laser line and a video camera interfaced to the computer, and is able to record 20000 surface coordinates with a resolution of 0.5 mm in 30 s. Simple triangulation is used to derive the required numerical representation of the surface from the digitally recorded video signals." (Vanezis et al., 1989)

The triangulation of the laser line is a means of eliminating the 'blind spots' that would arise from the shadows creating by the facial features such as the nose (Arridge et al., 1985). Initially the skull data is scanned by the system and skin depth data is added, at which point the computer is able to generate a tissue thickness over the surface of the skull. However, the system is unable to recreate areas without a bony structure to support them. These areas include the eyes, ears, nose, and mouth. Despite this problem the computer is able to create a 'mask' image without these features. Subsequently the problem of creating the features was overcome by incorporating scanned face data from living subjects. The computer then remodels and adjusts the size and position of the features of the face until they match the features of the mask; that is, simply until the anatomical and anthropomorphic features of the face correspond with those of the skull data (Vanezis et al., 1989). Initial testing of the technique indicates that a reconstruction can be created from skeletal remains. However, differences in the soft tissue features of the initial face data produce slightly different end results. The creators of this method see this fact as a benefit because by providing a range of slightly different faces to choose from the chances of a positive identification are increased (Vanezis et al., 1989). To date this technique has not been adequately tested. It is the aim of this study to examine the system through the utilization of identified skeletal remains in as a means to verify the reliability of the laser imaging method.

IV. METHODS AND MATERIALS

The University College, London University, Medical Physics Department has developed a method of facial reconstruction using three dimensional laser imaging. Currently, this technology has been purchased by The York Archaeological Trust for the purpose of reproducing the faces of Viking inhabitants of the city, employing the skeletal remains of Viking individuals unearthed on excavations in the York area. The reconstructed faces are then placed in the Jorvik Viking Center museum as part of a realistic representation of Viking life. At the present time only one of these faces is on display as a part of the museum; however, six more faces are in the process of being generated and installed into the exhibit. It is the aim of the museum staff, utilizing three dimensional laser imaging, to eventually replace all the Vikings mannequins in the exhibit with the original faces of those that once lived in Viking York.

Although the results of the faces that have been created by this method thus far appear to be successful, neither the York Archaeological Trust nor University College, London University have been able to conduct adequate testing of this process. This deficit is largely due to the historic nature of the subjects, and the inability to gain access to modern subjects to use in testing. This lack of analysis upon their product raises questions about what otherwise appears to be a highly beneficial technique. Lack of comparative testing has prompted both institutions to be more than willing to allow their system to be investigated.

The technique utilized by the University College involves the placement of a skull on a rotating platform as the focal point of a laser beam which is fanned out into a straight line (Figure 1). A video camera placed obliquely to the skull records the distortions in the laser beam created by the surface contours. These skeletal distortions are recorded from two directions through the use of four surface-silvered mirrors which allow for the triangulation of all points along the laser beam (Figure 2). As the skull rotates numerous points are measured in order to generate a three dimensional computer image of the skull. In the second phase of the process a living individual of comparable age, race, sex, and overall size to the skull under examination is scanned using the same process. Once a skeletal image and a facial image are produced the process of recreating a final image may proceed.

The two images are brought up onto the computer screen (Figure 3), and are 'pegged', a process similar to that which is conducted during clay reconstructions. The computer generates a matrix of peg marker points (Figure 4) based on the anatomical marker points of recorded skin depth thickness developed by Rhine (1984). A total of 44 marker points is used, six more pegs than traditional marker systems (Figure 5). Numbers 22 and 42 are positioned on the medial aspect of the frontal process of the zygomatic bone mid way between the superior and inferior borders of the eye orbit. Markers 23 and 43 are located on the lateral borders of the nasal aperture, and 24 and 44 are on the distal portion of the lingual surface of the upper first

Figure 1. Placement of a skull on the rotating platform.

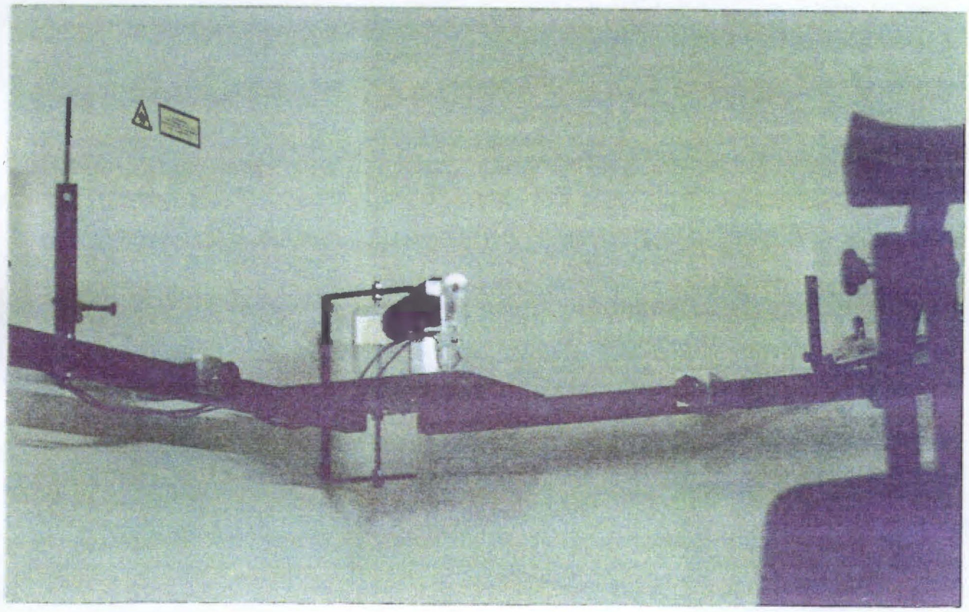


Figure 2. Laser and triangulation equipment.

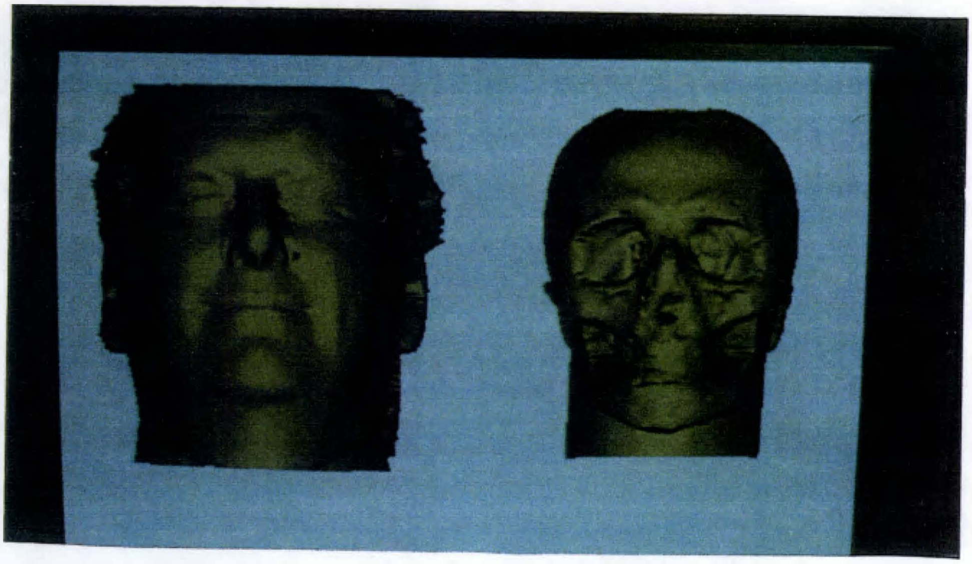


Figure 3. Face and skull images on the computer screen.

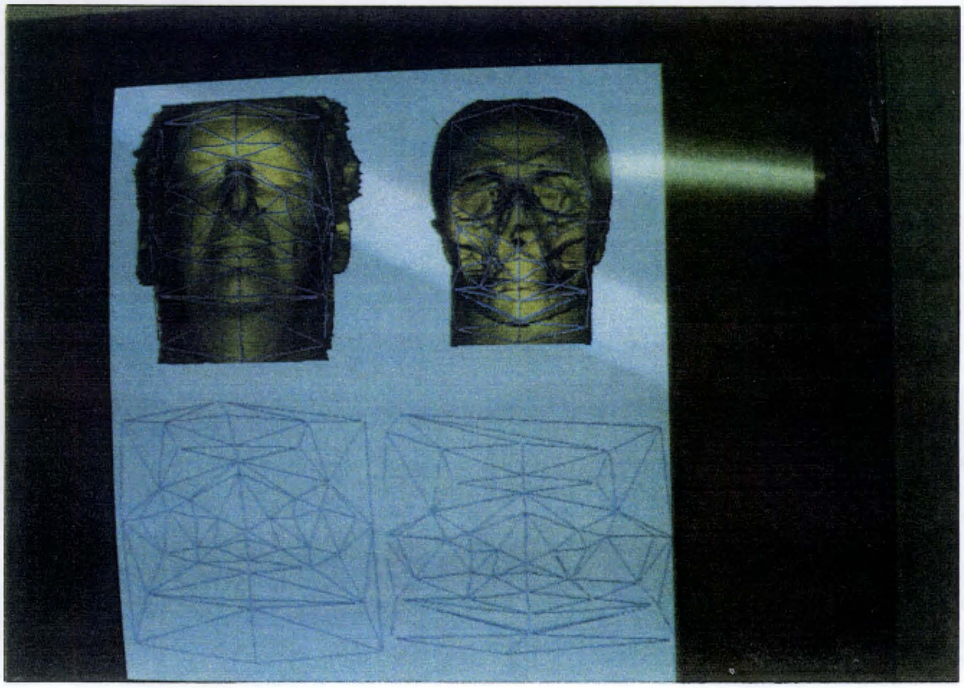


Figure 4. Computer generated peg matrix.

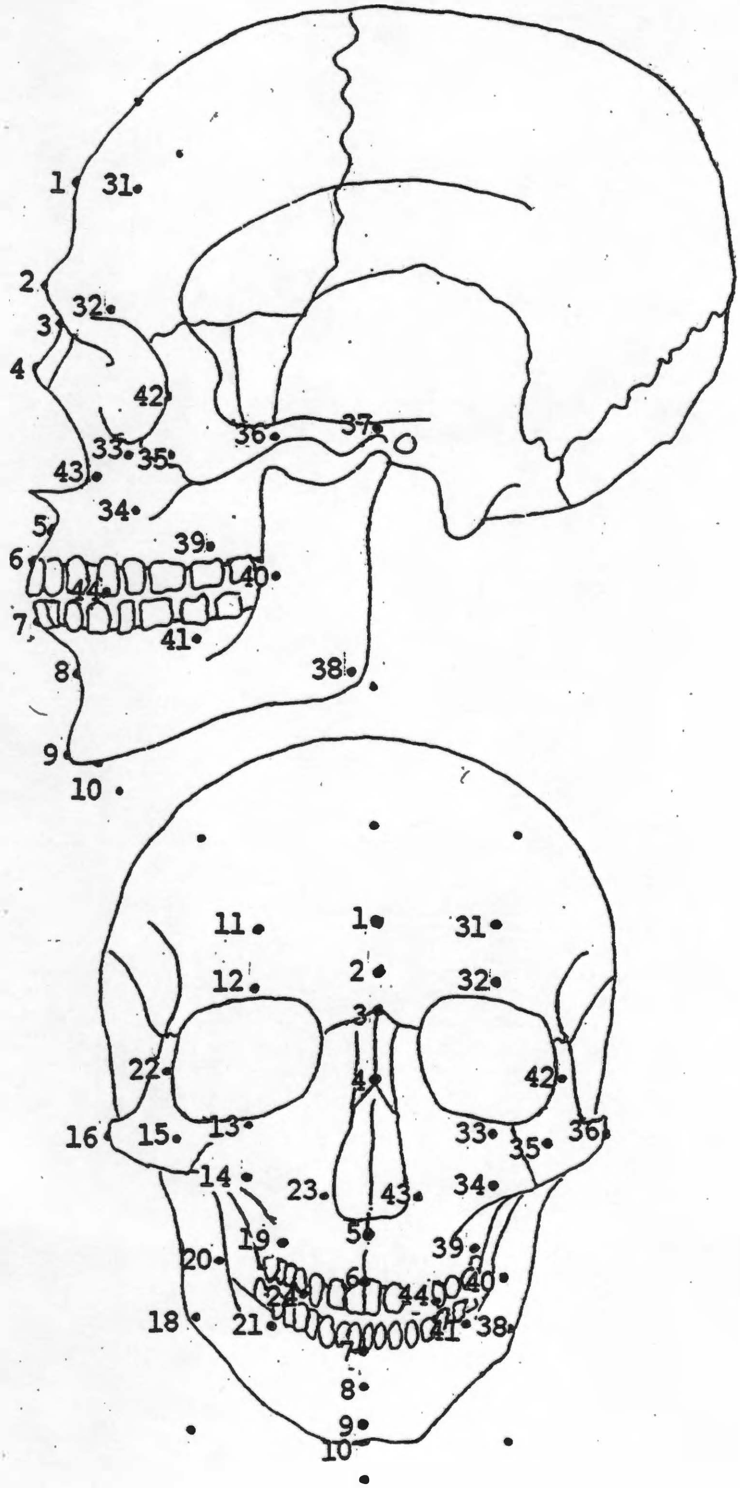


Figure 5. Peg point data the technique utilizes.

premolar. Six additional peripheral marker points are placed at the edge of the face or skull image (Figure 6). All the peg markers have to be arranged manually to their correct position on both the skull and face image. The pegged image can be rotated in order to pin point the best place for the anatomical marker. The skin depth of the peg markers can, at this point, be altered depending on the race, sex and build of the image that is to be created. Once this process has been completed, the two images are aligned by the computer. This process enables the computer to rotate, shift and re-size the face data to match the orientation, location, and size of the skull data. After this has been done, the two separate images can then be combined to form a third which is assumed to represent the original appearance of the individual's skeletal remains. The image is then saved (Figure 7), and reproduced by a computer operated milling machine which sculpts the three dimensional image out of hard foam block. This is then given to a sculptor who uses it as a template for a second model that incorporates facial expression. However, this final step should not be necessary for basic identification purposes, because it adds additional time and expense factors when a simple two dimensional representation would be sufficient for law enforcement agency requirements.

The system design, at this point, is best equipped to reconstruct the faces of Caucasian individuals, although an Asian face had been used to recreate the facial image of an Asian homo erectus skull. However, the system is primarily utilized for the reconstruction of

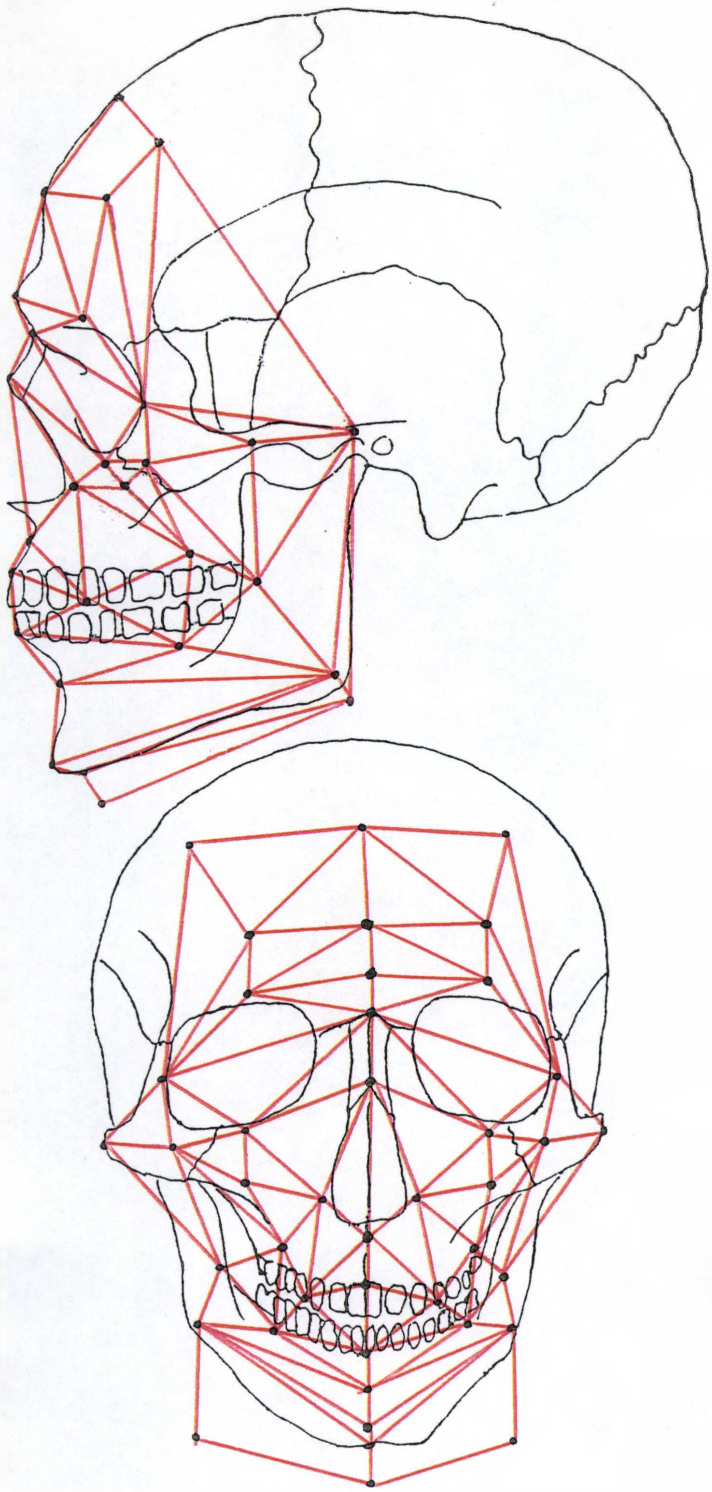


Figure 6. Peg points joined to form the imaging matrix.

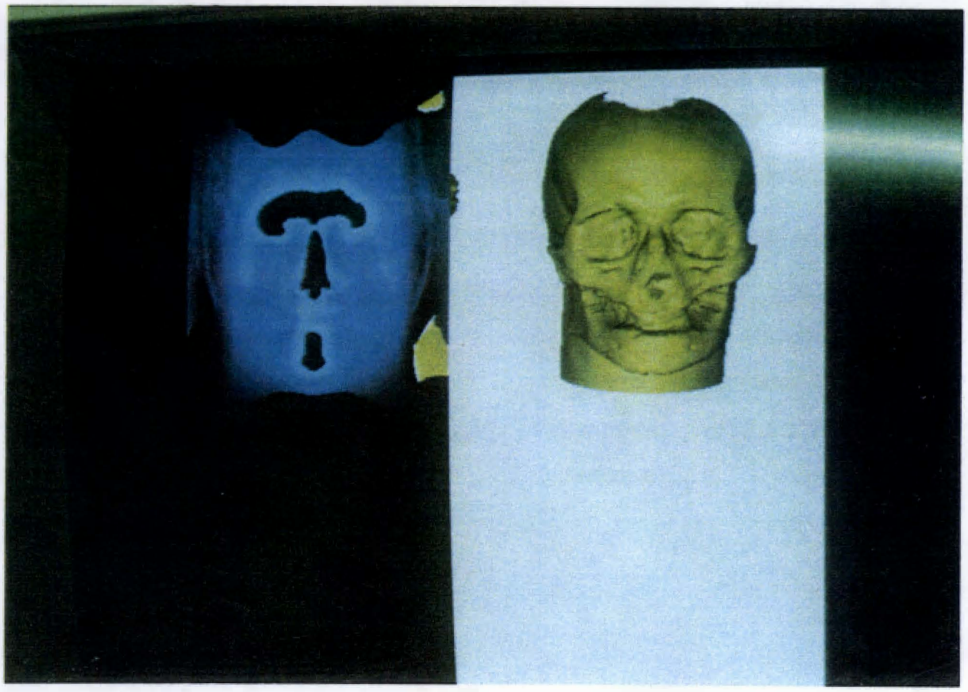


Figure 7. Process of saving the new reconstructed image.

historic white individuals. This factor was the main limiting constraint when considering a sample. Permission was given by Dr. William M. Bass to use the skeletal and photographic materials available in the collection he created and developed that is currently maintained at the University of Tennessee Knoxville. In order for the sample to be consistent it was decided to also limit the sample to adult males, which is the largest single category available in the William M. Bass donated skeletal collection belonging to the Department of Anthropology. The sample size was limited by the practical need to transport the skeletal remains from Knoxville, Tennessee to York, England by hand. The last constraint on the sample consisted of the number of individuals available that had some fashion of photograph taken prior to their decomposition. A number of skulls fitting this criterion were available at the Anthropological Research Facility at the University of Tennessee. This meant that both the skulls and their photographs could be used as a test of the laser imaging system. A blind test of the system with a comparison of the final computer generated image and the individual's photograph would provide the type of results that can confirm or reject the validity of the technique. In order to conduct a blind test the aid of Dr. Emily Craig was enlisted.

An examination of all the photographs that were available in the adult white male category was conducted by Dr. Craig. From these photographs she was able to pick out those individuals whose photographs were deemed most appropriate and useful to the project. The number of appropriate subjects available consisted of six sets of remains. Of these six, four were already in the donated collection in the osteology laboratory, one had been collected from the Anthropological Research Facility and was awaiting processing and the final set of remains was still under investigation at the Anthropological Research Facility. At this point it was decided to process the remains waiting in the Anthropology Annex. A final number of five individuals was chosen in order to facilitate an accurate examination of the technique, as well as being portable for travel purposes.

Once the sample size was confirmed transport permits were obtained. An application for an ATA Carnet was made to the United States Council for International Business, necessary for the transportation of research materials both out of and back into the country. A letter of transport of biological remains was requested from the Centers for Disease Control, Atlanta, Georgia, in order to prove that the articles being transported were in no manner contagious or in any other way a health risk. Finally a letter of research intent was provided by the York Archaeological Trust, York, England, to legitimize the transport and use of human remains. All of these arrived shortly before departing the country.

Once the five skulls had been brought to the laboratory facilities at the York Archaeological Trust, each skull was scanned into the computer. The facilities were housed in a building with a solid concrete floor, necessary in order to eliminate vibrations from the outside environment, especially traffic, to which the equipment can be sensitive. In order to obtain the best image possible the scanning is conducted in a dark room, where the recording equipment is best able to pick up the laser reflection on the skull.

The skulls themselves had to be prepared by having their eye orbits and nasal cavities filled with tissue paper (Figures 8 and 9). This was necessary in order to provide the laser a reflective surface to scan. Leaving the cavities empty would create depths in the final image for which the reconstruction program would be unable to compensate for. This problem also meant that a gunshot wound in the frontal bone of one of the skulls had to be taped over to provide a smooth, whole surface to scan (Figure 10). However, the scan was unaffected by small radiating fractures in the skull. The mandibles were then taped to the crania in their anatomical position. Any denture ware present with the remains was placed in its original position, in order to best approximate the face during life (Figure 11). Unfortunately, one set of remains was edentureless and no dental plate was in evidence. This skull was scanned first with putty taking the place of the dentition, and secondly with less putty to represent no dentition or any other type of dental prosthetics. This was done in order to examine any differences the face change software would make to the same skull with the mandible in two different positions. Once the mandible was articulated with the cranium, the skull was placed on a stirafoam pedestal and mounted on a platform. The platform consisted of a wooden device that can be manually swapped with a head rest depending on the subject being scanned. The pedestal and the head rest are required in order to obtain the correct amount of

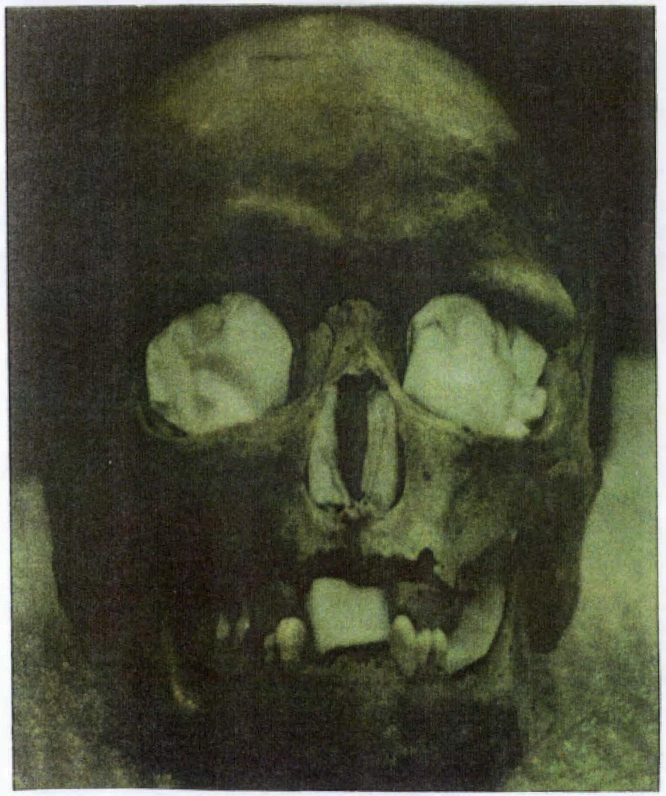


Figure 8. Preparation of skull 1891 for scanning.

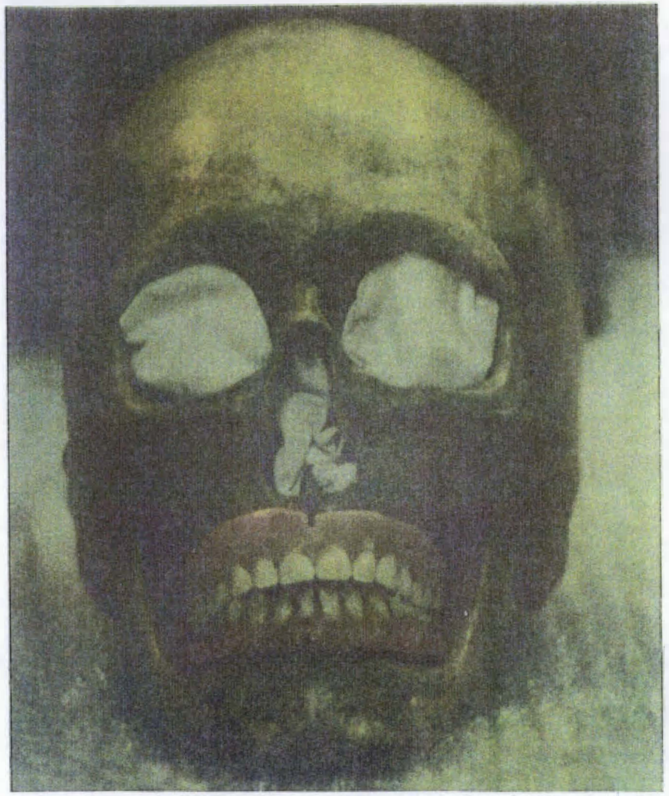


Figure 9. Preparation of skull 1291 for scanning.

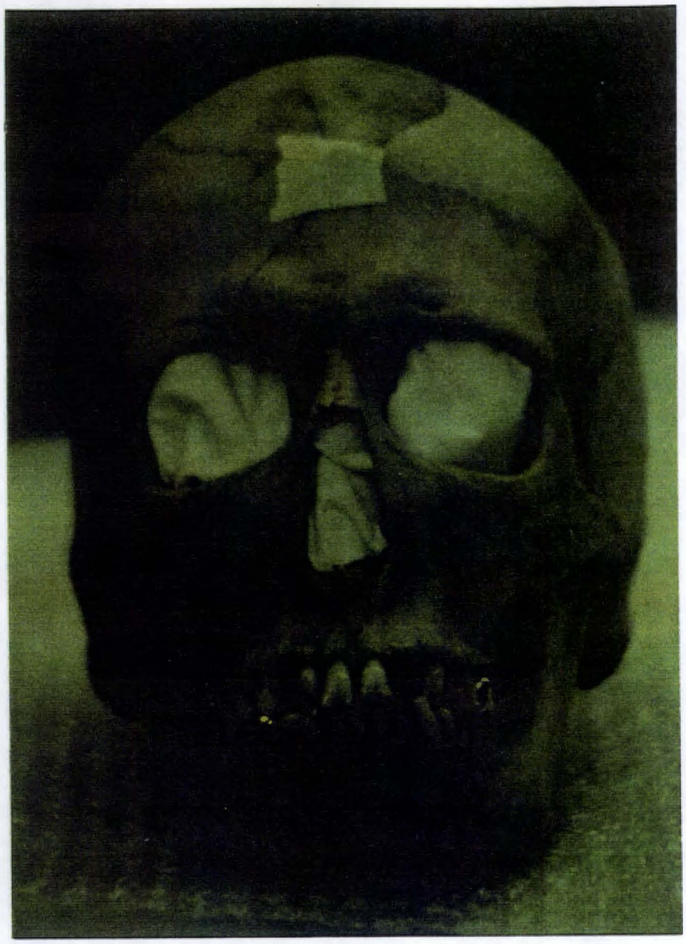


Figure 10. Taping and preparation of skull 2293 for scanning.

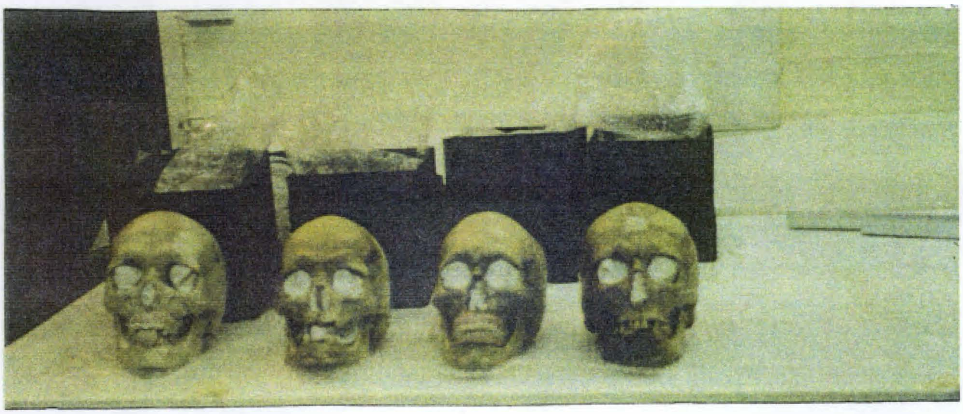


Figure 11. Dentures and mandibles positioned on skulls 1492, 1891, 1291, and 2293 in preparation for scanning.

'tilt' to the subject. Tilt is necessary so that the laser can get a maximal image of the subject's chin and nose. The chair can also be raised and lowered by a hand crank, again so that the remains or individual can be scanned in the optimal position. The chair is then manually rotated until the laser beam projects down the mid-sagittal plane of the skull. This position is then entered into the computer, then the chair is again manually rotated clockwise until the start angle is reached. At this point the program is initiated and the computer rotates the chair anti-clockwise at a speed that enables the computer to read the laser image data. Once the process is completed the computer compiles the laser image data into a three dimensional computer image.

After the image is computerized it is possible to examine and alter the image one point at a time. This allows for the alteration of any points that have been inaccurately plotted by the imaging system, such as those where the beam reflects badly causing a 'spike' in the image, to be replaced back into a better position in the data. Such points would disrupt the face change program. Because the program is designed to recreate the smooth surfaces of a face or a skull, hair can be a problem. Hair tends not to be smooth and individual strands do not lie next to each other, but rather presents a complex matrix of light and dark for the imaging system to deal with. The image that it produces tends to look strange on the face representations. Hair may need to be powdered down with talcum powder so that it becomes more reflective. This can be potentially problematic if the living subject has more facial hair than merely eye brows. All the living subjects used in this study were clean shaven.

Five living subjects were selected who demonstrated similar traits to the five skulls; all the living subjects were white males. The age at death of all the skeletal remains was known, ranging from 57 to 73 years of age; therefore, the living subjects were all picked from the 50's to 70's age range. After the skulls and the living subjects were scanned into the computer they were then taken to another part of the York Archaeological Trust and photographed in both front and right profile views.

Once all the skulls and living individuals' images were recorded in the computer the process of pegging, aligning, and creating a new image was undertaken. After each new image was created and deemed acceptable, the image was then saved to the hard drive, and then converted into a computer imaging 'tif' file which allowed the image to be printed out onto a hard copy. These were then used to assess the accuracy of the face change program.

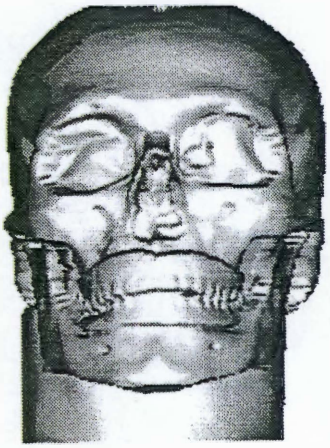
In order to determine whether the computer was able to adjust each face to fit each skull, it was decided to combine each face with each skull. This process meant that each of five living subjects was matched with each skull, producing a total of thirty new images. By doing this it would be possible to determine whether the program relies too much upon the face data. A visual review of all the thirty images permits a determination of this and is conducted prior to comparisons with pre-decompositional photographs. As a final step, this comparison permits assessment of the accuracy of three dimensional laser imaging technique for facial reconstruction. Thus the program could be run more than once without the results being biased.

V. RESULTS

The initial scanning of the skeletal material and the living subjects presented some minor problems during this investigation. Although the actual amount of time it took for a full scan was only about 1 minute the computer had problems running the system. The problems were initially attributed to the heat of the room (which was excessively warm due to the presence of a hot pipe that ran around the base of the room) and an air conditioner was found to cool the room down. Later, it was discovered that adjusting one of the plug connections on the back of the computer allowed for the system to run smoothly. However, this did cause some worry as a schedule had already been set up for the scanning of the live subjects who had kindly donated their time to this project, and having to reschedule all of them would have been an unwarranted inconvenience.

Once the computer had completed the scanning process and compiled the data, the three dimensional computer generated image of the material could then be examined and compared with the original object (Figure 12), and points altered if necessary. The image produced by the program, at first glance may not seem to resemble the original, however, exposure to numerous scanned images helps one become familiar with the computer generated format. In the case of the living subjects, the image produced is further 'distorted' by the need to tilt the subject's head slightly backwards. This is necessary in order to allow the laser and imaging technology to obtain a full scan of

Skull 1291.



Skull 1492.

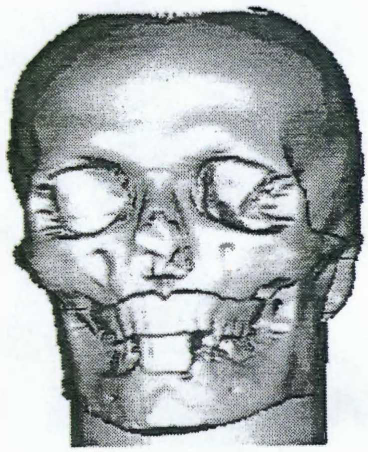
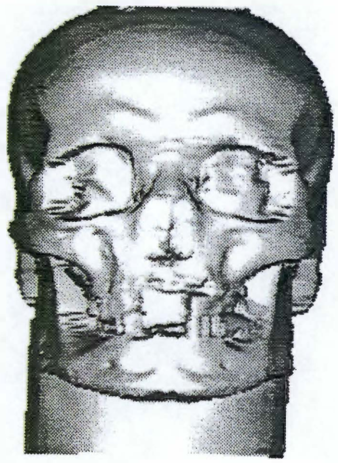


Figure 12. The skulls and their computer generatad images.

Skull 1891.



Skull 2293.

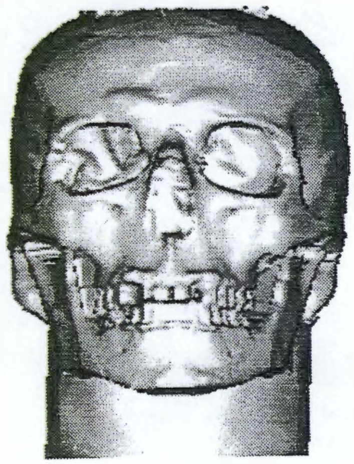


Figure 12 *(Continued)*. The skulls and their computer generated images.

the individual's head without missing any of the facial features, such as the chin and nose. However, this has the result of providing an image of the individual that is not usually seen in an average photograph (Figures 13). Despite these slight problems, the computer images are still distinctly recognizable as individuals, and can be rotated to provide a more 'normal' image.

Upon completion of scanning the data into the computer, the remaining process consisted of running the face change software until the face data had been combined with the skull data. The process of pegging and re-pegging the data combined with completely aligning the images, running the face change process, and saving the final result, if it was satisfactory, was a lengthy process taking up to an hour if all the results were satisfactory and considerably longer if they were not. This being the case the creation of a complete set of results was a time intensive process.

One of the problems with the process that would create an unsatisfactory result occurred when a peg point on the skull and face images were situated too far apart. This becomes a problem when the software tries to stretch the face of the individual to the marker on the skull regardless and the resulting image becomes distorted. The only solution to this problem is to return to the initial pegged images and adjust the peg markers so that they are in a position more similar to each other. Once this is achieved the process of aligning and face shifting can be conducted again. These steps were repeated until a relatively undistorted image is produced. This type of distortion can

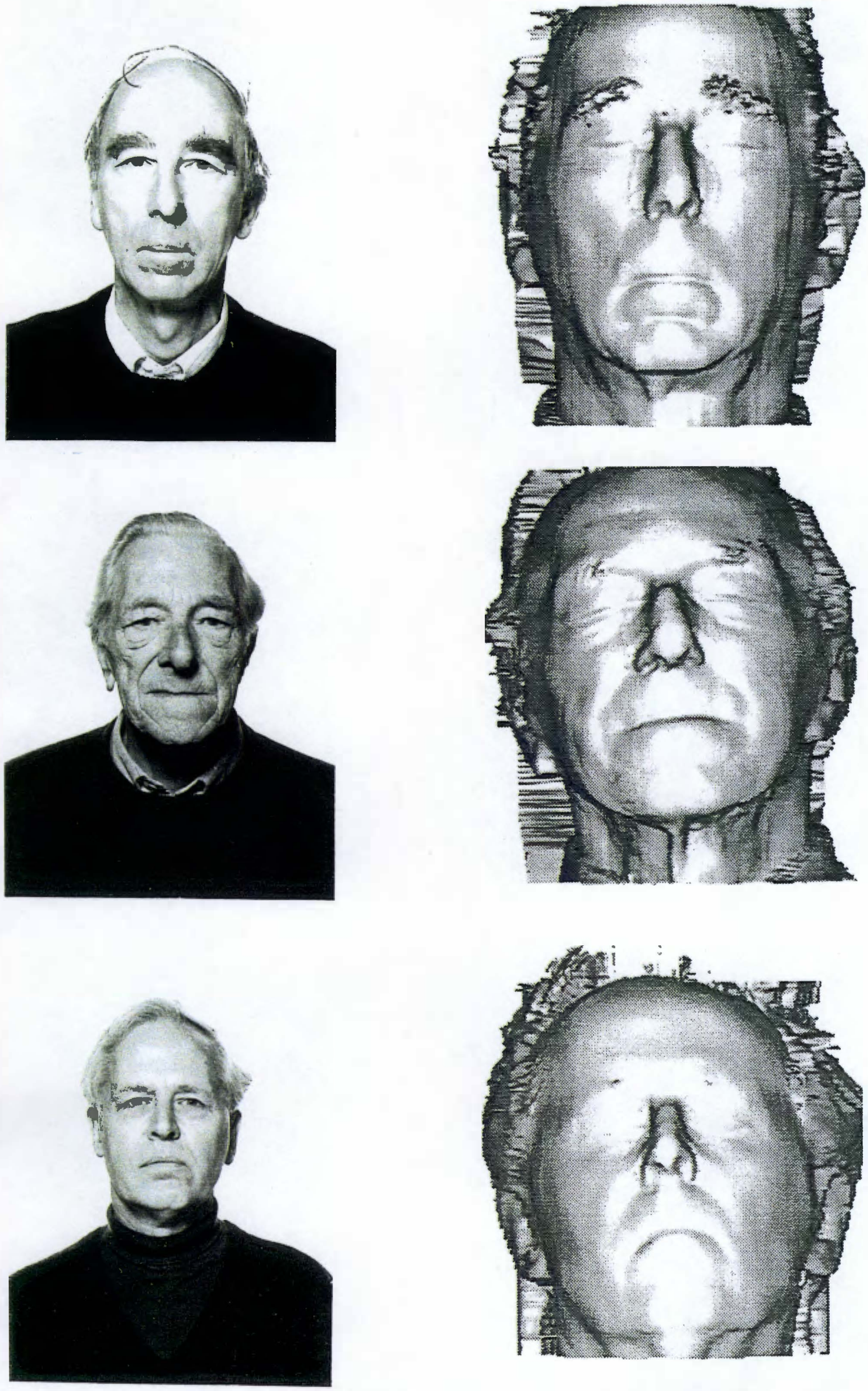


Figure 13. Volunteer individuals and their computer generated images.

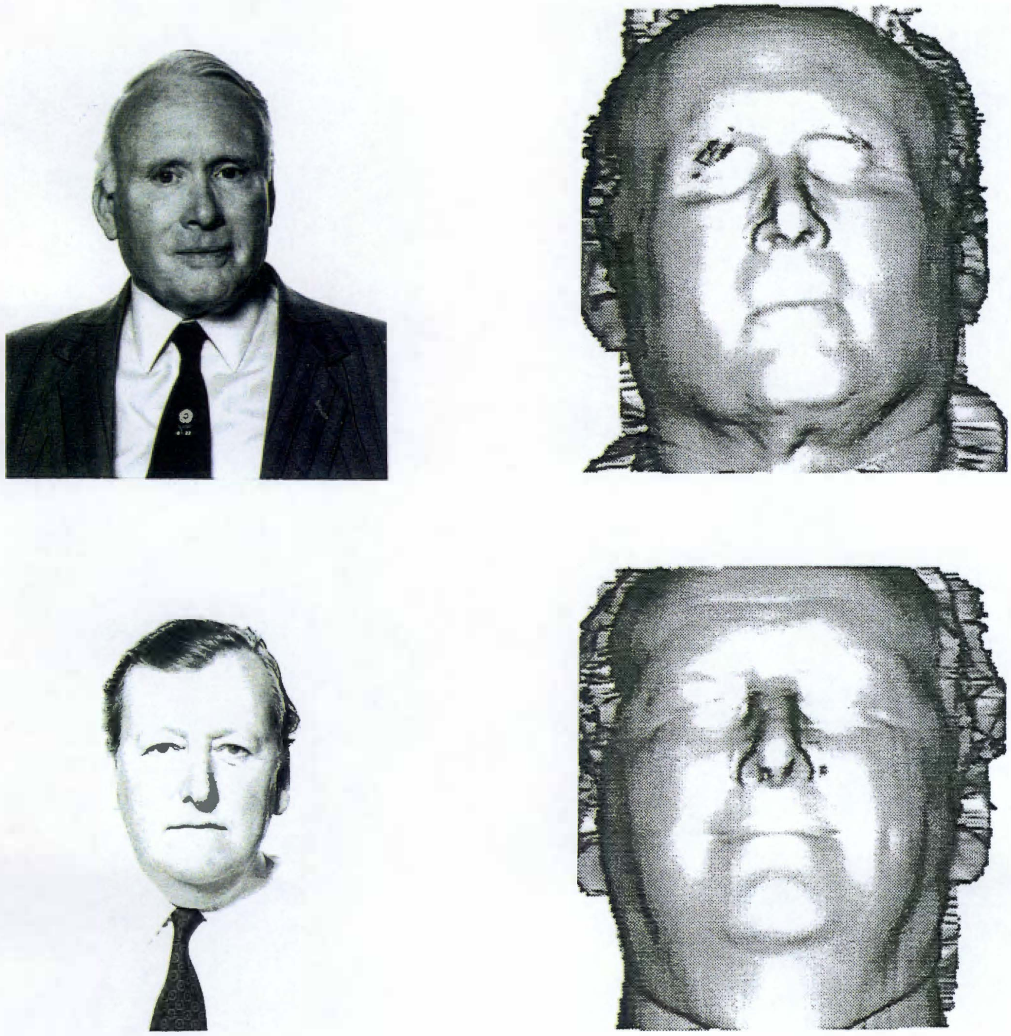
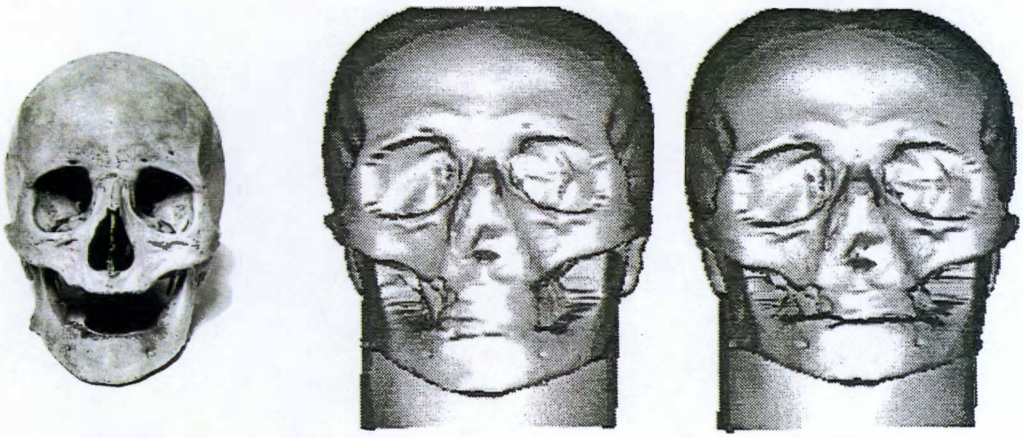


Figure 13 *(continued)*. Volunteer individuals and their computer generated images.

be observed in the set of faces produced for the skull image 1092.2, and to a less extreme extent in 1092.1. Because the skull 1092 has no teeth the pegging process was made harder partly due to the absence of points number 24 and 44, and partly due to the reabsorption of the bone resulting from the tooth loss which made points number 6, 7, 19, 21, 39, and 41 difficult to place. This problem was less extreme in the 1092.1 series as putty was added in place of the missing teeth (Figure 14), as a means of recreating the position of the mandible assuming the individual wore dentures. Less putty was used in the 1092.2 image to represent the same edenturless individual if he did not wear dentures. This caused a problem with the imaging software because the positioning of the mandible created an under bite, characteristic of the faces of older edenturless individuals, which the program was, in some respects unable to compensate for. The problems of placing the peg points on 1092.2 were heightened by the mandible position which subsequently made it harder to overlay the living face without distortions. After repeated attempts to alter the peg points in order to eliminate, or at least reduce these distortions, the still somewhat unsatisfactorily results can be seen in the set of images for 1092.2 (bottom row) in Figure 15.

Once the complete set of images were created they were then saved to a 'tif' file. Two dimensional images can be printed and viewed. As a means for testing the validity of this technique, the computer generated images were compared to the skulls and to the photographs of the living individuals. The representations were



1092.1 1092.2

Figure 14. Skull 1092 and the computer generated image of 1092.1 and 1092.2 showing the altered mandible position.

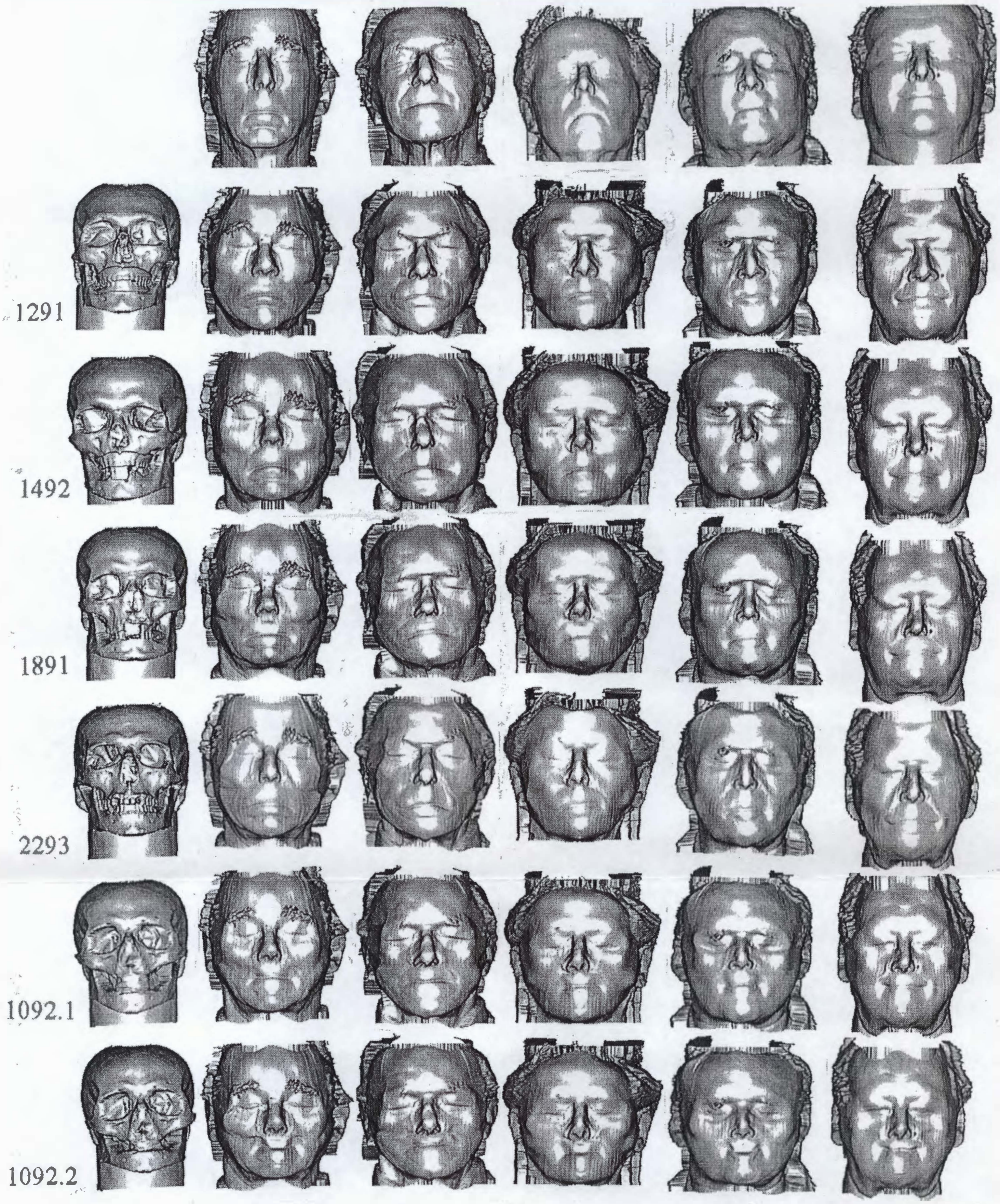


Figure 15. First completed table of computer generated images.

arranged in a square matrix with the skeletal remains situated on the vertical axis and the living faces taking up the horizontal axis (Figure 15). From an analysis of this diagram a determination could be made as to whether the living face or the skull had a greater influence on the final product. The living faces were clearly altered by the program, however, through a comparison between them and the generated images it was still easy to determine which initial face generated which image. Subsequently, it was difficult to determine which skull the reconstructed image had been created from. These results become particularly obvious when all the images are viewed together.

Of all the faces the software had a particular problem altering the features of the overweight individual (individual number 5). It is possible that the extra fat had masked the facial features and smoothed out the face. This factor also increases the problems of the initial pegging of the face. A second problem can also be observed on the fifth face, the individual had a slight smile as he was being scanned. Subsequently, this feature has been included in all the generated images, in some cases with comical results. The same problem can also be observed in the soft tissue facial features of all the individuals, which make them recognizable as the individuals they are, and can be observed particularly in the shape of the nose and type of eyebrows the living individuals exhibit. Part of this problem comes from the continual facial development that is inherent in the aging process, in particular the features that become more prominent with age. These features also happen to be the soft tissue features for which the computer is unable to compensate, and which subsequently become incorporated into the image being generated.

After an examination of the complete set of images was conducted, it was decided that the images of the living individuals were influencing the reconstructed images to an unacceptable extent. This was determined solely on a visual examination of the images, the original photographs of the skeletal remains were left unexamined. After consulting with Dr. Peter Vanezis, one of the creators of the system, it was decided to repeat the imaging process, but with an altered system of pegging the images. First the pegs on the skeletal remains were positioned as accurately as possible. The skull's peg matrix was then superimposed on to the face image and the peg markers for the face were then altered to resemble the positioning of the skeletal peg markers. The face alignment and shift process was then run as before. The similarity of peg marker positions meant that the distortion problems encountered in the first set of results were significantly reduced. Even the distortion problems that particularly plagued skull 1092.2 were eliminated.

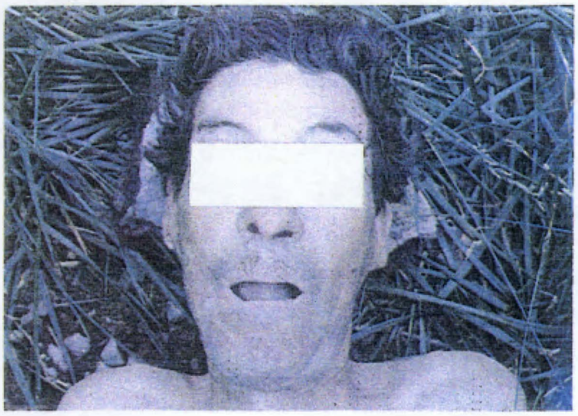
Once a complete set of images was created, hard copies were again printed out and arranged into a grid of reconstructed faces. One additional 'living' face was added to the row of faces used for the reconstruction. This took the form of a mask that represented an artist's recreation of the 'average' physical make-up of the European community. The mask was created using the Electronic Face Identification Technique (EFIT) developed at Aberdeen University.

This technology was combined with statistical data regarding the demographic composition of the European population (Brown, 1992). The mask face was significantly younger than the rest of the faces used in the study, however, it was felt that the average nature of the mask recreation would help negate the effect that the more prominent facial features were having.

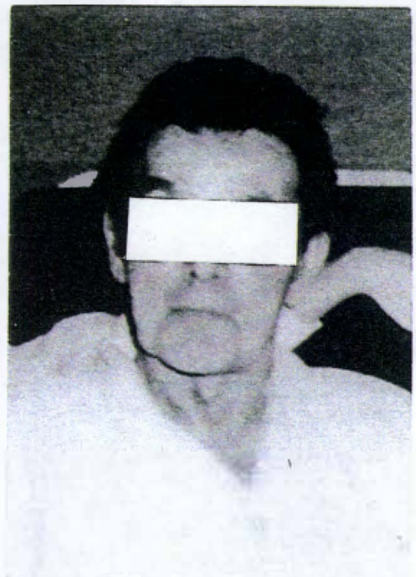
The scanning process had problems recording the mask, creating numerous 'spikes' in the image possibly due to the reflective quality of the plastic of which the mask was made. Once all the problem points were altered then the mask image went through the pegging, aligning, and shifting process. However, the mask image had greater than average problems with distortions and the quality of the end result was lower than the other images. The overall results of the second set of reconstructed images, though exhibiting less problems of a distorting nature, were all much more uniform in their appearance (Figure 16), with the likeness of the living individual having a greater influence on the outcome than the skeletal material.

Both the accuracy of the technique and the differing methods of pegging the faces were then tested through the examination of the original pre-decompositional photographs (Figure 17). A blind test was conducted in which the individuals taking the test were provided with the five photographs (without the eyes covered), general information regarding the aims of the system, and the specific information that each row of faces belonged to a particular skull and that the last two rows were the same set of skeletal remains. The test

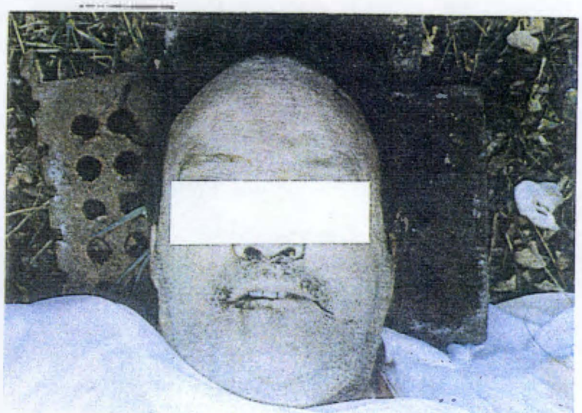
Figure 16. Second completed table of computer generated images.



1291



1492



1891

Figure 17. Pre-decompositional photographs that accompanied the remains.

2293

1092

Figure 17 *(continued)*. Pre-decompositional photographs that accompanied the remains.

The test was given to 31 people with both anthropological and non-anthropological backgrounds. However, regardless of background, both groups felt the task was impossible. When pressed the majority was able to line up one photograph per row, though several people were not convinced that each photograph belonged to separate rows and assigned more than one photograph to a row and in one case four photographs were assigned to the last two rows (all of which belonged to the same set of remains). The order in which the two sets of reconstructed faces were presented was alternated to eliminate the possibility of the results being biased through an overload of images on the person taking the test.

Once the sample of 31 people had been tested, all the identifications were then counted and put into tabular format (Table 1 and 2). A visual examination of the numbers of correct identifications indicate that the images from the first set of reconstructions were more correctly identified, while the method utilized in producing the second set of images reduced the number of correct identifications. These findings were then tested by means of a chi-squared test for significance (Appendix A). The test of the first sheet provided a Chi-square value of 43.401 with a probability of less than 0.001. Although the value is not great, this indicates that the positive identification of the photographs and the reconstructed images of the skeletal material are related. However, the results for the second set of images provided a Chi-square value of 23.100 with a probability of 0.111, which indicate that the positive identification of the

Table 1: Identification count of first sheet of images.

		Skeletal Remains				
Photograph		1291	1492	1891	2293	1092
	1291	11	2	7	7	4
	1492	10	6	7	6	2
	1891	2	5	8	7	9
	2293	5	11	4	9	2
	1092	3	6	5	2	15

Table 2: Identification count of second sheet of images.

		Skeletal Remains				
Photograph		1291	1492	1891	2293	1092
	1291	10	6	7	5	3
	1492	4	4	5	6	12
	1891	4	9	7	6	5
	2293	7	6	4	4	10
	1092	2	5	7	11	6

photographs with the correct set of reconstructions are not related. Further, by adding together the row percentages of the correct answers then dividing the sum by five it was possible to determine that positive identifications occurred at the rate of 31.612% in the first set of results and 19.998% in the second.

Of the individuals who took the test, those people who had a physical anthropological background tended to match-up more of the photographs correctly. After questioning people on how they came to decide on their final line-up, the individuals who did better indicated that they tended to study the width and length of the photographed faces and compare that factor with the computer generated image. The people who fared worse regarded the images as a whole or examined facial features such as the nose and lips of the photographs and images, and used that as a basis to decide. However, even with this in mind, the number of people who successfully identified the remains of 1092 with the photograph in the first set of images far out number any of the other results. After further discussions with the test takers, the identification of this individual was attributed to the altered mandible position which was evident in the images and the photograph, and provided an easier point of identification.

VI. CONCLUSION

The results of this test indicate that the system has some major problems to overcome, some of which are obvious and with further development of the program are rectifiable. Other difficulties are related to the way the software is utilized and the images perceived. Perhaps the most obvious problem is the manner in which the program reconstructs the soft tissues of the face that have no bony structure to support it. By taking these areas from the images of the living individuals the final result is automatically skewed. However, if it is possible for these points to be reconstructed by an artist, it should be possible to re-write the computer software to incorporate the same techniques and formulas for reconstructing these areas into the program.

A second problem arises form the amount of sensitivity the recording process can provide. The bone structure of a skull may give clues to particular identifiable features, such as damage to the facial structure. The fact that the image of skull 2293 exhibited none of the damage that the remains displayed could provide an obstacle. Scars and other morphological problems that can be observed on the bony structure, attributable to birth defects or accidents, present highly unique and identifiable features; reconstructions that do not take these into account may be misleading. If these features are not present on the reconstruction it may be construed to be a different individual all together and disregarded by the observer.

In relation to this, the testing of the system indicates that the way in which facial images are recognized by different individuals is important. The identification of a set of remains to a large extent will be conducted by members of the general public who have little or no concept of the principles that govern the make-up of a face. Instead they will be asked to recognize an individual they know. This being the case the issues of height and width of the face are factors that come second to the shape of the soft tissue structures of the face. Obviously a contingency for these areas needs to be developed. The study may have been handicapped by the fact that the reconstructed individuals were unknown to the people attempting to identify them. It is possible that the reconstructed images contain subtle features or nuances that would be familiar to someone who knew them. However, this problem was offset by the fact that people taking the test knew that the individual in each photograph was represented by one of the sets of images.

Not only are the people who will be expected to recognize the image important, but just as essential is the skill of the individual creating the image. Although the computer program seems simple in its methodology and use, it is conceivable that the individual creating the image affects the result in some fashion. In this study the images were created with no prior knowledge of how the system works, with instruction and advice being given as the test was run. The software is user friendly and is easy to utilize, however, it is possible that some of the finer nuances of the system are unknown. Though there was no prior knowledge of the program, an understanding of anatomical structure and osteology helped in the positioning of the peg markers. Whether this point would alter the results if the reconstructions were conducted without this knowledge is unknown. However, at this time the sensitivity of the system may not be great enough to be concerned with such issues.

A further difficulty arises from the age factor that this test had to contend with. Because of the aged nature of the skeletal material the reliability of the results may have been affected. The use of older faces for the reconstruction of the skulls could have had an effect on the results due to the exaggerated nature that the facial features exhibit as the age process continues. However, the features of the skeletal material also are of an aged nature and therefore the use of older individuals in the study is not necessarily incorrect. However, the system at this time is unable to compensate for the living image. This factor means that the infinite diversity of face shape will provide an infinite combination for the final image.

Although the results of the examination of this technique, as it presently exists, are not completely promising, the system does have potential for further development. Through continual testing and adjustment of the program a more accurate methodology will develop. If minor adjustments in the method of creating the reconstructed images produce a reduction in how well the results can be identified, then user technique may also factor into the results. Future testing should focus not only on how to reduce the influence the living face has on the skeletal remains, but also focus on pinpointing and eliminating potential user influence. It is hoped that this test is able to provide a constructive examination of the method and suggest possible areas for future development and enhancement. If the technique can be modified and improved, its roll in providing a valuable resource for law enforcement agencies will be inestimable.

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APPENDICES

APPENDIX A. CHI SQUARE TEST FOR INDEPENDENCE.

Three Dimensional Laser Imaging Data: Sheet 1 Statistical Test

TABLE OF PHOTO BY SKULL

PHOTO SKULL

Frequency
Expected
Percent
Row Pct
Col Pct

PHOTO	1092	1291	1492	1891	2293	Total
1092	15	3	6	5	2	31
	6.4	6.2	6	6.2	6.2	
	9.68	1.94	3.87	3.23	1.29	20.00
	48.39	9.68	19.35	16.13	6.45	
	46.88	9.68	20.00	16.13	6.45	
1291	4	11	2	7	7	31
	6.4	6.2	6	6.2	6.2	
	2.58	7.10	1.29	4.52	4.52	20.00
	12.90	35.48	6.45	22.58	22.58	
	12.50	35.48	6.67	22.58	22.58	
1492	2	10	6	7	6	31
	6.4	6.2	6	6.2	6.2	
	1.29	6.45	3.87	4.52	3.87	20.00
	6.45	32.26	19.35	22.58	19.35	
	6.25	32.26	20.00	22.58	19.35	
1891	9	2	5	8	7	31
	6.4	6.2	6	6.2	6.2	
	5.81	1.29	3.23	5.16	4.52	20.00
	29.03	6.45	16.13	25.81	22.58	
	28.13	6.45	16.67	25.81	22.58	
2293	2	5	11	4	9	31
	6.4	6.2	6	6.2	6.2	
	1.29	3.23	7.10	2.58	5.81	20.00
	6.45	16.13	35.48	12.90	29.03	
	6.25	16.13	36.67	12.90	29.03	
Total	32	31	30	31	31	155
	20.65	20.00	19.35	20.00	20.00	100.00

Three Dimensional Laser Imaging Data: Sheet 1 Statistical Test

STATISTICS FOR TABLE OF PHOTO BY SKULL

Statistic	DF	Value	Prob
Chi-Square	16	43.401	0.000
Likelihood Ratio Chi-Square	16	43.890	0.000
Mantel-Haenszel Chi-Square	1	8.664	0.003
Phi Coefficient		0.529	
Contingency Coefficient		0.468	
Cramer's V		0.265	

Sample Size = 155

Three Dimensional Laser Imaging Data: Sheet 2 Statistical Test

TABLE OF PHOTO BY SKULL

PHOTO Frequency Expected Percent Row Pct Col Pct	SKULL 1092	1291	1492	1891	2293	Total
1092	6	2	5	7	11	31
	7.2	5.4	6	6	6.4	
	3.87	1.29	3.23	4.52	7.10	20.00
	19.35	6.45	16.13	22.58	35.48	
	16.67	7.41	16.67	23.33	34.38	
1291	3	10	6	7	5	31
	7.2	5.4	6	6	6.4	
	1.94	6.45	3.87	4.52	3.23	20.00
	9.68	32.26	19.35	22.58	16.13	
	8.33	37.04	20.00	23.33	15.63	
1492	12	4	4	5	6	31
	7.2	5.4	6	6	6.4	
	7.74	2.58	2.58	3.23	3.87	20.00
	38.71	12.90	12.90	16.13	19.35	
	33.33	14.81	13.33	16.67	18.75	
1891	5	4	9	7	6	31
	7.2	5.4	6	6	6.4	
	3.23	2.58	5.81	4.52	3.87	20.00
	16.13	12.90	29.03	22.58	19.35	
	13.89	14.81	30.00	23.33	18.75	
2293	10	7	6	4	4	31
	7.2	5.4	6	6	6.4	
	6.45	4.52	3.87	2.58	2.58	20.00
	32.26	22.58	19.35	12.90	12.90	
	27.78	25.93	20.00	13.33	12.50	
Total	36	27	30	30	32	155
	23.23	17.42	19.35	19.35	20.65	100.00

Three Dimensional Laser Imaging Data: Sheet 2 Statistical Test

STATISTICS FOR TABLE OF PHOTO BY SKULL

Statistic	DF	Value	Prob
Chi-Square	16	23.100	0.111
Likelihood Ratio Chi-Square	16	22.701	0.122
Mantel-Haenszel Chi-Square	1	4.738	0.030
Phi Coefficient		0.386	
Contingency Coefficient		0.360	
Cramer's V		0.193	

Sample Size = 155

APPENDIX B.

SUGGESTED READING ON TOPICS RELATING TO FACIAL RECONSTRUCTION

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