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A Forensic Identification Utility to Create Facial Approximations using Cone-Beam Computed Tomography of 100 Hispanic Females: A Pilot Study

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A FORENSIC IDENTIFICATION UTILITY TO CREATE FACIAL APPROXIMATIONS USING CONE-BEAM COMPUTED TOMOGRAPHY OF 100 HISPANIC FEMALES: A PILOT STUDY

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Abstract

Introduction: Estimation of facial soft tissue appearance from human skeletal remains is often necessary in forensic identification. This process has been referred to as facial reconstruction or facial approximation and is a branch of forensic facial anthropology. Original methods for facial approximation originated in nineteenth century Europe and consisted of artists shaping clay over skull models using average soft tissue depths measured in cadavers. The last two decades have introduced numerous computerized techniques that have digitized this process while attempting to accurately and objectively define the relationship between a skull and its overlying soft tissue. This pilot study describes a method of facial approximation that combines cephalometric techniques for characterization of the craniofacial complex commonly used in the field of orthodontics with a database of cone-beam computed tomography (CBCT) skull images. Facial likenesses for an unknown skull are automatically located within the database by comparing cephalometric values recorded on the unknown skull with those within the database. A recently proposed method of sex determination based on the anatomy of the mastoid process, glabellar process, and frontal sinus area is also applied to the sample used in this study. **Methods:** A database consisting of one-hundred (100) cone-beam computed tomography (CBCT) skull images of Hispanic female patients of the University of Las Vegas, Nevada School of Dental Medicine Orthodontic Department [age range 8 to 23 years (mean 13.5 years)] was constructed. A cephalometric analysis consisting of twelve (12) landmarks and nineteen (19) skull measurements [sixteen (16) angular and three (3) proportional] was defined and applied to all database entries. Facial approximations were created for three skulls by sequentially removing three (3) random entries from the database and treating these as unknown (leave-one-out cross validation). A weighted least-sum-of-squares (WLSS) regression algorithm was applied to measure the cephalometric similarity between each entry in the database and the unknown skull data to find the three (3) most cephalometrically similar skulls in the database (three closest matches). Accuracy was assessed through expert face pool resemblance ranking. Soft tissue profiles associated with the three best matches were grouped with three random database entries to create a face pool array of size six (6) for each unknown. Fourteen (14) post-doctoral orthodontic graduate students were utilized as expert face pool evaluators. Sex determination accuracy was then assessed by comparing the values of eight (8) cephalometric measurements taken on this sample to those already described and proven efficacious on other samples in the literature. **Results:** Intraexaminer reliability was acceptable for all cephalometric measurements. Expert face pool resemblance rankings results implied that the described process was able to select database entries that approximated the unknown face better than random database entries. In Face Pools One, Two, and Three the three highest ranked faces contained two, two, and three algorithm-selected faces, respectively. Sex determination data recorded on this sample was comparable to data described in the literature. **Conclusions:** Contemporary methods of facial approximation have shown that estimation of soft tissues from skeletal data can be achieved by employing computationally and graphically complex techniques. It now also seems plausible to rapidly estimate the general shape of an unidentified skull's facial profile by comparison of the unknown skull's cephalometric data to those in a database of orthodontic patients. Further research involving the described method is warranted.

Acknowledgements

For my loved ones. This humble effort is perhaps the most tangible product to date reflecting their inexhaustible support and fulfilling company. I am also thankful to all the instructors that have led me along my academic path, particularly my Master's Thesis Committee and the clinical orthodontic faculty at UNLV, and to my dearest cohorts that have been such excellent company. Thank you.

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Chapter 1: Introduction

Forensic anthropology can be accurately summarized as the assessment of skeletonized human remains and their environments (Ballerini et al., 2007). It is similar to forensic pathology, where a human cadaver is examined at the scene of a crime to establish time and cause of death. In the same manner the anthropologist, when nothing remains of a victim but bones, must execute the search and proper retrieval of the skeleton and deduce a cause of death (Cattaneo, 2007).

The most important application of forensic anthropology, however, remains identification of human beings from their skeletal remains (Wilkinson, 2004; Ballerini et al., 2007; Cattaneo, 2007).

Forensic facial anthropology is a subspecialty of the field that aims to create the soft tissue facial likeness of a deceased individual from their skull (Gerasimov, 1971; Prag and Neave, 1997; Taylor, 2001; Wilkinson, 2004). This technique is useful in stalemates, when investigation of skeletal remains provide no further clues to the identity of the deceased (Wilkinson, 2006). Craniofacial reconstructions can be used to stimulate the memory of the public to generate leads toward proper identification of the unknown individual (Cattaneo, 2007). It has shown significant success in the capacity (Wilkinson, 2010).

Forensic facial anthropology is not necessarily only applied to single cases of unknown identity; it has been shown to be a valuable tool in mass identification efforts such as the study of war crime victims or in mass disasters like Hurricane Katrina (Cattaneo, 2007; Wilkinson, 2010). Other successful mass identification efforts have been documented worldwide (Komar, 2003; Djuric, 2004; Steadman and Haglund, 2005).

The process of creating an estimation of facial soft tissue form from skeletonized remains of the skull has been termed craniofacial reconstruction in the literature (Wilkinson, 2006). Some authors have expressed cynicism regarding the process, acknowledging the fact that it is an estimation and creates potentially inaccurate and unreliable results (Stephan, 2003a). However, it still remains possible to produce a “reasonable” recognizable face from skeletal information alone (De Greef and Willems, 2005). Conceding this inherent inaccuracy, some authors prefer to refer to the technique as facial approximation (Catteneo, 2007).

Facial approximation is justified by the fact that the craniofacial substrate may, to a certain extent, be considered as a matrix supporting facial soft tissue (Verzé, 2009). All facial approximation techniques are rooted in attempting to define the relationship between hard-and-soft tissues in the craniofacial complex. The aim of facial approximation is to create a suitably accurate representation of an unidentified skull’s true face to generate a resemblance to a missing person (Tilotta et al. 2010).

The process of identification from skeletal remains begins with the application of all anthropologic means to create a biological profile consisting of determination of age, sex, race, stature, pathologies, and other anomalies (Claes et al., 2010b). DNA evidence can now also produce much of this information (Herschaft et al., 2007). If this information alone is insufficient to lead to suspicion of identity, it can be applied to a facial approximation method to create an estimation of the unknown person’s facial visage. Once a suspicion of possible identity is formed after presentation of the facial approximation to the public, positive identification must be performed. This is usually left to geneticists, fingerprint experts, or odontologists (Cattaneo, 2007).

Craniofacial approximation has exhibited substantial technical maturation beginning with refinement of manual methods and more recent multidisciplinary computer assisted approaches (Ricci, Marella, and Apostol, 2006). The concept gained popularity in nineteenth century Europe—artisans modeled clay over depth markers placed on the skull without much attention to anatomic accuracy (Verzé, 2009). Later, in the United States, Snow et al. modified and standardized this method and developed what became known as the American method (Snow et al., 1970; De Greef and Willems, 2005). Around the same time, Gerasimov developed a method that estimated the shape of the face by modeling the muscles of mastication and facial expression (Gerasimov, 1955). This was referred to as the Russian method (Ullrich and Stephan, 2011).

With the intention of applying sound scientific method to the art of facial approximation, much literature has been published on the subject of deriving soft tissue shape from skeletal information. Complete books or chapters have been published on various methods (Gerasimov, 1971; Stewart, 1979; Krogman & Iscan, 1986; Iscan & Helmer, 1993; Prag & Neave, 1997; Clement & Ranson, 1998; Taylor & Angel, 1998; Taylor, 2001; Ĭordanov, 2003; Wilkinson, 2004; Vermeulen, 2012; Vandermeulen et al., 2012). Numerous reviews with substantial bibliographies have also been authored in peer-reviewed journals regarding the subject (Vanezis et al., 1983; Auselbrook, Iscan, Slabbert, & Becker, 1995; Tyrrell, Evison, Chamberlain, and Green, 1997; Stoney & Koelmeyer, 1999; P. Vanezis, M. Vanezis, McCombe, & Niblett 2000; Quatrehomme & Iscan, 2000; De Greef and Willems, 2005; P. Vanezis, M. Vanezis, Mccombe, and Niblett, 2000; Verzé, 2009; Claes et al., 2010b; Wilkinson, 2010).

Many guidelines have been published to best estimate soft tissue structures. These include skull based estimations for soft tissue mouth width, eyeball projection, ear height, nose projection, pronasale projection, superciliare position, lip closure line, and lip position (Prag & Neave, 1997; Wilkinson, 2004; Stephan & Cicolini, 2008; Rynn, Wilkinson, & Peters, 2010; Wilkinson, 2010).

Advances in computer imaging and processing have digitized the process of facial approximation. Initial computer-aided systems used methods similar to clay reconstruction, using soft tissue depth markers and algorithms that smooth a face-mesh over these markers. Recently developed systems are derivations of volume deformation models which consist of soft tissue warping, where the face of an anthropologically similar individual (age, sex, race, etc.) is warped onto the matched soft tissue markers of the unknown skull (Nelson & Michael, 1998; Abate, Nappi, Ricciardi, & Tortora, 2004). A 71% accuracy rate has been reported for approximations using volume deformation models (Wilkinson, 2010).

Statistical and vector-based models have been recently proposed in the literature to mathematically reconstruct the most likely soft tissue match for an unidentified skull. Accuracy measures indicate success in identification (recognition) that surpasses existing modalities of facial approximation (Tilotta et al. 2010).

Recent literature suggests that the best measure of accuracy for a facial approximation is face pool assessment. In this method, an assessor is presented with a facial approximation and a group of faces. One of the faces in this group belongs to the face whose skull was approximated. The assessor selects the face out of the group that most closely resembles the approximation. A measure for accuracy is established when the event of correct target selection (selection of the correct face) is compared to the probability of selection of the correct face by chance (Stephan and Cicolini, 2008).

Other accuracy measures have been reported in previous studies. Morphometric comparison is based on the comparison of matched soft tissue measurements between the approximation of a skull and its actual, natural face (target). Resemblance ratings are another accuracy measurement scheme consisting of a judge assigning a level of resemblance (a number) between the approximation and the target. Morphometric analysis and resemblance ratings have been criticized as not correctly correlating with the ability of an approximation to induce recognition of a target (Stephan, 2002a; Stephan & Cicolini, 2008; Wilkinson, 2010).

Despite the progress that has been made in the field of forensic facial anthropology current methods of facial approximation have major limitations. Firstly, methods are still based on soft tissue depth based prediction models. According to Stephan (2003a), the soft tissue depth driven ―reconstruction” method has never been fully justified and validated. With the exception of computerization of some methods, few changes have been introduced into the process of approximating a human face in over 200 years (Stephan, 2003a). Secondly, facial approximation practitioners recognize that, with few exceptions, the location and size of the facial muscles cannot be accurately established. This is a consequence of muscles of facial expression which originate and/or insert into soft tissue and do not interface only with the skull (e.g. risorious, orbicularis oris, zygomaticus major and minor, levator labii superioris, mentalis, depressor anguli oris, etc.). This makes accurate prediction unlikely (Stephan, 2003a). Lastly, it has been reported that in a population of Turkish orthodontic patients between age 7 and 17, approximately 50% of the variability of soft tissue profile shape was related to the underlying hard tissue, leaving the other 50% to be attributed to independent soft tissue specific factors (Halazonetis, 2005).

The inaccuracies inherent in current methods of facial approximation warrant the exploration of other estimation-based methods. This project outlines a method of facial approximation that uses a database of one-hundred cone-beam computed tomography (CBCT) images of Hispanic females between the ages of 8 to 23 years (mean 13 years) whose radiographs were recorded as part of their orthodontic treatment at the Orthodontic Department of the School of Dental Medicine at the University of Nevada, Las Vegas. It provides the utility of rapid creation of skeletally similar facial approximations. The materials and methods of this research project are purposefully similar to current orthodontic record taking and diagnosing practices. As facial reconstruction practitioners have already initiated, it is conceivable that orthodontic professionals may collectively create and continuously expand a large-scale facial approximation and identification database for use in forensic investigations (Tilotta et al., 2009).

Chapter 2: Literature Review

Origins of Facial Approximation

Historically, different cultures have shown differing levels of deference for the dead. In certain civilizations bones or mummies of the deceased have been exalted, as in ancient Egypt, where elaborate attempts were made at preservation of the body for an eternity. This was considered a method for ensuring spiritual immortality (Lynnerup, 2007). Other groups have considered the corpses of their dead the source of revulsion, cremating them and leaving only basic chemical compounds in the form of gases and bone fragments (Verzé, 2009).

According to a recent history of facial reconstruction provided by Verzé (2009) the development of facial reconstruction originated from the concept of ancestor worship. Beginning with the start of the Neolithic Age around 10,000 BC the residents of Jericho—an area on the West Bank in present day Palestine—regularly buried their dead under the floors of their homes. Perhaps by understanding that the mandible is connected to the base of the skull through ligamentous attachment and separates during decomposition, they isolated what they considered the skull and followed the custom of separately burying the mandible (Verzé, 2009).

Numerous other examples of what appears to be ancestor worship—particularly to the severed head or skull—are recurrent in the ancient world. Again in Jericho, the practice of skull plastering was undertaken around 8500-8000 BC by the pre-pottery Neolithic A culture and also around 7500-5500 BC among the pre-pottery Neolithic B culture. An archaeological expedition in Jericho in 1953 uncovered nine skulls that were covered in plaster to emulate faces and had shells fixed in position to mimic eyes (Verzé, 2009). Another expedition in the area in 1958 uncovered a single skull and subsequent findings mirrored this pattern of preservation and reverence for the dead. Despite the fact that each skull was unique, the lack of a mandible and general inexactitude of the process implied that this was an exercise in honoring the dead, not an attempt at reflecting the true visage of the individual before death (Verzé, 2009).

A wax or plaster cast of the face of the deceased, or so called death mask, has also appeared throughout ancient and modern history in various cultures to remember the dead (Gibson, 1985; Kaufman & McNeil, 1989; Meschutt, Taff, & Boglioli, 1992). This process creates a result that is anatomically unique and relatively accurate, however it is more similar to a carving or sculpture than to a modern approximation in that it captures the features of the face superficially and does not create them using the skull as a substrate (Verzé, 2009).

In the Middle Ages, as a result of difficulty in identifying dead individuals—most often criminals or missing persons—public streets were used to display corpses (Verzé, 2009). The heads were eventually severed and displayed in a container with a soluble preservative to prevent decomposition (Tyrrell, Evison, Chamberlain, & Green, 1997).

Later, during the Renaissance period in Italy, Andrea del Verrochio and Michelangelo continued to develop the art of constructing death masks using wax. Early dissection efforts had also commenced in fifteenth century Italy to explore human anatomy. Other artists in the sixteenth century eventually began to use wax to model the entire human anatomy and the use of cadavers in medical schools subsequently decreased (Wilkinson, 2004).

Numerous artists continued to exhibit their talents at depicting human anatomy during the seventeenth century. *Anatomica plastica*, or wax modeling of anatomy, was developed by Ercole Lelli (1702-1766) in Italy during this period. This practice modeled the whole body using the skeleton as a framework. Lelli and his peers cultivated the concept of scientific art and were the first to realize that the skeleton was the ideal canvas to model soft tissue (Wilkinson, 2004).

Despite these previous advances in scientific artistry, seemingly barbaric methods were still being employed to solve crimes as late as the second half of the nineteenth century. As Verzé (2009) describes, in March 1875, a severed head was found on a bank of the Thames River in England. The head was washed, the hair was combed, and it was impaled with a stake for display in St. Margaret's Churchyard in Westminster. Reminiscent of practices in the Middle Ages, as it went unidentified and decomposition set in it was placed in a container, immersed in spirit, for further viewing (Verzé, 2004).

Initial Scientific Attempts

The first scientists to show interest in recreating soft tissue shape and resemblance from the skull were anatomists. This exercise was first undertaken to validate the authenticity of remains that were thought to belong to famous people. Welcker (1884) used two-dimensional overlay techniques to compare images of a face to its alleged skull. He validated the skull claimed to belong Raphael—the Italian painter and architect of the High Renaissance—by comparing a self-portrait to a scaled image of the skull drawn at the same perspective. Welcker also validated the skull alleged to belong to Kant—the German philosopher—to a supposed death mask by using similar techniques. Welcker is also credited with undertaking the first documented work on collecting facial soft tissue depth data in 1883 (Tyrell, Evison, Chamberlain, & Green, 1997; Wilkinson, 2004; Verzé, 2004);

During this period the German anatomists His (1895) and Kollman (1898) completed similar work. His successfully identified the alleged remains of the famous German composer Bach (1685-1750) by using tissue depth data he collected from a limited number of cadavers. Using this data he modeled a soft tissue bust over a plaster model of the skull of Bach. The results of this process were satisfactorily compared with portraits and busts of Bach (Krogman & Iscan, 1986; Prag & Neave, 1997).

Kollman followed a similar process and recreated the bust of Dante, the famed Italian poet of the Middle Ages, from his supposed remains. Kollman also attempted to recreate the face of a woman from Auvenier, France whose excavated skull dated back to the Stone Age. He measured soft tissue thicknesses from hundreds of women in that area and produced technical drawings, then hired a sculptor to create a three-dimensional bust of the woman, and in doing so Kollman is credited as having completed one of the first authentic scientific reconstructions (Tyrell, Evison, Chamberlain, & Green, 1997; Verzé, 2004; Wilkinson, 2004). This effort constituted one of the earliest recorded examples of the contemporary archeological exercise of creating unverifiable faces for people from the distant past (Hill, Macleod, & Watson, 1993; Cesarani et al., 2004; Wilkinson, 2010; Papagrigorakis et al., 2011).

Multiple practitioners were completing similar work throughout Europe. Tandler (1909) used Welcker's methods to successfully confirm the skull of Haydn (1732-1809), the prolific Austrian composer from the classical period, before it was interred in a mausoleum in the German city of Wuppertal (Verzé, 2009).

A unique opportunity for multiple anatomists and anthropologists from around the world to compare their work arose in 1908, when a well preserved Neanderthal skull was excavated in the Chapelle oux Saint in France. Comparison of the results of these independent approximations of the same skull led to the realization that each –reconstruction” was substantially different (Verzé, 2009).

During this period it became increasingly obvious that disparate results were obtained from different practitioners. In 1913 the anatomist Von Heggeling measured soft tissue thicknesses for a male cadaver and commissioned two sculptures to independently construct facial reconstructions on the same skull. The results were completely different and as a result common sentiment shifted towards the belief that facial reconstruction was wholly unreliable (Prag and Neave, 1997).

Scientific Development

By the turn of the twentieth century, anthropologists were able to determine the sex and race of a skull in addition to the approximate age at death (Farkas, 1994). This capacity was showcased in New York in 1916 as a set of unidentified bones were unearthed in a Brooklyn cellar. The remains were measured and assessed to belong to an Italian man. Creation of an approximation ensued. A neck was reconstructed out of rolled up newspapers, brown eye analogues were fitted, and plasticine was sculpted over the skull. As the approximation was displayed for viewing several local Italians immediately identified the approximation as Domenico La Rosa. Although professionals concede that this result might have been fortuitous, it was nevertheless a turning point in forensics—it was becoming apparent that estimating the features of the deceased over their facial bones could be highly beneficial in forensic investigation efforts (Smyth, 1980).

Russian Method. Despite this renewed interest in the facial ―reconstruction" process, the technique was laden with inaccuracies and hitches. Through the patronage of Professor A.D. Grigoriev, chair of forensic sciences at the University of Irkutsk, Siberia, a student of archaeology and paleontology was about to lead the field into a new era. This student was Mikhail Gerisimov (1907-1970) (Verzé, 2009).

No practitioner of facial approximation has been the recipient of more fascination and intrigue from peers than Gerasimov (Prag & Neave, 1997; Taylor, 2001; Gibson, 2007; Wilkinson, 2004; Ullrich & Stephan, 2011). He is notable to many for proclaiming close to 100% accuracy (Gerasimov, 1968; Gerasimov, 1971; Ullrich & Stephan, 2011). His technique is the foundation for many current facial approximation methods (Prag & Neave, 1997; Taylor & Angel, 1998; Ĭordanov, 2003; Wilkinson, 2004; Ullrich & Stephan, 2011).

According to Verzé, Gerasimov created what became known as the ―Russian Method" by isolating the parts of the skull where the soft tissue was thinnest and most reproducible. He also modeled the muscular structure of each skull based on the remnants of muscle attachment on facial bones. Gerasimov's approximations were completed with an initial basic modeling stage followed by a final detail modeling stage. He seemingly introduced a subjective, artistic aspect in the second step of the process by claiming that this stage required an unquantifiable level of ―extensive" experience and training (Verzé, 2009). Unsurprisingly, Gerasimov himself admitted having reproducibility issues (Gerasimov, 1968; Gerasmov, 1971; Ullrich and Stephan, 2011).

Gerasimov developed many methods for extrapolating the shape and size of specific soft tissue features from skeletal structures. For example, he created guidelines for nose shape based on nasal bones, eyebrow form from the forehead prominence, the soft tissue mouth from the teeth and maxillae, and the eyes from the nasal root, orbital bones, and tear ducts (Wilkinson, 2004; Verzé, 2009; Ullrich and Stephan, 2011). Gerasimov also estimated ear shape and size, a notoriously difficult task, from the mastoid process of the temporal bone, ramus of the mandible, and external auditory meatus (Verzé, 2009; Ullrich & Stephan, 2011).

There is controversy regarding how much attention Gerasimov paid to soft tissue depths. Some authors assert that he paid little attention to the depth of tissues at various points in the skull and instead focused on the ―anatomical method” of muscle size and shape (Smyth, 1980; Taylor, 2001; Wilkinson, 2004; Verzé, 2009). Ullrich and Stephan (2011) have asserted that this is an erroneous conclusion and give numerous examples of Gerasimov’s work that show an extensive use of soft tissue depth values (Gerasimov, 1955; Gerasimov, 1968; Ullrich and Stephan, 2011).

Verzé (2009) states Gerasimov's claim that his approximations were successful in 150 forensic cases. Similar to previous practitioners, Gerasimov applied his technique to recreate the faces of many famous historical figures. The Laboratory for Plastic Reconstruction was created under his directorship in Moscow in 1950 at the Ethnographical Institute, USSR Academy of Sciences (Verzé, 2009). In 1953 the Soviet Ministry of Culture opened the tomb of Ivan the Terrible (1530-1584) and commissioned

Gerasimov to recreate his face. In 1961 Gerasimov traveled to identify and eventually approximate the skull of the German poet Schiller (1759-1805) from a mass grave (Gerasimov, 1971; Prag and Neave, 1997).

American Method. Around this time the science of facial approximation had already spread to the United States. The prominent American forensic anthropologist Wilder (1912) brought the concept of facial approximation to North America by creating faces for Native American skulls (Wilkinson, 2004; Verzé, 2009).

At Columbia University, McGregor (1915) also began creating faces for skulls. He approximated faces belonging to prehistoric skulls and captured the imagination of the public through their display at the Natural History Museum in New York (Wilkinson, 2004).

The American anthropologist Krogman is credited with undertaking the first rigorous exploration of the subject of facial approximation in the United States. He teamed up with a sculptor and did a case study of an approximation on a cadaver. When he compared the results of the study to initial photographs of the cadaver he concluded that there was indeed a resemblance (Tyrell, Evison, Chamberlain, & Green, 1997; Verzé, 2009).

The ―American Method" as it came to be known in the literature was the result of Krogman's work and collaboration with forensic artist Betty Pat Gatliff and physical anthropologist Clyde Snow (Snow, Gatliff, and McWilliams, 1970). The American method makes extensive use of soft tissue depths through the use of tables specific for age, gender, and race (Verzé, 2009). While the Russian method was termed as an “anatomical” method, the American method was classified as being “anthropometric” (Lee, Wilkinson, and Hwang, 2012).

The anthropologist Karen Taylor introduced a refinement of the American method of facial approximation in 2001 by delineating two separate steps for the reconstruction process. She introduced an initial technical phase consisting of anthropologic information collection, skull preparation, soft tissue depth marking, and rough facial contour production. The second stage was dedicated to a finishing the approximation by introducing facial feature detail into the carving. Taylor was invited to present her facial approximation method at the FBI academy in Quantico, Virginia during an international symposium on the forensic aspects of managing mass disasters (Taylor, 2001; Verzé, 2009).

UK Manchester Method. In the second half of the last century numerous practitioners throughout Europe modified existing techniques to develop their own facial approximation methods. Helmer in Germany (1984) and Neave in Britian (1997) made particularly substantial contributions to the field. Helmer created approximations using the American method while Neave created an amalgamation of American and Russian means in a method subsequently coined the “UK Manchester Method” (Verzé, 2009). In this method soft tissue depths are employed to create general facial shape, while muscle attachment sites are also considered to establish various details regarding facial detail and form (Verzé, 2009). This method has been adopted by a plethora of practitioners (Hill, Macleod, and Watson, 1993; Hill, Macleod, and Crothers, 1996; Wilkinson, 2004).

Facial Reconstruction and Cephalometric Analysis

Jarabak (1972) has defined cephalometrics as the science that uses lateral skull radiograph measurements to segment the dentofacial complex in order to assess the relationship among segments. Individual growth increments and the resultant changes on the entire craniofacial complex can also be monitored using cephalometrics (Jarabak, 1972). This process is commonly used in the field orthodontics to quantify craniofacial form by relating skeletal structures to each other. Landmarks are used to define skeletal angles, measurements, and proportions (Steiner, 1953; Downs 1956). It can also be used to assess the changes resulting from orthodontic treatment (Brodie, Downs, Goldstein, & Myer, 1938). The science has been applied to facial approximation. A two-dimensional manual method of craniofacial reconstruction described by George (1987) combined an initial cephalometric analysis to characterize craniofacial form with subsequent soft tissue depth plotting at numerous points on the skull to estimate a profile shape for unknown skulls.

Computerized Facial Reconstruction

The process of manually created facial reconstruction—regardless of the specific technique—has been criticized as being highly subjective, laborious, requiring artistic interpretation, and producing a single facial reconstruction (Lee, Wilkinson, and Hwang, 2011). Furthermore, facial approximations created by different artists always result in different faces (Haglund & Reay, 1991; Schofield, & Evison, 2005). Over the last two decades a surge in computer science and medical imaging has resulted in numerous computerized systems for craniofacial reconstruction that aim to create objective, reproducible facial reconstructions (Claes et al., 2010b). Software based methods can make facial reconstruction accessible to a wide range of people without the need for extensive expertise, and the development of software for this purpose is of benefit to various law enforcement agencies by allowing automated systematic generation of multiple reconstructions for the same individual (Claes et al., 2010b). A plethora of methods have been recently described or are currently being investigated, however these new methods have not been packaged into an simple software interface for use by forensic investigative authorities (Vandermeulen et al., 2012).

Claes et al. (2010b) have contributed an exhaustive overview that unifies contemporary efforts in the highly active field of computerized facial reconstruction into one framework, and in doing so have introduced new terminology. This framework consists of the following elements: anthropologic examination, skull digitization, craniofacial model, target skull representation, model to skull registration, visualization, and validation (Claes et al., 2010b).

Anthropologic Evaluation. The human skull contains enough unique complexity to be as distinct as a fingerprint (Schimmler, Helmer, & Rieger, 1993). After retrieval, an unknown skull is assessed to derive properties such as approximate age, gender, ancestry, and stature (Reichs, 1992). A body mass index can often be established based on any remaining soft tissue on the face and body, or based on any clothing available at the crime scene (Claes et al., 2010b). A software package (FORDISC 3.0) is also available to assist in estimating an unknown skull's ancestry and gender (Ousley & Jantz, 2005). Alternatively, gender can be assigned to an unknown skull with almost complete certainty based on the shape and size of the mastoid process, frontal sinus, and glabella

(Hsiao, Chang, & Liu, 1996; Patil & Mody, 2005; Veyre-Goulet, Mercier, Robin, & Guerin, 2008). This information can also be derived from DNA analysis (Herschaft, 2007). To date, no completely automated (computerized) skull classification systems exist, but it is conceivable that such systems will be developed in much the same way that facial archetypes describing anthropologic groups or syndromic individuals have already been defined (Shaweesh, Clement, Thomas, & Bankier 2006; Claes et al., 2010b).

Unknown Skull Digitization. Initial methods for importing a digitized version of the skull in computer systems consisted of laser scanning technology (Moss, Linney, Grindrod, & Mosse, 1989; Vanezis, 1989). Advances in medical imaging have made computer-tomography (CT) a convenient method of deriving digital skull models. All computerized reconstruction techniques today use CT scanners to digitize the skull (Claes et al., 2010b). Cone-beam computed tomography (CBCT) is a variant of medical CT that is commonly used in dentistry that can produce similar resolution in digitization of the skull while producing lower levels of radiation (Figure 1) (Mah, Danforth, Bumann, & Hatcher, 2003; Scarfe, Farman, & Sukovic, 2006; Cotton, Geisler, Holden, Schwartz, & Schindler, 2007; Mah, Huang, & Choo, 2011). CBCT imaging is now also being used in contemporary facial reconstruction studies (Lee, Wilkinson, and Hwang, 2012).

Each imaging technique has it's limitations. CT and CBCT introduce significant artifacts as a result of dental amalgam fillings, and laser scanning processes result in resolution and detail deficiencies (Claes et al., 2010b). Compared to CT, CBCT has the benefit of image production with the subject in seated position. CT scanners operate with the patient in supine position, and this can introduce gravitation deformation of soft tissues (Pluym et al., 2009).

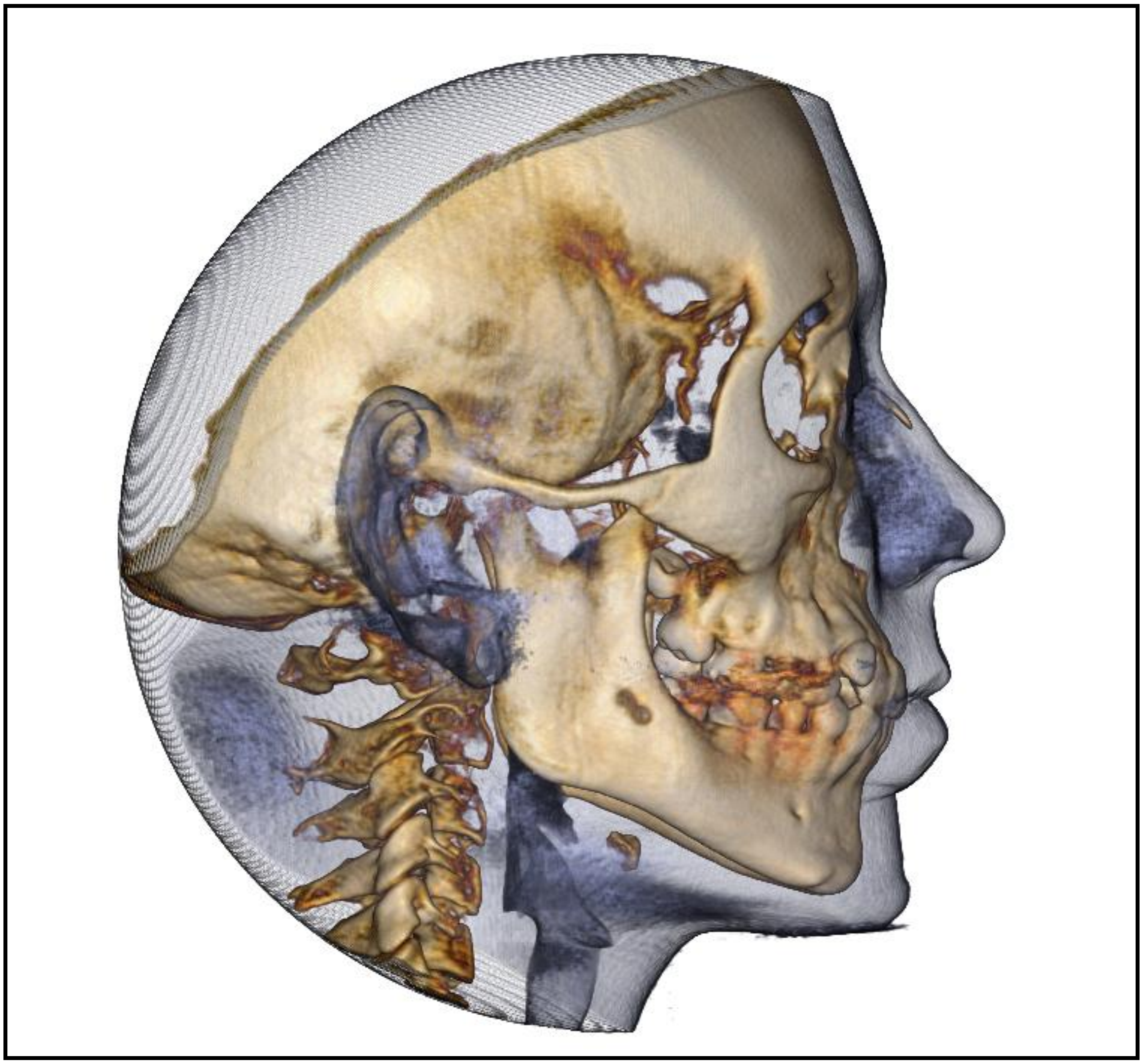

Figure 1- Cone-beam computed tomography (CBCT) skull image. This image shows both skeletal and soft tissue shape. InVivo medical imaging software package (Anatomage, San Jose, Calif).

Craniofacial Model. According to Claes et al. (2010b), an essential step in the computerized facial reconstruction framework is the definition of a craniofacial model (CFM). Conceptually, this step is the incorporation of artificial intelligence that is functionally analogous to the human artist that creates manual facial reconstructions. The craniofacial model is responsible for extrapolating the relationship between skull structures and facial form based on a database of example relationships (Claes et al., 2010b). An example relationship exists in each living person, because in a live person a skull is matched with an actual face that we can observe. This relationship is conserved during skull digitization due to the anatomical accuracy inherent in CT or CBCT imaging (Suomalainen, Vehmas, Kortesniemi, Robinson, & Peltola, 2008; Murphy, Drage, Carabott, & Adams, 2012). This step of the reconstruction process involves the extrapolation of a face from skeletal data and it has been likened to solving a missing data regression problem. More precisely, the task of estimating the facial visage of a bare skull may be statistically understood as a semi-parametric regression problem with random design (Tilotta, Glaunès, Richard, & Rozenholc, 2010). The design of a face based over its underlying skull is considered random because of the variation that presents solely as a result of each individual's soft tissue specific variation which cannot be attributed to skeletal variation alone (Halazonetis, 2005). According to the framework developed by Claes et al., the CFM portion of computerized facial reconstruction is further subdivided into the following categories: craniofacial template (CFT), craniofacial information (CFI), and craniofacial deformation (CFD) (Claes et al., 2010b; Vandermeulen et al., 2012).

Craniofacial Template. According to Claes et al. (2010b), a craniofacial template (CFT) is the complete face that functions as the "canvas" of facial reconstruction. Similar to altering a piece of clothing, this template is modified, in three dimensions, to fit the unique unknown skull. Moreover, this template can either be an entire face as one unit or broken up into separate features such as the nose, mouth, and ears which are subsequently "stitched" together over the skull. A single or multiple CFT's may be used. By definition, in the single CFT model all information is based on one reference. This can be either a single skull-to-face relationship (one person), or an average of a group of skulls

Author and Reference	Craniofacial Model (CFM)	
	Template (CFT)	Information (CFI)
Vanezis (1989)	Single/Specific	Face/Tissue thicknesses
Vanezis et al. (2000)	Single/Specific	Face/Tissue thicknesses
Evenhouse et al. (1992)	Single/–	Face/Tissue thicknesses
Evison (1996, 2000)	Single/Specific	Face/–
Micheal & Chen (1996)	Single/Specific	Face/–
Shahrom et al. (1996)	Single/Generic	Face /Tissue thicknesses
Archer (1997)	Single/Generic	Face /Tissue thicknesses
Archer et al. (1998)	Single/Generic	Face /Tissue thicknesses
Quatrehomme (1997)	Single/Specific	Face/Skull
Seibert (1997)	Single/Specific	Face/Skull
Nelson & Michael (1998)	Single/Specific	Face/–
Attardi et al. (1999)	Single/Specific	Face/Skull
Bullock (1999)	Single/Generic	Face/Tissue thicknesses
Plasencia (1999)	Single/–	Face/–
Jones (2001)	Single/Specific	Face/Skull
Kähler et al. (2003)	Single/Generic	Face/Muscles
Claes et al. (2004a, 2004b, 2005a, 2005b, 2006)	Multiple/Generic	Face/Tissue thicknesses
Claes (2007)	Multiple/Generic	Face/tissue thicknesses
Claes et al. (2010a)	Multiple/Generic	Face/tissue thicknesses
Vandermeulen et al. (2005a, 2005b)	Multiple/Specific	Face/Skull
Vandermeulen et al. (2006)	Multiple/Specific	Face/Skull
Pei et al. (2004)	Single/Generic	Face/Skull
Pei et al. (2008)	Single/Specific	Face/–
Andersson & Valfridsson (2005)	Single/Generic	Face/Tissue thicknesses
Berar et al. (2005a, 2005b, 2006)	Multiple/Generic	Face/skull
Davy et al. (2005)	Single/Generic	Face/–
Muller et al. (2005)	Single/Specific	Face/Skull
Mang et al. (2006)	Single/Specific	Face/Skull
Subsol & Quatrehomme (2005)	Single/Specific	Face/Skull
Tu et al. (2005)	Multiple/Specific	Face/Skull
Turner et al. (2005)	Multiple/Specific	Face/–
Paysan et al. (2009)	Multiple/Generic	Face/Skull
Tilotta et al. (2010)	Multiple/Specific	Face/Skull

Table 1- Recent computerized methods of facial reconstruction (CFT and CFI). Craniofacial template (CFT) and information (CFI) of computerized craniofacial reconstruction methods over the past 20 years in quasi chronological order (modified from Claes et al., 2010b).

(anthropologic group of age, gender, ancestry etc. matched). In the multiple CFT model the result of a reconstruction process can be multiple "specific" reconstructions based on each CFT, or an average of all reconstructions combined into one result. The combined result is referred to as "generic" (Table 1). The proper selection of a CFT (based on anthropologic examination) is critical to the accuracy of the facial approximation (Claes et al., 2010b).

Claes et al. have drawn an interesting analogy regarding the use of singular versus multiple CFT's. If the CFM is the homologue to a craniofacial reconstruction expert/artist, using one template is analogous to limiting the artist's knowledge to only one human face. All reconstructions will be biased toward that CFM, and this is referred to as *model bias*. The artist of course has a huge visual library of faces stored in their memory, and applies the best CFT (in their biased opinion) to each reconstruction effort. Thus, using multiple CFT's best models the human process of facial reconstruction. However, simply averaging the qualities of multiple CFT's results in an overly smooth and non-specific facial result. Thus, the science and art of computerized facial approximation consists of picking the proper CFT (Claes et al., 2010b).

Craniofacial Information. The term craniofacial information (CFI) refers to the specific knowledge that is applied to relate facial tissue to underlying skulls. This can be a set of tissue thicknesses, skull surfaces, facial surfaces, and/or facial muscles (Table 1) (Claes et al., 2010b). For example, Kähler, Haber, & Seidel (2003) used one generic CFT consisting of the outer facial surface and 24 facial muscles, and by doing so also introduce the concept of animating facial reconstructions. Claes et al., for example, have successfully used a combination of facial surface knowledge and soft tissue thicknesses measured at 52 anatomical landmarks (Claes, De Greef, Willems, Vandermeulen, & Suetens, 2004; Claes, Vandermeulen, De Greef, Willems, & Suetens, 2004; Claes, Vandermeulen, De Greef, Willems, & Suetens, 2005; Claes, Vandermeulen, Suetens, De Greef, & Willems, 2005; De Greef et al., 2005; Claes, Vandermeulen, De Greef, Willems, & Suetens, 2006; De Greef et al., 2006).

As Claes et al. (2010b) explain, this step is unique from the skull digitization step mentioned previously because it does not necessarily require hard-tissue bony visualization. It merely requires the establishment of information relating a face to its underlying skull. As a result, an alternative to CT or CBCT imaging in this step is magnetic resonance imaging (MRI). MRI scanners have been used to derive soft tissue depths for this purpose (Mang, Müller, & Buzug, 2004; Paysan et al., 2009). MRI scanners have the added benefit of producing no ionizing radiation (Mang, Müller, & Buzug, 2004). Similar to the use of laser scanners for skull digitization, they have also been used in combination with ultrasound technology for facial shape capturing and tissue depth data. Unfortunately, this results in a sparse (< 100) set of anatomical landmarks on the face (where the ultrasound device was used to measure depth) compared to the dense anatomical tissue-depth data that can be derived from CT or CBCT imaging (Claes et al., 2010b). A unique approach reported by Paysan et al. (2009) describes the use of CT imaging for skull data, laser scanning for soft tissue shape data, and MRI imaging for soft tissue depth measurement.

Craniofacial Deformation. The craniofacial deformation (CFD) method describes how the CFT is manipulated to best fit the skull (Table 2) (Claes et al., 2010b). Methods

Author and Reference	Craniofacial Model (CFM)
	Deformation (CFD)
Vanezis (1989)	Generic/Non-uniform Scaling
Vanezis et al. (2000)	Generic/–
Evenhouse et al. (1992)	Generic/Polygon based deformations
Evison (1996, 2000)	Generic/–
Micheal & Chen (1996)	Generic/Volume Distortion Functions
Shahrom et al. (1996)	Generic/–
Archer (1997)	Generic/Radial Basis Functions
Archer et al. (1998)	Generic/Radial Basis Functions
Quatrehomme (1997)	Generic/Radial Basis Functions
Seibert (1997)	Generic/Radial Basis Functions
Nelson & Michael (1998)	Generic/Local cylindrical coordinate
Attardi et al. (1999)	Generic/Diffused Scattered Motion Fields
Bullock (1999)	Generic/Radial Basis Functions
Plasencia (1999)	Generic/polygon based deformations
Jones (2001)	Generic/–
Kähler et al. (2003)	Generic/–
Claes et al. (2004a, 2004b, 2005a, 2005b, 2006)	Face-Specific/PCA
Claes (2007)	Face-Specific/PCA
Claes et al. (2010a)	Face-Specific/PCA
Vandermeulen et al. (2005a, 2005b)	Generic/Digital Cosine Transformations
Vandermeulen et al. (2006)	Generic/Radial Basis Functions
Pei et al. (2004)	Generic/Radial Basis Functions
Pei et al. (2008)	Generic/–
Andersson & Valfridsson (2005)	Generic/–
Berar et al. (2005a, 2005b, 2006)	Face-specific/PCA
Davy et al. (2005)	Generic/Radial Basis Functions
Muller et al. (2005)	Generic/Radial Basis Functions
Mang et al. (2006)	Generic/Radial Basis Functions
Subsol & Quatrehomme (2005)	Generic/Radial Basis Functions
Tu et al. (2005)	Generic/Radial Basis Functions
Turner et al. (2005)	Generic/Radial Basis Functions
Paysan et al. (2009)	Face-Specific/PCA
Tilotta et al. (2010)	Generic/Local semi-rigid

Table 2- Recent computerized methods of facial reconstruction (CFD). Craniofacial deformation (CFD) models of computerized craniofacial reconstruction methods over the past 20 years in quasi chronological order (modified from Claes et al., 2010b).

for approaching this task are diverse, particularly in terms of computational complexity. Rigid transformations are a subset of transformation geometry that only apply a translation or rotation to the CFT, whereas affine transformations also incorporate scale and skew to deform the facial template (Claes et al., 2010b).

According to Claes et al. (2010b) a majority of facial reconstruction methods use generic affine transformations. These incorporate size and shape changes smoothly into the shape, and in situations where the difference between the unknown skull and the CFT is large, facial shapes are often created that are not anatomic. For example, an increase in nasal length is often concomitant with a dorsal hump (Claes et al., 2010b). A solution to this issue is the use of *face-specific* transformations, first proposed by Claes, De Greef, Willems, Vandermeulen, & Suetens (2004). The disadvantage of face-specific transformations is that they require a learning phase where a principle component analysis (PCA) is applied to the database and as a result these are specific to each database (Claes et al., 2010b). In the case where a database is too small or has low inter-subject variance deformation possibilities become restricted and faces atypical to the database are difficult to create (Claes et al., 2010b).

Target Skull Representation. The fourth component of computerized facial reconstruction as described by Claes et al. (2010b) is target skull representation (TSR), which is related to the craniofacial model (CFM) previously described. In a manual reconstruction, for example, the target skull representation is a copy of the skull with dowels of a specific length at specific anatomical landmarks (representing average tissue depths) covered by clay (Figure 2) (Claes et al, 2010). Some of the computerized reconstruction methods are digitized versions of this exact process by using

Author and Reference	Target skull representation
Vanezis (1989)	Sparse
Vanezis et al. (2000)	Sparse
Evenhouse et al. (1992)	Sparse
Evison (1996, 2000)	–
Micheal & Chen (1996)	–
Shahrom et al. (1996)	Sparse
Archer (1997)	Sparse
Archer et al. (1998)	Sparse
Quatrehomme (1997)	Dense/Crestlines
Seibert (1997)	Dense/Feature Points
Nelson & Michael (1998)	Dense/Feature Points
Attardi et al. (1999)	Sparse
Bullock (1999)	Sparse
Plasencia (1999)	Sparse
Jones (2001)	Dense/Feature Points
Kähler et al. (2003)	Sparse
Claes et al. (2004a, 2004b, 2005a, 2005b, 2006)	Sparse
Claes (2007)	Implicit/Signed distance Transform
Claes et al. (2010a)	Implicit/Signed distance Transform
Vandermeulen et al. (2005a, 2005b)	Implicit/Signed distance Transform
Vandermeulen et al. (2006)	Implicit/Signed distance Transform
Pei et al. (2004)	–
Pei et al. (2008)	Dense/Range Image
Andersson & Valfridsson (2005)	Sparse
Berar et al. (2005a, 2005b, 2006)	Dense/Feature Points
Davy et al. (2005)	Sparse
Muller et al. (2005)	Sparse
Mang et al. (2006)	Sparse
Subsol & Quatrehomme (2005)	Dense/Crestlines
Tu et al. (2005)	Dense/Range Image
Turner et al. (2005)	Dense/Crestlines
Paysan et al. (2009)	Dense/Feature Points
Tilotta et al. (2010)	Implicit/Extended Normal Vector Field

Table 3- Recent computerized methods of facial reconstruction (TSR). Target skull representation (TSR) of computerized craniofacial reconstruction methods over the past 20 years in quasi chronological order (modified from Claes et al., 2010b).

virtual dowels that are sparsely placed at various anatomical locations on a virtual copy of the skull (Table 3). Other methods expand this concept by placing extra dowels at mathematically calculated points between the standard sparse anatomical landmarks (Attardi et al., 2000; Davy, Gilbert, Schofield, & Evison 2005).

Other methods use tissue growth algorithms that start at virtual dowel positions and interpolate the areas in between to create a polygonal mask (Vanezis, 1989; Bullock, 1999; Plasencia, 1999; Andersson & Valfridsson, 2005). These methods are capable of stitching together separate anatomical features to create one facial model (Claes et al., 2010b). Davy, Gilbert, Schofield, and Evison (2005) reported a similar method; instead of modeling separate features, separate facial muscles were first modeled onto the skull and the facial features and skin were subsequently added. In their initial efforts Claes et al. also used a sparse set of landmarks, however the soft tissue thicknesses were incorporated into the craniofacial model and did not need to be incorporated into the target skull representation as a separate step (Claes, Vandermeulen, De Greef, Willems, & Suetens, 2004; Claes, Vandermeulen, Suetens, De Greef, & Willems, 2004; Claes, Vandermeulen, De Greef, Willems, & Suetens, 2005; Claes, Vandermeulen, De Greef, Willems, & Suetens, 2006). Methods of skull representation based on or resulting from anatomic landmarks, as described above, are referred to as *sparse cranio-metric skull representations* (Claes et al, 2010b).

By incorporating soft tissue surface information into the craniofacial template (CFT) the possibility for *dense skull representation* becomes evident (Claes et al., 2010b). A dense distribution of cranio-metric points can be automatically selected, and in the most extreme case every point on the digital representation of a skull surface can be selected (Claes et al., 2010b). A alternative method is the isolation and use of all points on crest-lines which follow distinct lines on the bony surface of the skull, such as the mandible, orbit, maxilla, or the cheekbones (Quatrehomme et al., 1997; Subsol & Quatrehomme, 2005). Vandermeulen et al. (2005) were first to describe a completely

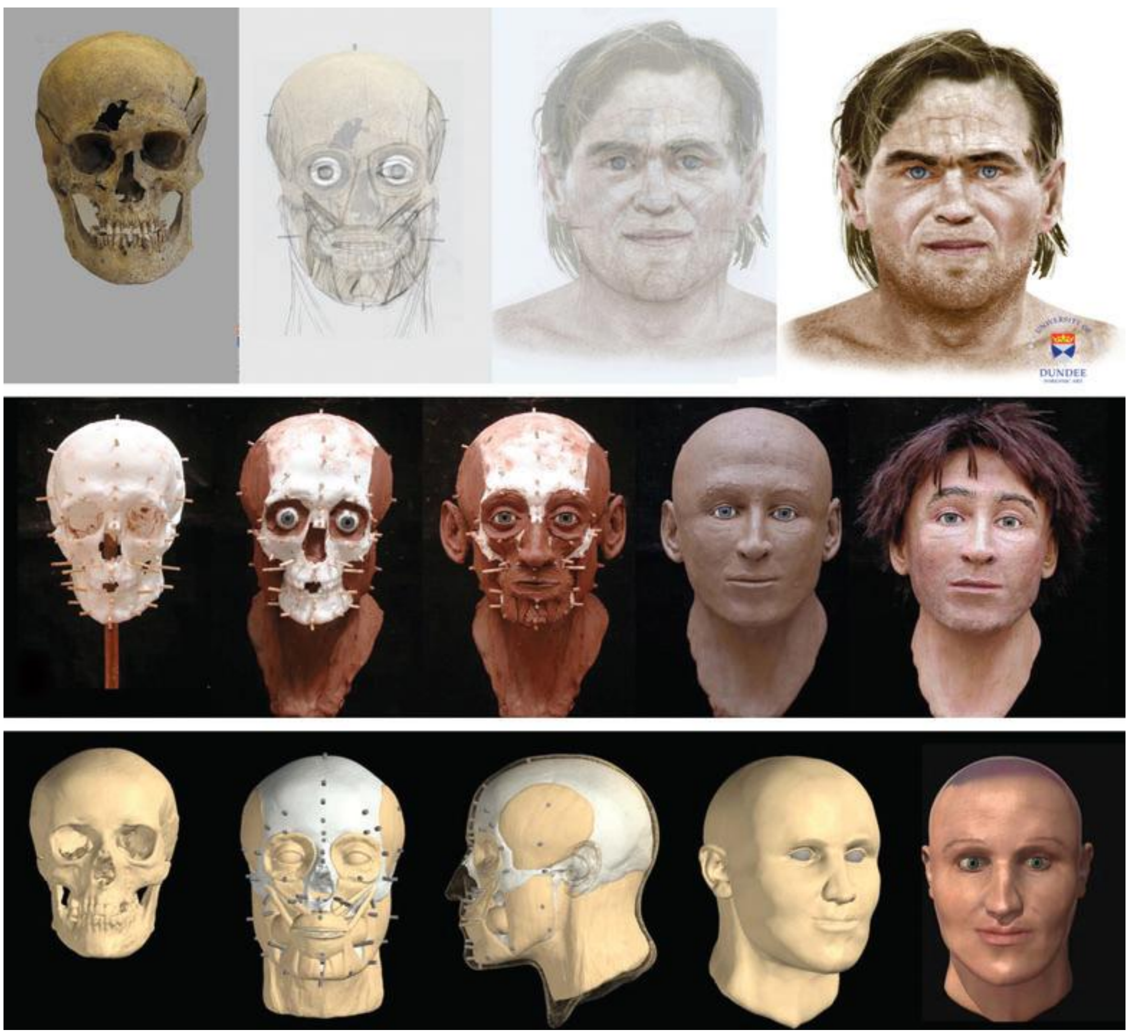

Figure 2- Examples of manual and computerized facial reconstructions. Facial reconstruction methods: two-dimensional manual (top), three-dimensional manual (middle), three-dimensional computerized (bottom) (from Wilkinson, 2010).

different method of skull representation that uses a signed distance transform (sDT), where each point in 3D is given a signed distance to the skull surface. This infinitely dense mapping gives a exact mapping of the skull surface and also creates smooth versions of the skull surface at matched iso-distances (Claes et al., 2010b).

Model to Skull Registration. The fifth component of the facial reconstruction framework provided by Claes et al. (2010b) is the registration of the target skull to the craniofacial model (CFM). An objective function is defined that relates the craniofacial template (CFT) to the target skull. The craniofacial deformation (CFD) model is combined with this objective function so that the ideal deformation is defined to minimize the difference between the CFT and the target skull. When this is attained, the deformations are applied to the CFT to produce an approximation of the target skull's facial form (Claes et al., 2010b).

Texturing: This step in the process of computerized facial reconstruction involves the application of a life-like texture; this is analogous to the refinement that can be introduced by a facial reconstruction artist by painting directly onto a clay model (Figure 2) (Claes et al., 2010b). Bruce et al. (1991) have shown that faces lacking surface detail and color are more difficult to properly identify. One method of solving this issue is by texture mapping, a process likened to digitally laying wallpaper over a surface (Davy, Gilbert, Schofield, & Evison, 2005; Subsol & Quatrehomme, 2005; Claes et al., 2010b). Alternatively, a two-dimensional sketch of the digital reconstruction can be made to make it more lifelike (Claes et al., 2010b). Care must be taken to not to skew the data with an overly distinct texture from an actual individual that introduces too much fine detail. Using the texture map of a particular individual in a reconstruction will trigger the recognition towards the source of the texture map instead of the actual reconstructed target (Claes et al., 2010b). One method of addressing this is to incorporate the texture map into the craniofacial model (CFM) such that the relationship between facial geometry and texture is learned by the CFM (Claes, 2007; Claes et al., 2010a; Claes et al., 2010b).

Validation: An essential aspect of the design framework for any reconstruction technique is an exploration of its usefulness as a forensic identification aid (Claes et al., 2010b). The difficulty in assessing a facial reconstruction in a forensic setting is the result of the practical and ethical dilemma that ensues as one attempts to use an actual unknown skull and an actual victim's family to validate a reconstruction method in a research environment (Wilkinson, 2010). As a result, numerous methods have been described in the literature to emulate this process. An intuitive method of accuracy assessment involves a leave-one-out cross-validation scenario which involves removing one face from the database and using this as an unknown to create a reconstruction, then applying measures to compare the facial surface of a reconstruction that results to the known facial structure for that skull (Claes et al., 2010b).

A quantitative measure that has been utilized is termed morphometric comparison, and may be accomplished rather easily for computerized facial reconstructions using three-dimensional modeling software such as Rapidform (3D Systems, Rock Hill, SC) (Wilkinson, 2010). The previously described Manchester Method was assessed in this manner and it was established that 67% of the recreated facial shape was within two millimeters of the actual known soft tissue (Wilkinson et al., 2006). However, the ultimate goal of facial reconstruction is not the linear accuracy of the reconstruction but rather its ability to induce recognition (identification success) (Claes et al., 2010b).

An intuitive way to analyze a reconstruction is to present a side-by-side comparison of the reconstructed face with the actual known face and use a judge to assign a so-called resemblance rating (Wilkinson, 2010). This method has been used extensively by various authors (Krogman & Iscan, 1986; Helmer, Rohricht, Petersen, & Mohr, 1993; Prag & Neave, 1997). As Stephan and Arthur (2006) have noted, this method appears to be most commonly used because of its relative ease and simplicity. However, this technique has been criticized for only measuring the similarity of a skull's reconstruction to its actual anatomic face and not actually measuring a reconstruction's ability to induce true recognition (Stephan, 2002a). According to De Greef and Willems (2005) caution should be exercised when evaluating previous work that used resemblance ratings to gauge accuracy; they declare that future studies should use the so-called face pool assessment method of validation.

Face pool assessment involves using the reconstructed face as a prompt and asking an assessor to identify the face that most closely resembles the prompt from within an array of faces. A measure of accuracy is established when incidence of correct target selection (the actual face) is compared to chance selection (Stephan and Arthur, 2006). Stephan and Arthur (2006) note that such tests potentially appear less often in the literature due to the increased time and effort they require to complete.

Criticism of Facial Reconstruction

Stephan (2003a) has substantiated his thoughts regarding some of the inherent weaknesses present in the current concept of facial reconstruction. As previously mentioned Stephan does not make use of the term facial "reconstruction" in his work and refers only to facial "approximation" (Stephan, 2003a; Stephan & Arthur, 2006; Stephan & Cicolini, 2008). Other authors have agreed that facial approximation is indeed the most accurate term (George, 1987; Stephan & Henneberg, 2001; Taylor, 2001). Stephan (2003a) conjectures that the reluctance to adopt the term "facial approximation" is a result of fact that "facial reconstruction" is a term that is more likely to garner interest and project a more influential aura.

Stephan (2003a) asserts that one cannot necessarily predict recognizable facial form from the skull alone, and he is not the first author to raise this concern (Suk, 1935; Montagu, 1947). Many of the muscles contributing to the shape of the face have only one attachment (e.g., zygomaticus major and minor, levator labii superioris, mentalis, depressor anguli oris, etc.) or no attachment (e.g. risorious, orbicularis oris) to bone, and this makes an accurate prediction of their size and shape difficult or impossible (Stephan, 2003a). Only two out of the 30 muscles contributing to the surface anatomy of the face have well demarcated interfaces with the skull (Stephan, 2003a). Furthermore, Stephan (2003a) points out that no studies have systematically related the size and shape of muscle attachment sites to muscle attribute prediction.

Stephan (2003a) also notes that while numerous studies exist for prediction of various facial structures (Gatliff, 1984; George, 1987; Fedosyutkin & Nainys, 1993; Gatliff & Taylor, 2001, Taylor, 2001; Stephan, 2003b; Stephan & Henneberg, 2003;

Stephan & Murphy, 2008), many are published without any empirical evidence for associations that are claimed. As a result, many of the anatomical estimation techniques that have been claimed have eventually been disproved (Farkas, Munro, & Kolar, 1987; Stephan, 2002b; Stephan, 2002c; Stephan, 2003b; Stephan, Henneberg, & Sampson, 2003; Wilkinson & Mautner, 2003). Furthermore, since numerous estimation methods have been defined for the same traits, it necessarily follows that there is inherent inaccuracy in these estimation processes (Stephan, 2003a).

Secondly, Stephan (2003a) has described instances where facial approximation has not been successful (Haglund & Reay, 1991; Stephan, 2001). It is also likely that many unsuccessful efforts to employ facial reconstruction as an identification aid have gone unreported (Stephan, 2001). Practitioner based reports of success are also potentially biased because facial approximation practitioners are generally enthusiastic about their work (Stephan, 2003a). Stephan (2003a) points out that practitioners of the Manchester method have reported an increase in successful identification from around 55% (Prag & Neave, 1997) to 75% (Wilkinson, & Whittaker, 2002) without a described change in technique.

Stephan appears to be the harshest critic within the field, concluding that practitioners are attempting to illegitimately gain credibility by employing "discliplinary politics" (Stephan, 2003a). According to Stephan (2003a), if improvements are to be made to the field the current weaknesses must be addressed and new directions be established.

Conclusion

Despite the substantial technical maturation displayed by the field of forensic facial reconstruction, current methods of approximating facial surfaces from underlying bones are less than ideal. Furthermore, the current foundation for craniofacial reconstruction has been brought under question (Stephan, 2003). Although various original and contemporary methods have been impressive in their results and computational complexity, it has been concluded that not all soft tissue data can be extrapolated from the hard tissue shape alone (Halazonetis, 2005). The inaccuracies inherent in current methods of facial approximation warrant the exploration of new estimation based methods, particularly those which may be employed by laypersons in forensic identification efforts.

In this project a new method for facial approximation is outlined. The method is based on facial characterization using lateral cephalometric measurements that are commonly used in the field of orthodontics, a branch of dentistry concerned with the correction of dental malocclusion and dentofacial orthopaedics (Graber, Vanarsdall, & Vig, 2011).

Chapter 3: Methods and Materials

Overview

This study consists of generation of soft tissue approximations for unknown skulls using a match generation algorithm to find structurally similar skeletal matches within a database of orthodontic patients (Figure 3).

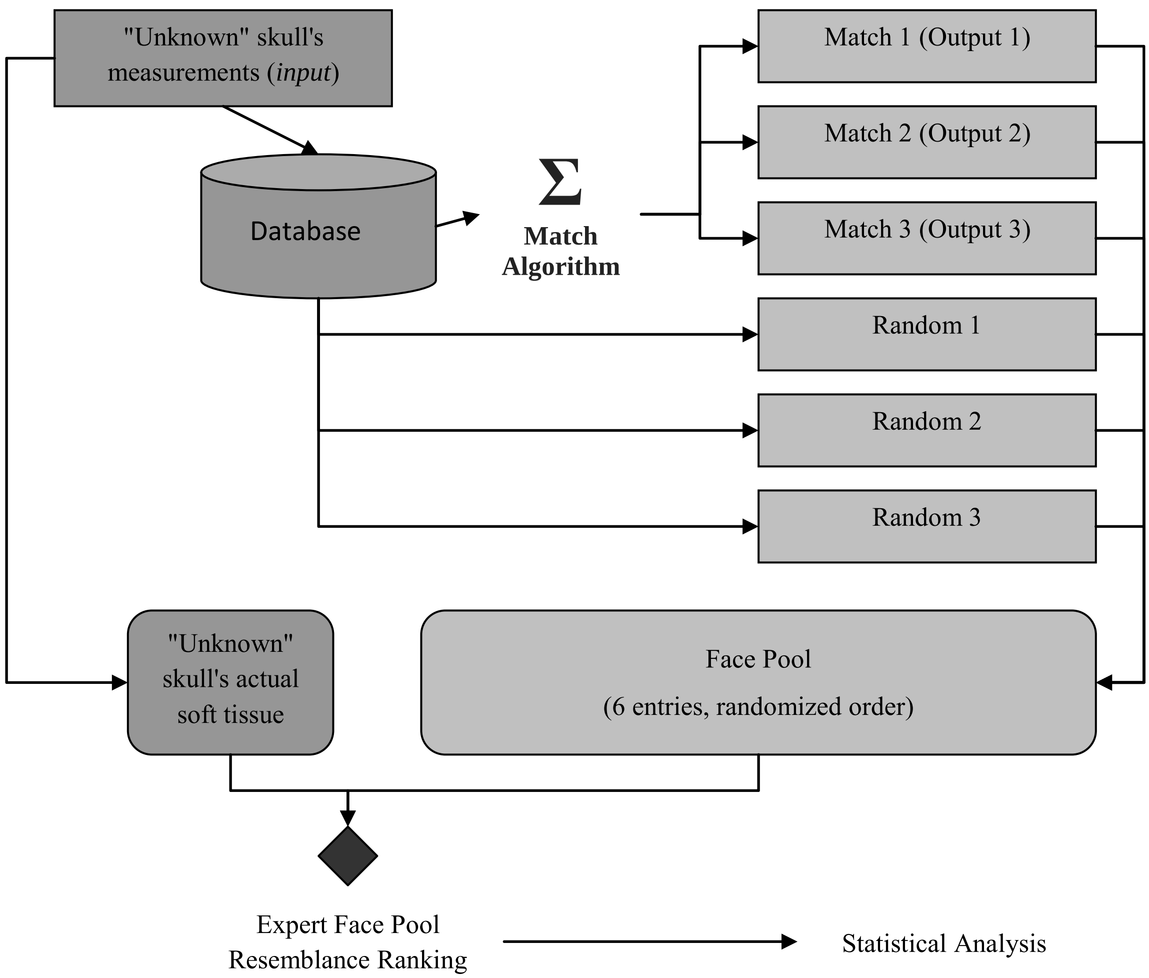

Figure 3- Overview of study design.

Study Population

A database consisting of one-hundred (100) cone-beam computed tomography (CBCT) skull images of Hispanic female patients of the University of Las Vegas, Nevada School of Dental Medicine Orthodontic Department [age range 8 to 23 years (mean 13.5 years, standard deviation 2.6 years)] was constructed. All CBCT scans were completed as part of the record taking process associated with orthodontic diagnosis and treatment planning. Proper consent was received from patients in regards to usage of their records for research purposes. Research protocol and consent forms were approved by the Office of Research Integrity – Human Subjects. Names were deleted to preserve the anonymity of the patients and entries were referenced using random numbers.

Previous studies have run into the problem of limited data for inclusion in their database. This is a result of limited access to medical three-dimensional images and the inability to capture skeletal information using laser scanners (Claes et al. 2010b). As a result, database sizes have consisted of less than 50 entries (Claes et al. 2010a; Tilotta et al. 2010; Wilkinson, 2010). The dental subspecialty of Orthodontics has recently increased use of CBCT imaging due to its superior diagnostic utility (Mah et al. 2011). The UNLV Orthodontic Department has a substantial archive of CBCT data for patients that have been treated for dental malocclusion.

Using a database with anthropologic homogeneity is justified because historically, craniofacial approximation is conducted after a biological profile (age, sex, ethnicity, etc.) has been established using all relevant forensic anthropological methods (Claes et al. 2010b). This age group was selected because it encompasses a period of intense growth and development of the craniofacial complex, when the interrelationship between hard and soft tissue shapes should be particularly close, without the added variability of the aging effects in adults (Halazonetis, 2005).

It was assumed that each entry was correctly categorized with respect to gender and ethnicity (Hispanic) since these are self reported. Also, it was assumed that the unknown skull has been correctly aged since age is also self reported.

Data Collection

For the facial reconstruction portion of this project twelve cephalometric landmarks were recorded (Figure 4). Twelve landmarks were also recorded for each skull for the purpose of sex determination, as described first by Hsiao, Chang, & Liu (1996) (Table 4). It is noteworthy to mention that these twelve landmarks are a subset of the original landmarks explored by Hsiao, Chang, & Liu (1996). However, Veyre-Goulet, Mercier, Robin, & Guerin (2008) duplicated the methods of Hsiao, Chang, & Liu (1996) using a subset of landmarks and maintained a 98% accuracy in correct sex determination. The measurements used by Veyre-Goulet, Mercier, Robin, & Guerin (2008) correspond precisely to the measurements used in the present study.

The work of Veyre-Goulet, Mercier, Robin, & Guerin (2008) was beneficial to this study because CBCT imaging devices are able to restrict their exposure area to a particular field of view and the entire skull image is not necessary for orthodontic imaging. As a result, posterior and super areas of the skull were not present in the CBCT images that were available for use in this study. Of the 100 total skulls in the database, 27 had a field of view that included data for the frontal sinus, glabellar process, and the mastoid

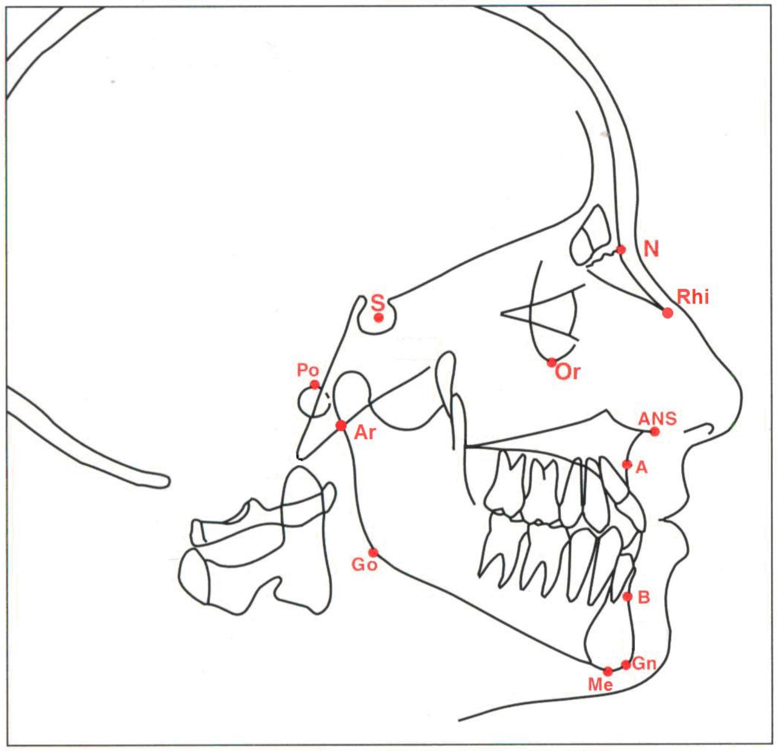

Figure 4 – Cephalometric landmarks used in study for facial reconstruction. Modified from (A. Jacobson & R. L. Jacobson, 2006, p. 78).

process regions of the skull. Sex determination data was collected for this subset of the database skulls.

Also related to the limited field of view present in this sample of CBCT radiographs was the absence of bregma (on the superior aspect of the skull) (Figure 5). This structure was estimated from the superior curvature of the anterior portion of the frontal bone that was present in the CBCT data. This estimation was necessary because the locations of H_1 and H_2 require knowledge regarding the position of bregma (Table 4).

All landmarks were recorded by a third year orthodontic resident using the three-dimensional cephalometric tracing plug-in of the InVivo medical imaging software package (Anatomage, San Jose, Calif). The first 50 skulls were retraced after a two week interval to establish intraobserver reliability.

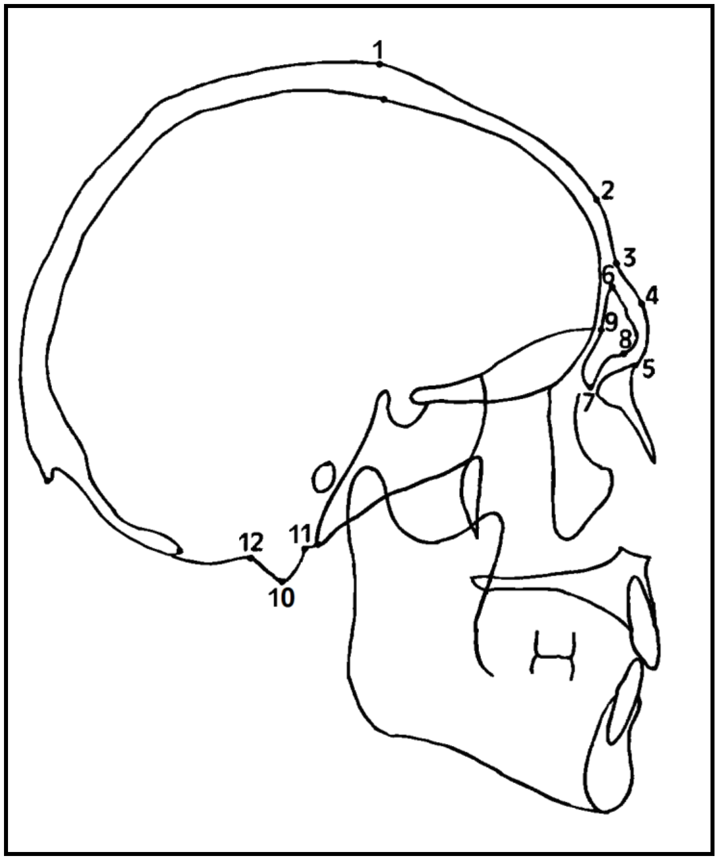

Figure 5 – Cephalometric landmarks used in study for sex identification.
1. Bregma, 2. Metopion, 3. Supraglabellare, 4. Glabella, 5. Nasion, 6. V_1, 7. V_2, 8. H_1, 9. H_2, 10. Mastoidale, 11. B_1, 12. B_2. Modified from (Hsiao, Chang, & Liu, 1996).

Cephalometric Analysis

Research on facial perception has suggested that the individual identity of a face is a function of the scale, position, and ratio of facial features relative to each other (De Greef and Willems, 2005). In an attempt to characterize the features of the face in this regard, a novel cephalometric analysis was applied on each lateral cephalogram in the database. For purposes of facial approximation a set of nineteen cephalometric measurements was defined. This analysis was based on the Björk-Jarabak facial polygon cephalometric analysis (Figure 6), however it was augmented with an amalgamation of

Landmark	Name	Description
Facial Reconstruction		
N	Nasion	Most anterior aspect of fronto-nasal suture.
S	Sella	Midpoint of sella turcica (hypophyseal fossa).
A	Subspinale	Most posterior point in concave anterior maxillary border.
B	Supramentale	Most posterior point in concave anterior mandibular border.
Ar	Articulare	Intersection of the posterior ramus of mandible with the cranial base.
Go	Gonion	Most posterior inferior point on angle of mandible.
Me	Menton	Inferior border of the symphysis of the mandible.
Gn	Gnathion	Midpoint between anterior and inferior points of chin.
ANS	Anterior Nasal Spine	Anterior tip of the nasal spine.
Or	Orbitale	Lowest point of the infraorbital rim.
Po	Porion	Most superior point of external auditory meatus.
Rhi	Rhinion	Most anterior point of nasal bone.
Sex Determination		
Ma	Mastoidale	Lowest point of the mastoid process.
B1	–	Anterior parameter of the mastoidal width at the level of cranial base.
B2	–	Posterior parameter of the mastoidal width at the level of cranial base.
Sg	Superglabellare	Most posterior midline point in the supraglabellar fossa, the concavity between glabella and metopion.
M	Metopion	Point where the line that connects the highest points of the frontal eminences crosses the sagittal plane.
G	Glabella	Most anterior point in the midsagittal plane between the superciliary arches.
V1	–	Upper parameter of the frontal sinus cavity.
V2	–	Lower parameter of the frontal sinus cavity.
H1	–	Anterior parameter of the frontal sinus cavity on bregma to nasion line, the line from the inner location of bregma to nasion.
H2	–	Posterior parameter of the frontal sinus cavity on bregma to nasion line.

Table 4 – Cephalometric landmarks used in study. Modified from (Hsiao, Chang, & Liu, 1996; Jacobson & Jacobson, 2006).

measurements defined in several other classic orthodontic cephalometric analyses (Steiner, 1953; Downs, 1956; Björk, 1969; Jarabak, 1972). Furthermore, several methods used in the literature to estimate soft tissue nasal shape as described by Rynn, Wilkinson, & Peters (2010) were incorporated into this analysis (Table 5a).

Methods that consisted of linear measurements between two nasal structures (e.g. between N and ANS) were modified into a novel angular form by converting these

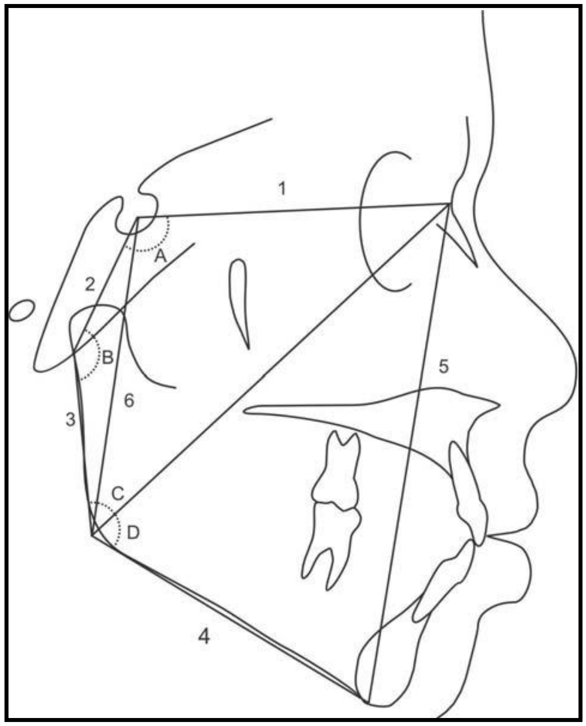

Figure 6 – Cephalometric measures adapted from Björk-Jarabak analysis. A. N-S-Ar (saddle angle); B. S-Ar-Go (articular angle); C. Ar-Go-N (upper gonial angle); D. N-Go-Me (lower gonial angle). Linear measurements: 1. S-N (anterior cranial base); 2. S-Ar (posterior cranial base); 3. Ar-Goc (posterior face height); 4. Go-Me (mandibular plane angle); 5. N-Me (anterior facial height) 6. S-Go (posterior face height) (from Kuramae, Magnani, Boeck, & Lucato, 2007).

measurement into an angle measured with sella at the vertex (e.g. N-S-ANS). This modification reflects the fact that in this study the size and projection of the nose relative to the size of the face is more important than the actual linear size of the nose itself. The complete cephalometric analyses are presented in Tables 5a and 5b. An actual three-dimensional tracing example from the database is presented in Figure 7. Examples of the measurements used for sex identification are shown in Figures 8a and 8b. All measurements and images were captured using the three-dimensional cephalometric tracing plug-in of the InVivo medical imaging software package version 5.0 (Anatomage, San Jose, Calif).

Measure	Type	Descriptor
Björk-Jarabak Analysis		
N-S-Ar	angle (three points)	Saddle angle.
S-Ar-Go	angle (three points)	Articular angle.
Ar-Go-N	angle (three points)	Upper gonial angle.
N-Go-Me	angle (three points)	Lower gonial angle.
N-S / S-Ar	ratio (two distances)	Anterior versus posterior cranial base length.
N-Me / S-Go	ratio (two distances)	Anterior versus posterior face height .
N-ANS / ANS-Me	ratio (two distances)	Upper versus lower face height.
Steiner Analysis		
S-N-A	angle (three points)	Cranial base (S-N) to anterior maxilla.
S-N-B	angle (three points)	Cranial base (S-N) to anterior mandible.
A-N-B	angle (three points)	Anterior maxilla relative to anterior maxilla via nasion.
SN-GoGn	angle (between lines)	Cranial base (S-N) to mandibular plane (Go-Gn).
U1-SN	angle (between lines)	Upper incisor angulation to cranial base (S-N).
IMPA	angle (between lines)	Lower incisor angulation to mandibular plane (Go-Me).
Downs Analysis		
FMA	angle (between lines)	Frankfort horizontal (Po-Or) to mandibular plane (Go-Me).
Nasal Approximation		
S-N-Rhi	angle (three points)	Cranial base (S-N) to rhinion.
Rhi-S-A	angle (three points)	Rhinion projection estimate.
N-S-ANS	angle (three points)	Nasal aperture size estimate via ANS.
N-S-A	angle (three points)	Nasal aperture size via anterior maxilla.
N-ANS-Rhi	angle (three points)	ANS projection versus rhinion projection.

Table 5a - Cephalometric analysis used in study for facial approximation.

Measure	Type	Descriptor
G-Sg-N	linear distance	Glabella to supraglabellare-nasion line distance.
MaHt	linear distance	Mastoid height from cranial base (Ma to B_1-B_2 line).
Sg-G-M	linear distance	Supraglabellare to glabella-metopion line distance.
FSHt	linear distance	Frontal sinus height (V_1-V_2 distance).
G-M-S-N	angle (between lines)	Angle between glabella-metopion line and cranial base (S-N).
MaWd	linear distance	Mastoid width at the level of cranial base (B_1-B_2 distance).
GPI	proportion (linear distance)	Glabella projection index = (glabella to supraglabellare-nasion line) x 100 ∕ (supraglabellare-nasion distance).
FSWd	linear distance	Frontal sinus width on bregma to nasion line (H_1 to H_2 distance).

Table 5b - Cephalometric analysis used in study for sex identification.

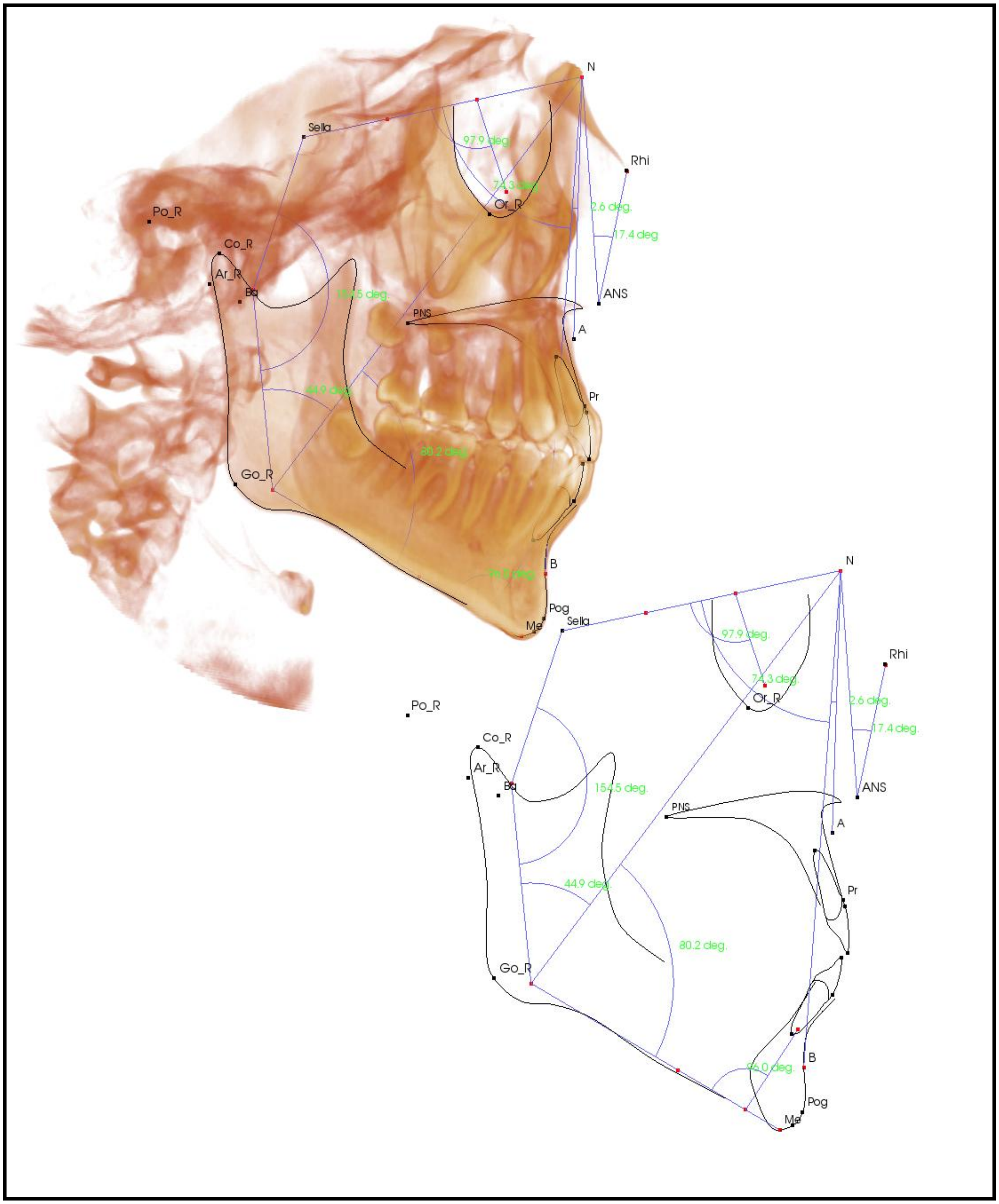

Figure 7 - Example three-dimensional cephalometric tracing. InVivo medical imaging software package (Anatomage, San Jose, Calif).

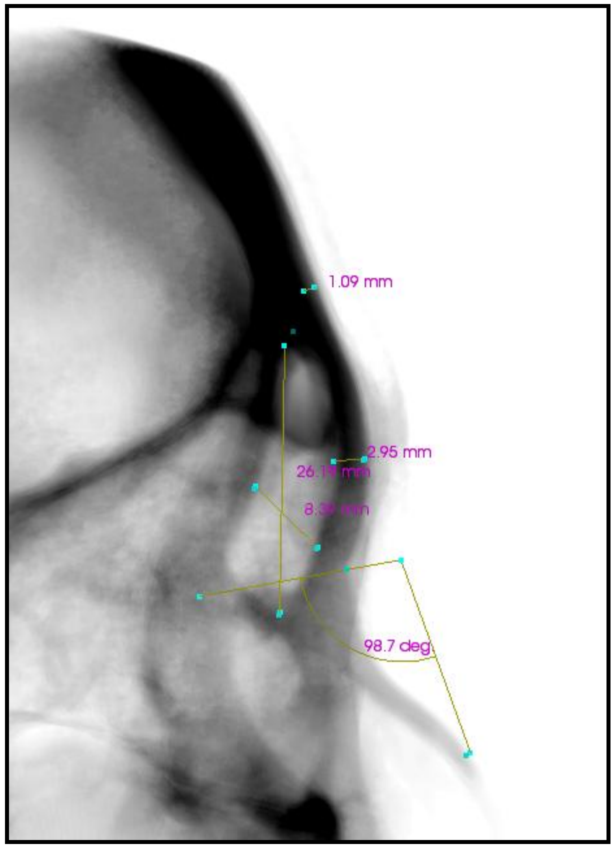

Figure 8a - Example frontal sinus and glabellar projection measurements. Used in sex identification portion of cephalometric analysis.

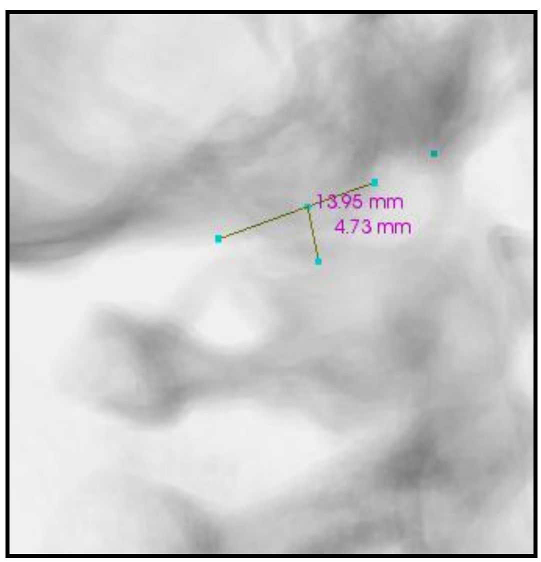

Figure 8b - Example mastoid process measurements. Used in sex identification portion of cephalometric analysis.

Database Search Algorithm

A leave-one-out cross-validation scenario was applied to the database by selecting a random entry, removing this entry, and defining it to be the unknown skull (*α)*. To establish a measure of cephalometric similarity, the unknown skull's cephalometric data was related to each skull in the database (β_x) by applying a weighted least-sum-of-squares (WLSS) regression algorithm (Figure 9) (Fox, 2008). This algorithm can be conceptualized as a generalized version of the Pythagorean theorem. Instead of finding the distance between two points in two-dimensional or three-dimensional space, the WLSS algorithm functions in a generalized vector space. Thus, it plots the unknown skull at the origin and calculates a distance between this origin and each skull in the database as a function of cephalometric data.

Lastly, the algorithm is *weighted* so that each cephalometric measurement is given a controlled amount of influence on the calculated distance (Table 6). An example of a high-weight measurement is Sella-Nasion-Rhinion, which is thought to estimate the angle of the nasal bridge relative to the cranial base. An example of a low-weight measurement is U1-Sella-Nasion (U1-SN), the angle of the upper central incisor relative to the cranial base. In this project weights were assigned according to the findings of Halazonetis (2007) which indicated that skeletal landmarks contained in the forehead, nasal, and chin areas contributed most to soft tissue profile shape. Landmarks in the cranial base and posterior mandibular area were of second order in terms of influence on soft tissue shape, followed lastly by the effects of dentition (Halazonetis, 2007). The output of the algorithm is the assignment of a score to each database entry. This score can be conceptualized as a distance to the unknown skull such that a lower score signifies skeletal similarity to the unknown.

Measure	Rank	Weight	Scaled Weight
Björk-Jarabak Analysis			
N-S-Ar	1.0	1.0000	0.0750
S-Ar-Go	2.0	0.5000	0.0375
Ar-Go-N	2.0	0.5000	0.0375
N-Go-Me	2.0	0.5000	0.0375
N-S / S-Ar	1.0	1.0000	0.0750
N-Me / S-Go	1.5	0.6667	0.0500
N-ANS / ANS-Me	1.0	1.0000	0.0750
Steiner Analysis			
S-N-A	1.0	1.0000	0.0750
S-N-B	1.0	1.0000	0.0750
A-N-B	1.0	1.0000	0.0750
S-N-Go-Gn	1.5	0.6667	0.0500
U1-SN	2.0	0.5000	0.0375
IMPA	2.0	0.5000	0.0375
Downs Analysis			
FMA	1.5	0.6667	0.0500
Nasal Approximation			
S-N-Rhi	1.0	1.0000	0.0750
Rhi-S-A	3.0	0.3333	0.0250
N-S-ANS	2.0	0.5000	0.0375
N-S-A	2.0	0.5000	0.0375
N-ANS-Rhi	2.0	0.5000	0.0375

Table 6 - Weights used in WLSS algorithm. Weight = Rank/Sum of all ranks. Scaled Weight = Weight / Sum of all weights.

For each database entry β_x in database, $x \in [1,99]$ the similarity between the unknown skull (α) and β_x is defined as:

$$\sum_{i=1}^{19} \sqrt{W_i (M_{i\alpha} - M_{i\beta_x})^2}$$

Figure 9 – Weighted least-sum-of-squares (WLSS) algorithm used in this study. $i \in [1,19]$, corresponding to the 19 cephalometric measurements used in this study. W_i corresponds to weight for measurement *i*. $M_{i\alpha}$ and $M_{i\beta x}$ correspond to unknown skull (α) and database entry (β_x) cephalometric measurement *i*, respectively.

Accuracy Assessment

Reconstruction accuracy was qualitatively measured using a novel assessment method resembling a combination of face pool assessment and resemblance ratings into a novel "expert face pool resemblance ranking" assessment. A database entry was selected at random, removed from the database, and chosen for leave-one-out cross validation. Each "unknown" skull was then input into the database and the three best database matches were combined with three random entries from the database in random order to create a face pool of six entries (Figure 3, page 27). This process was repeated three times to produce three separate faces pools for three unknowns (Figures 10a-10c).

The profile views that collectively constitute each face pool were made using monochromatic CBCT-generated soft tissue profile renderings. The purpose of using a CBCT-generated rendering for this purpose instead of the profile photograph that is part of the orthodontic record taking process is to highlight the soft tissue aspect of recognition and minimize the recognizable effect of skin tone and hair (Claes et al, 2010b). Each CBCT-generated profile view was be scaled to uniform height to negate the effects of total facial height in the process of recognition.

Descriptive data regarding these face pools is shown in Table 7. These face pools were placed on a line below the known facial profile of the "unknown" skull selected for leave-one-out cross validation (Figures 10a-10c) and presented to 14 post-doctoral graduate students of the University of Las Vegas, Nevada School of Dental Medicine Orthodontic Department. Instructions were given to rank each entry in the face pool in order of resemblance to the face on the top line (the unknown skull's actual face) with a value of (1) signifying most and (6) signifying least similar.

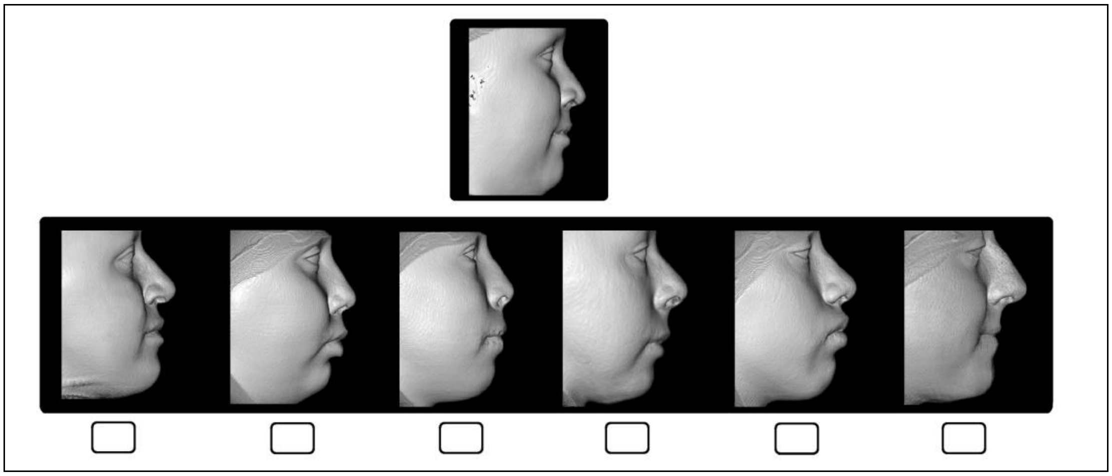

Figure 10a – Face Pool One.

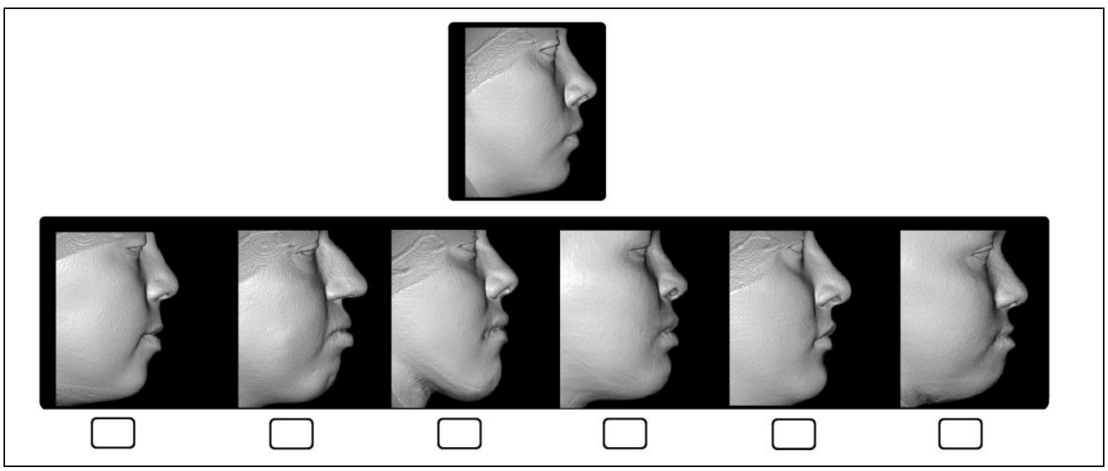

Figure 10b – Face Pool Two.

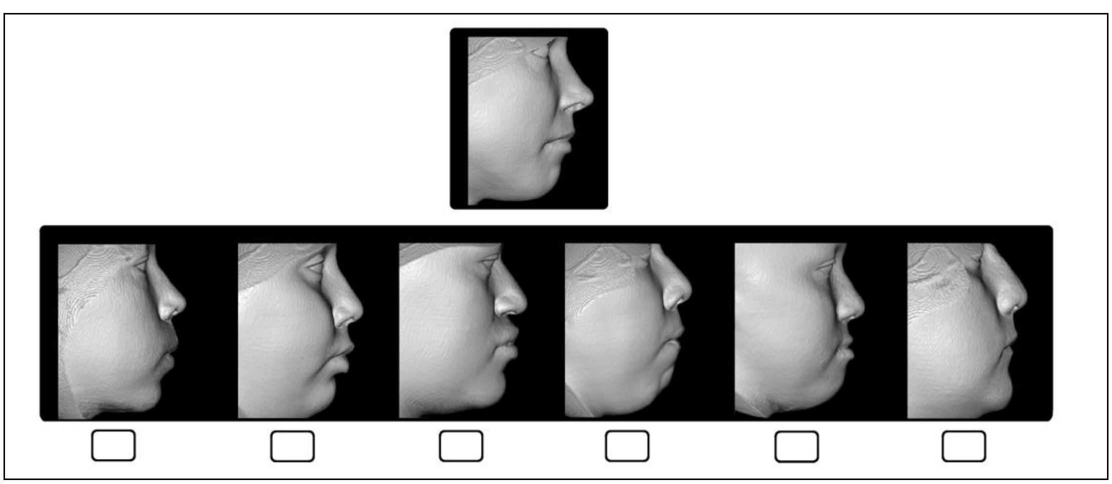

Figure 10c – Face Pool Three.

	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
	Face Pool One					
Algorithm rank:	∞	3	1	2	∞	∞
Algorithm score:	5.34	1.99	1.79	1.89	3.19	5.6
	Face Pool Two					
Algorithm rank:	3	∞	2	∞	1	∞
Algorithm score:	2.97	3.5	2.75	4.21	2.65	3.54
	Face Pool Three					
Algorithm rank:	1	3	∞	∞	2	∞
Algorithm score:	2.77	3.15	8.69	5.74	2.87	7.13

Table 7 – Rankings and algorithm scores for face pool entries. Faces 1-6 correspond to far left (1) through far right (6) in face pool. Algorithm scores and rank are relative and unique to unknown skull corresponding to face in top line of each face pool. A rank of ∞ indicate that this face was a random entry.

Statistical Analysis

To establish a measure of reliability for the cephalometric data the first 50 facial reconstruction measurements were retraced (T_1 - T_0 = 2 weeks). To establish reliability for the sex identification data all skulls with a sufficiently large field of view for sex identification (n = 27) were retraced (T_1 - T_0 = 2 weeks). Intraclass correlation coefficient (ICC), 2-way mixed, single measures were completed in SPSS version 20.0 (SPSS Inc, Chicago, IL). The following levels were defined: 0.90 to 0.99 was considered as strong reliability, 0.80 to 0.89 as good, 0.70 to 0.79 as fair, and less than 0.69 as poor (Morphett, Crawford, & Lee, 2003). In this study an ICC was considered acceptable if it had a fair rating (0.70-0.79) or greater.

For comparison between this study's sex identification cephalometric data and the values reported for Taiwanese adult females reported by Hsiao, Chang, & Liu (1996) a qualitative comparison of means and variances was performed. More rigorous analysis was not possible due to a lack of raw data for previously reported results. Due to different expected means for anatomic measurements of individual ethnic groups this was not necessarily a shortcoming of the study (Hsiao, Chang, & Liu, 1996; Patil & Mody, 2005; Veyre-Goulet, Mercier, Robin, & Guerin, 2008).

Median and mode values were calculated for the nominal ranks recorded for each face in the expert face pool resemblance rankings and were juxtaposed with the ranks reported by the match algorithm (algorithm rank) (Table 7).

Summary

The method outlined in this study can be classified using the terminology described by Claes et al. (2010b). All skulls and soft tissues have been digitized using cone-beam computed tomography (CBCT). The craniofacial template (CFT) can be considered as multiple/specific because information from multiple faces is encoded in the database and each skull in the database forms a unique final approximation. As a result, multiple approximations can be made for each unknown skull.

Furthermore, the craniofacial information (CFI) is the cephalometric data belonging to each skull. This is how soft tissue is related to underlying skeletal structures. However, no attempt is made at emulating this relationship over an unknown skull. It is assumed that if the database is large enough and skull data is precisely matched to the unknown skull with respect to anthropologic factors, the most cephalometrically similar entry within the database will match the unknown person sufficiently well to induce recognition or otherwise facilitate a forensic investigation. Also, there is no craniofacial deformation (CFD) aspect to this project. The target skull representation is a CBCT soft tissue image corresponding to a skeletally similar skull in the database. Lastly, this study makes no attempt at texturing the resultant CBCT images to achieve human skin tones.

Chapter 4: Results

Intraexaminer Reliability

Intraclass correlation coefficient (ICC) scores for the facial reconstruction and sex identification cephalometric measurements are shown in Tables 8a and 8b. 17 out of 18 facial reconstruction measurements were considered as having strong reliability (greater than 0.90). One out of the 18 measurements exhibited lower levels of reliability. Namely, ANB scored a reliability score of 0.893. According to Morphett, Crawford, & Lee (2003) this corresponds to good reliability (0.80 to 0.89). All sex identification data exhibited strong reliability (greater than 0.90).

	Intraclass Correlation
SNA	0.981
SNB	0.979
ANB	0.893
S-N-Rhi	0.980
Upper Gonial Angle	0.961
Ant/Post cranial base	0.908
Ant/Post face height	0.959
N-S-A	0.958
N-ANS-Rhi	0.979
Articular Angle	0.942
Lower Gonial Angle	0.981
Upper/Lower Face Height	0.969
SN-GoGn	0.991
FMA	0.982
Rhi-S-A	0.945
N-S-ANS	0.951
U1 to SN	0.983
IMPA	0.988

Table 8a – Intraclass correlation coefficient (ICC) for facial reconstruction data.

	Intraclass Correlation
G-Sg-N	0.936
Sg-G-M	0.986
FSHt	0.986
G-M-S-N	0.972
MaWd	0.922
GPI	0.971
FSWd	0.972
MaHt	0.930

Table 8b – Intraclass correlation coefficient (ICC) for sex identification data.

Expert Face Pool Resemblance Ranking

Face pools (Figures 10a-10c) were presented to a group of 14 orthodontic postdoctoral graduate students of the University of Nevada, Las Vegas School of Dental Medicine Orthodontic Department. Evaluators were asked to rank the faces in the face pool in order of most (1) to least (6) resemblance to the prompt face. Results are shown in Tables 9a-9b. As previously described three of the faces in each face fool correspond to randomly chosen database entries and this is reflected in these figures by demarcation of their algorithm rank as ∞.

	Face Pool One					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
Expert Assessed Ranks (n = 14)	4	2	1	5	3	6
	5	3	1	2	4	6
	6	5	3	2	4	1
	5	3	2	1	4	6
	2	4	3	1	5	6
	5	2	1	3	6	4
	6	4	1	3	5	2
	6	5	4	1	3	2
	6	4	2	1	5	3
	5	4	3	1	6	2
	6	5	2	3	4	1
	5	4	1	2	6	3
	3	1	2	5	6	4
	2	5	6	1	4	3
Median assessed rank:	5.0	4.0	2.0	2.0	4.5	3.0
Mode assessed rank:	5	4	1	1	4	6
Algorithm rank:	∞	3	1	2	∞	∞
Algorithm score:	5.34	1.99	1.79	1.89	3.19	5.6

Table 9a – Expert face pool resemblance rankings for Face Pool One. Algorithm rank of ∞ signifies random database entry.

	Face Pool Two					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
Expert Assessed Ranks (n = 14)	1	2	6	5	3	4
	2	5	6	3	1	4
	1	6	5	3	2	4
	3	5	6	2	1	4
	2	4	5	3	1	6
	1	6	5	3	2	4
	1	3	6	2	5	4
	2	4	6	3	1	5
	1	5	6	2	3	4
	2	6	4	3	1	5
	1	5	6	2	3	4
	2	6	5	4	1	3
	1	6	4	3	2	5
	1	5	6	3	2	4
Median assessed rank:	1.0	5.0	6.0	3.0	2.0	4.0
Mode assessed rank:	1	5	6	3	1	4
Algorithm rank:	3	∞	2	∞	1	∞
Algorithm score:	2.97	3.5	2.75	4.21	2.65	3.54

Table 9b – Expert face pool resemblance rankings for Face Pool Two. Algorithm rank of ∞ signifies random database entry.

	Face Pool Three					
	Face 1	Face 2	Face 3	Face 4	Face 5	Face 6
Expert Assessed Ranks (n = 14)	2	1	3	4	5	6
	2	1	3	5	4	6
	4	5	3	2	6	1
	1	2	4	6	3	5
	1	2	6	3	5	4
	2	1	3	5	4	6
	2	1	5	6	3	4
	4	1	2	6	5	3
	2	1	4	6	3	5
	2	1	3	6	5	4
	2	1	5	6	3	4
	2	1	6	5	4	3
	1	2	4	6	3	5
	2	1	3	5	4	6
Median assessed rank:	2.0	1.0	3.5	5.5	4.0	4.5
Mode assessed rank:	2	1	3	6	3	6
Algorithm rank:	1	3	∞	∞	2	∞
Algorithm score:	2.77	3.15	8.69	5.74	2.87	7.13

Table 9c – Expert face pool resemblance rankings for Face Pool Three. Algorithm rank of ∞ signifies random database entry.

Expert face pool resemblance ranking data is presented in graph form in Figures 11a-11f, 12a-12f, and 13a-13f for Face Pools One, Two, and Three, respectively. Due to the nominal nature of this data descriptive statistics exploring central tendencies are not available. However, potentially interesting measures for this data are comparisons of median assessed rank, mode assessed rank, and algorithm rank. Figure 14 shows the sources (algorithm versus random) of the highest three ranked faces (with respect to modes) per face pool.

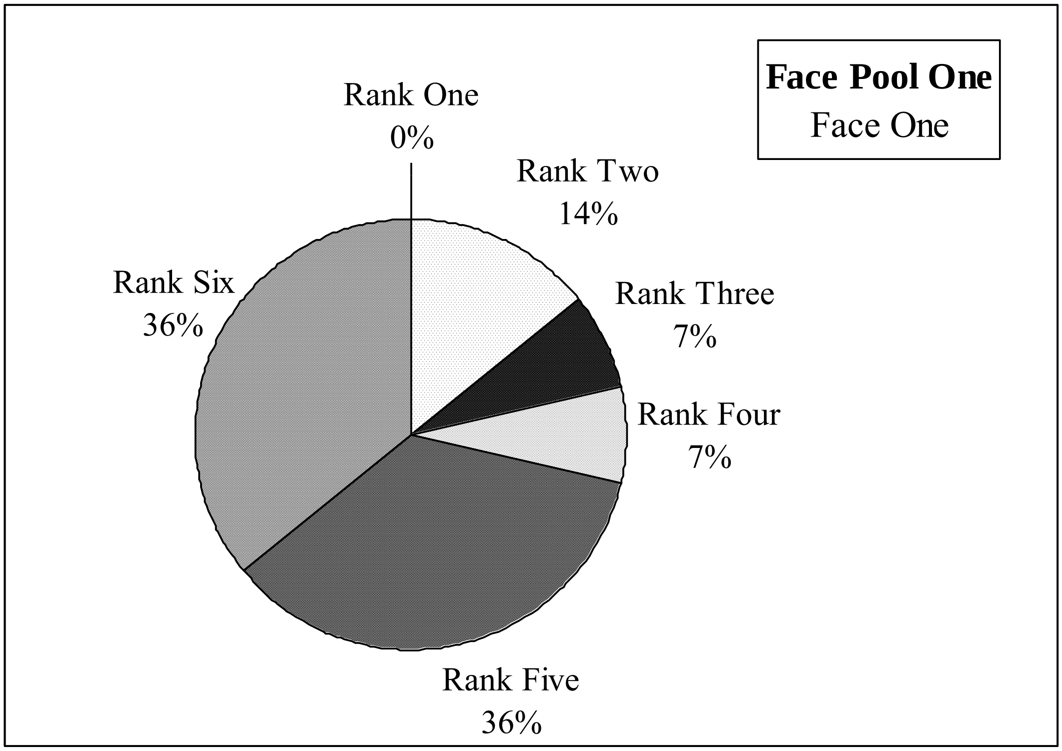

Figure 11a – Face Pool One - Face One - Expert resemblance rankings. [Median: 5, Mode: 5.5, Algorithm rank: ∞].

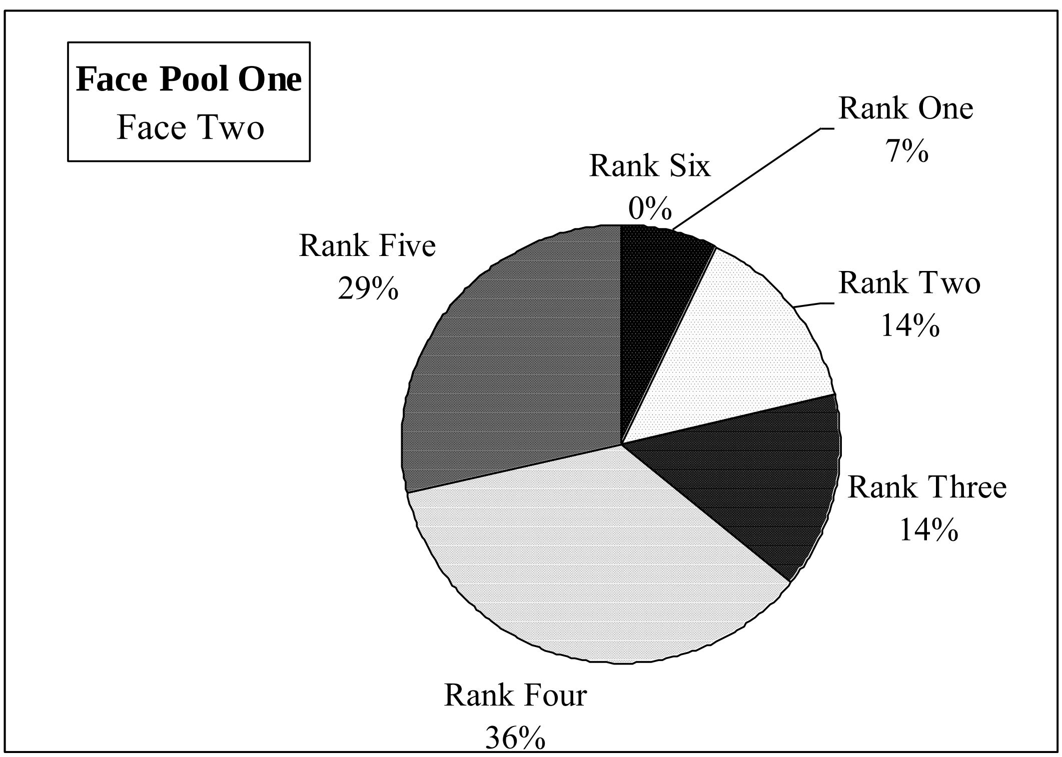

Figure 11b – Face Pool One - Face Two - Expert resemblance rankings. [Median: 4, Mode: 4, Algorithm rank: 3].

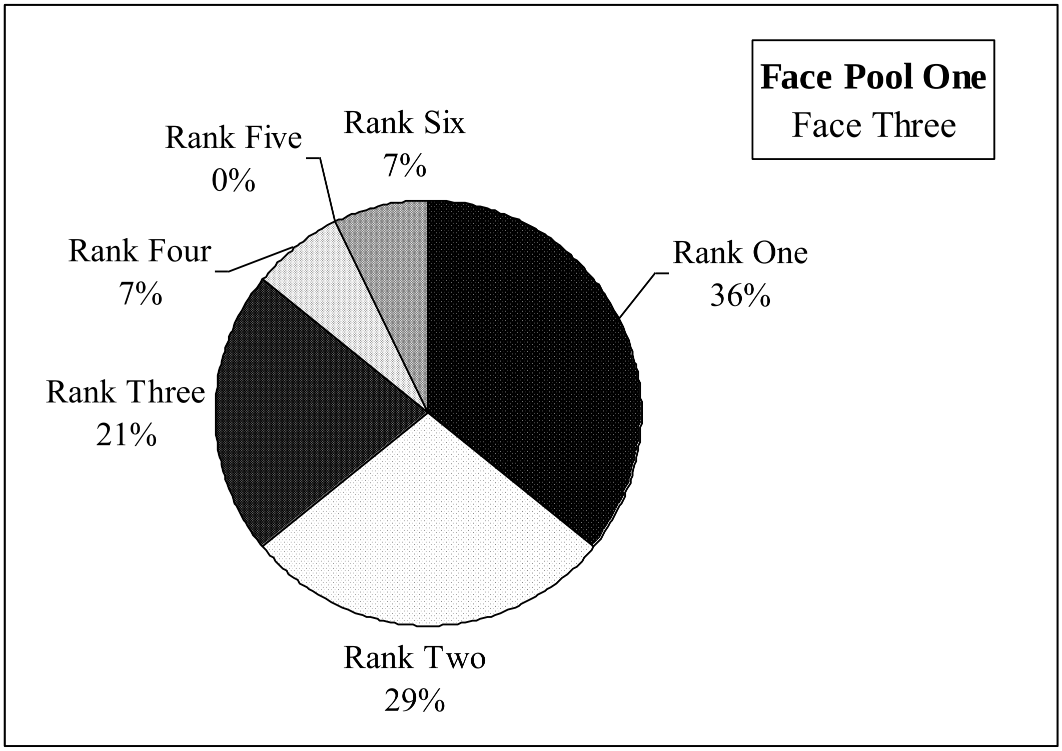

Figure 11c – Face Pool One - Face Three - Expert resemblance rankings. [Median: 2, Mode: 1, Algorithm rank: 1].

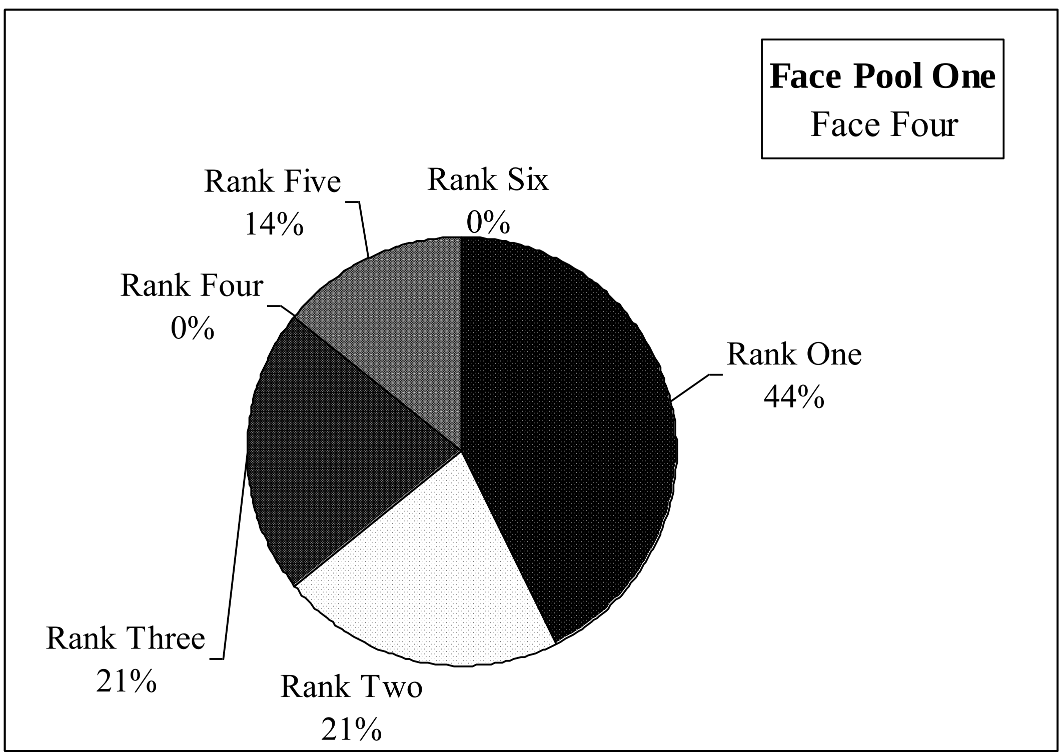

Figure 11d – Face Pool One - Face Four - Expert resemblance rankings. [Median: 2, Mode: 1, Algorithm rank: 2].

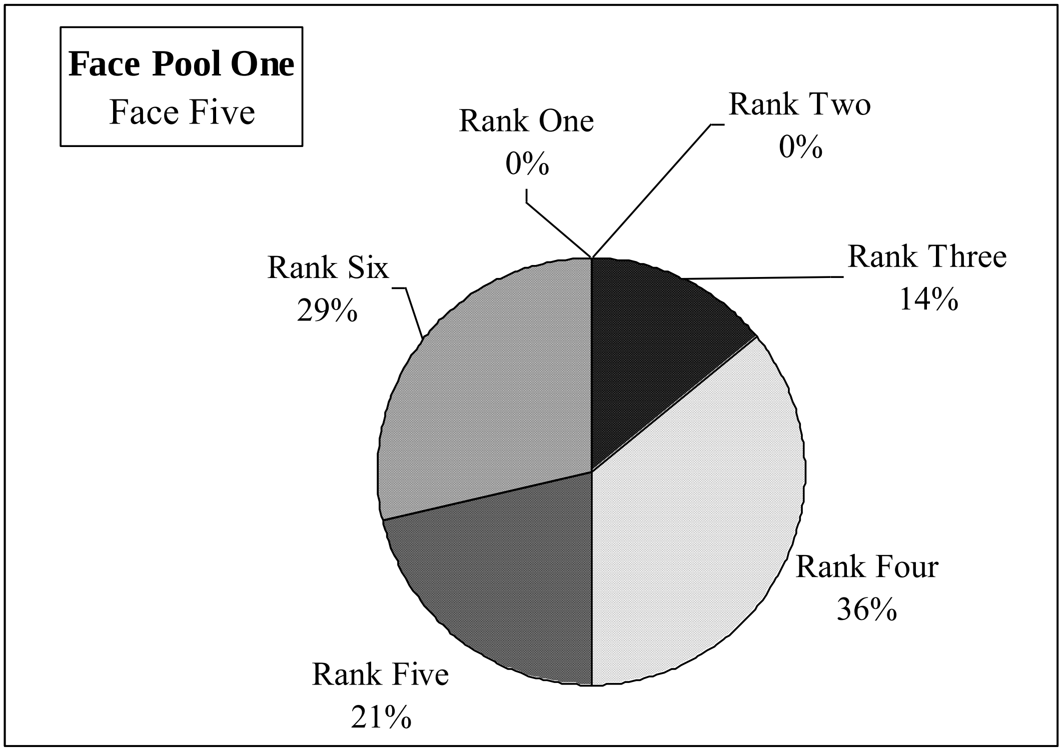

Figure 11e – Face Pool One - Face Five - Expert resemblance rankings. [Median: 4.5, Mode: 4, Algorithm rank: ∞].

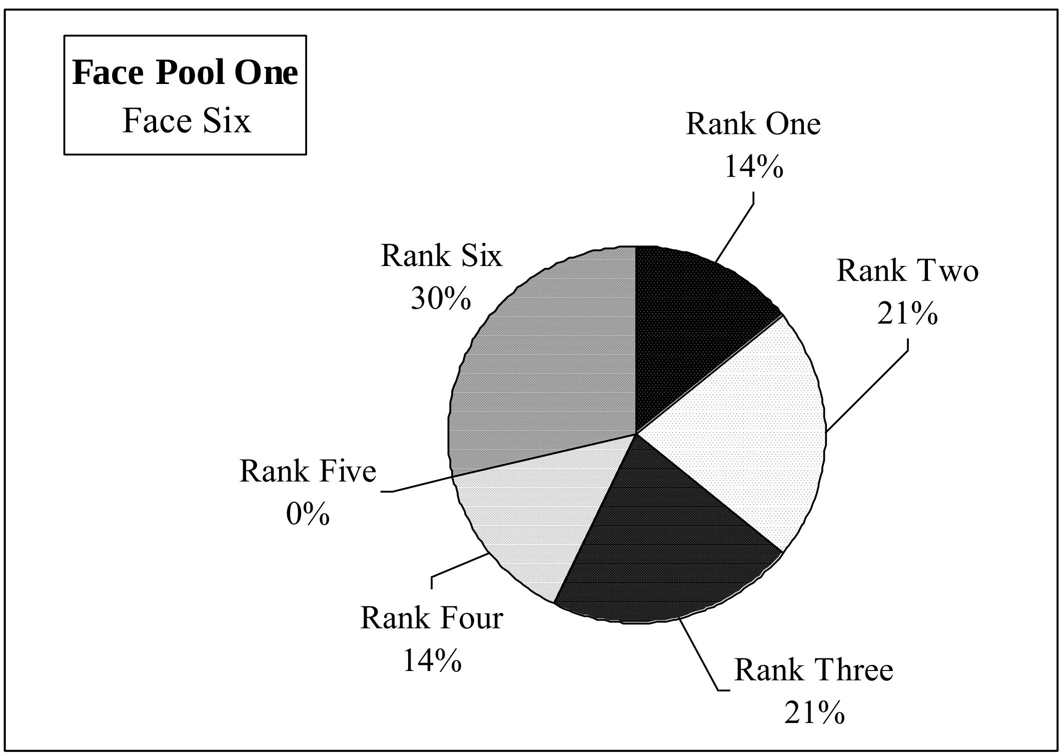

Figure 11f – Face Pool One - Face Six - Expert resemblance rankings. [Median: 3, Mode: 6, Algorithm rank: ∞].

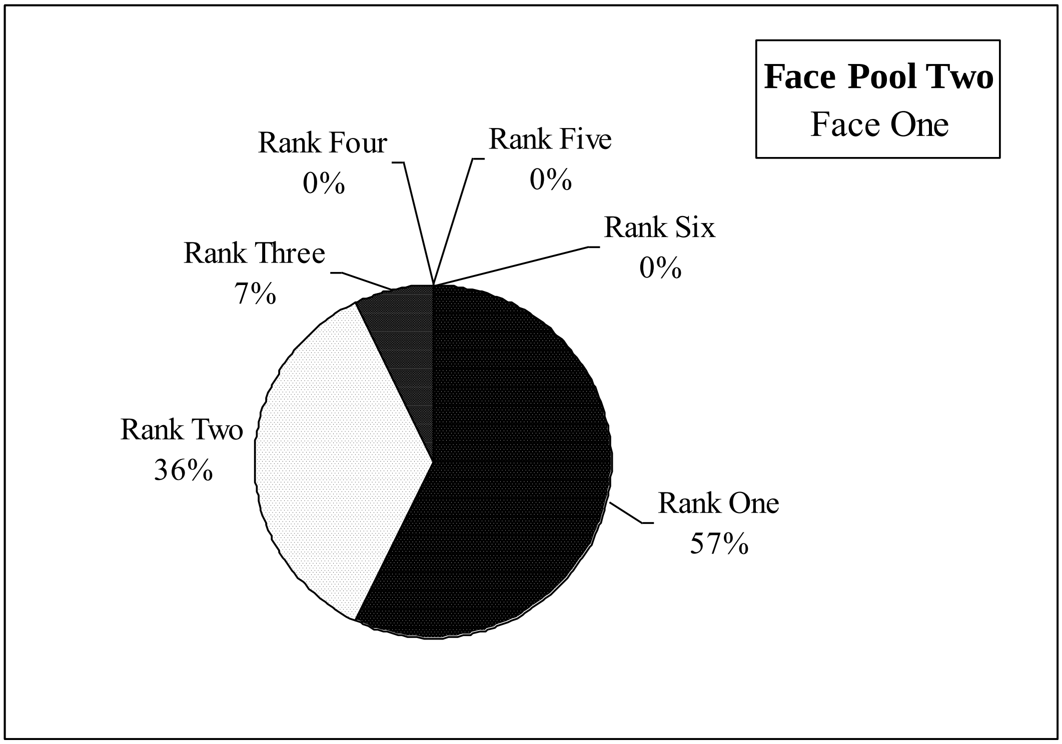

Figure 12a – Face Pool Two - Face One - Expert resemblance rankings. [Median: 1, Mode: 1, Algorithm rank: 3].

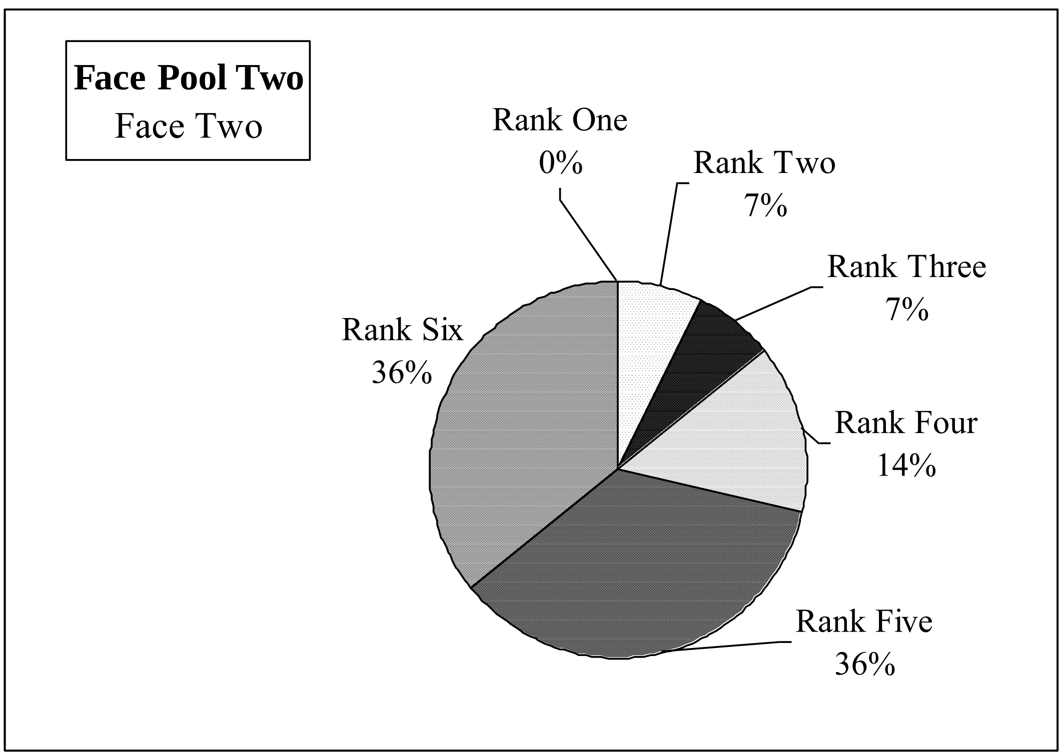

Figure 12b – Face Pool Two - Face Two - Expert resemblance rankings. [Median: 5, Mode: 5, 6, Algorithm rank: ∞].

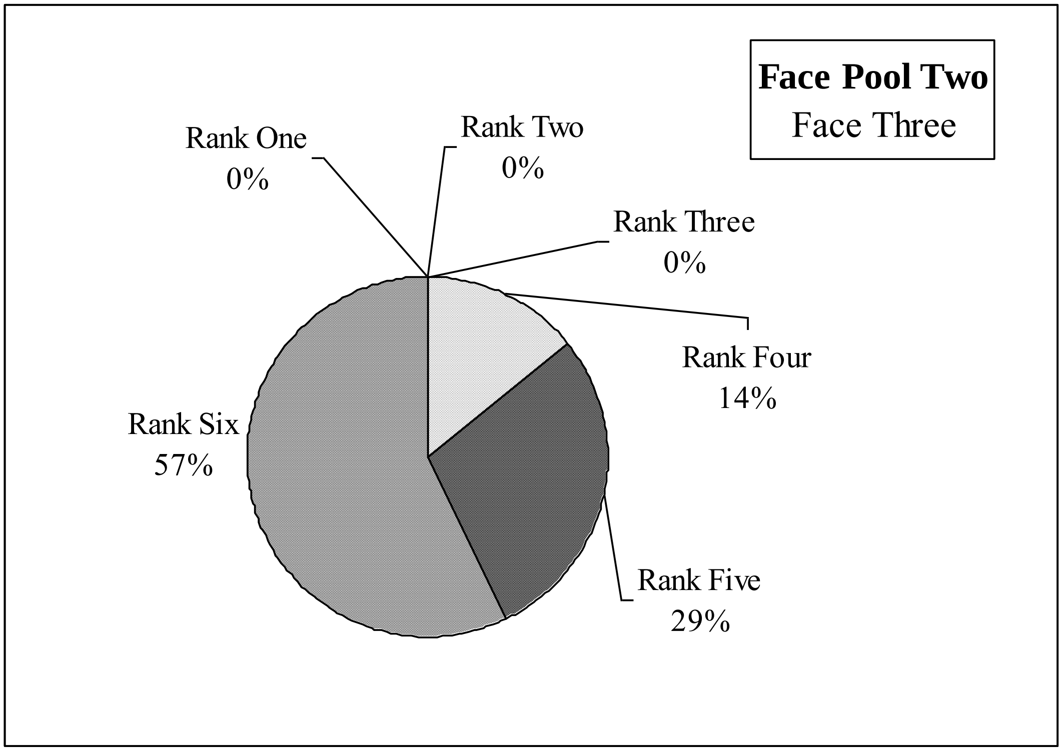

Figure 12c – Face Pool Two - Face Three - Expert resemblance rankings. [Median: 6, Mode: 6, Algorithm rank: ∞].

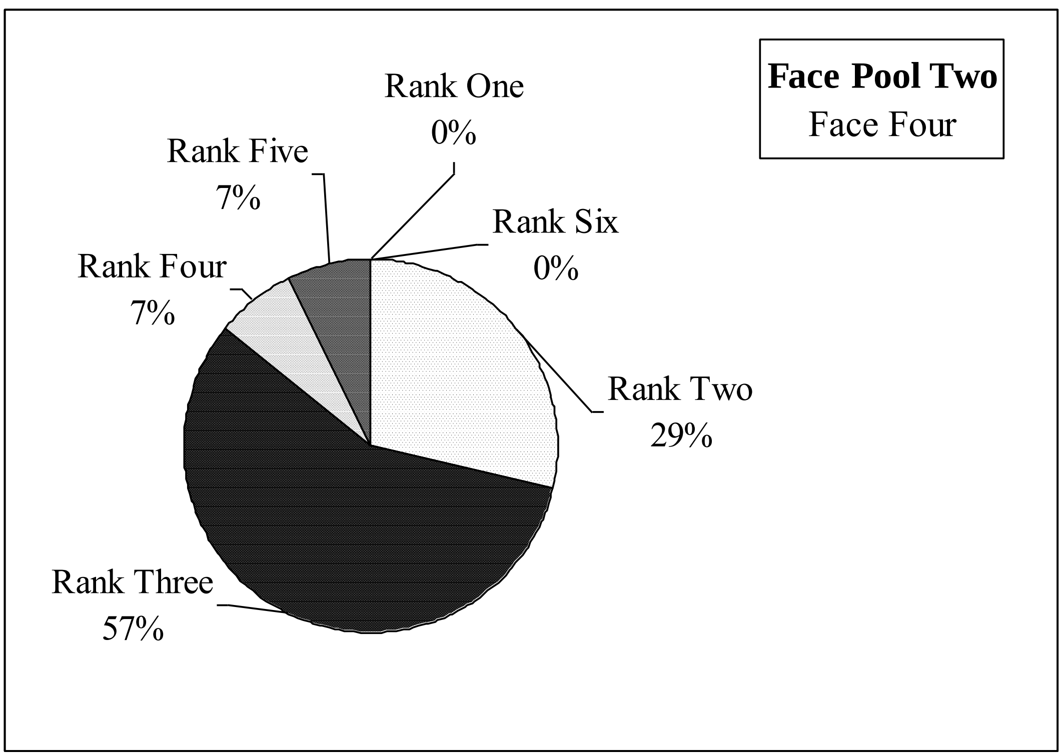

Figure 12d – Face Pool Two - Face Four - Expert resemblance rankings. [Median: 3, Mode: 3, Algorithm rank: ∞].

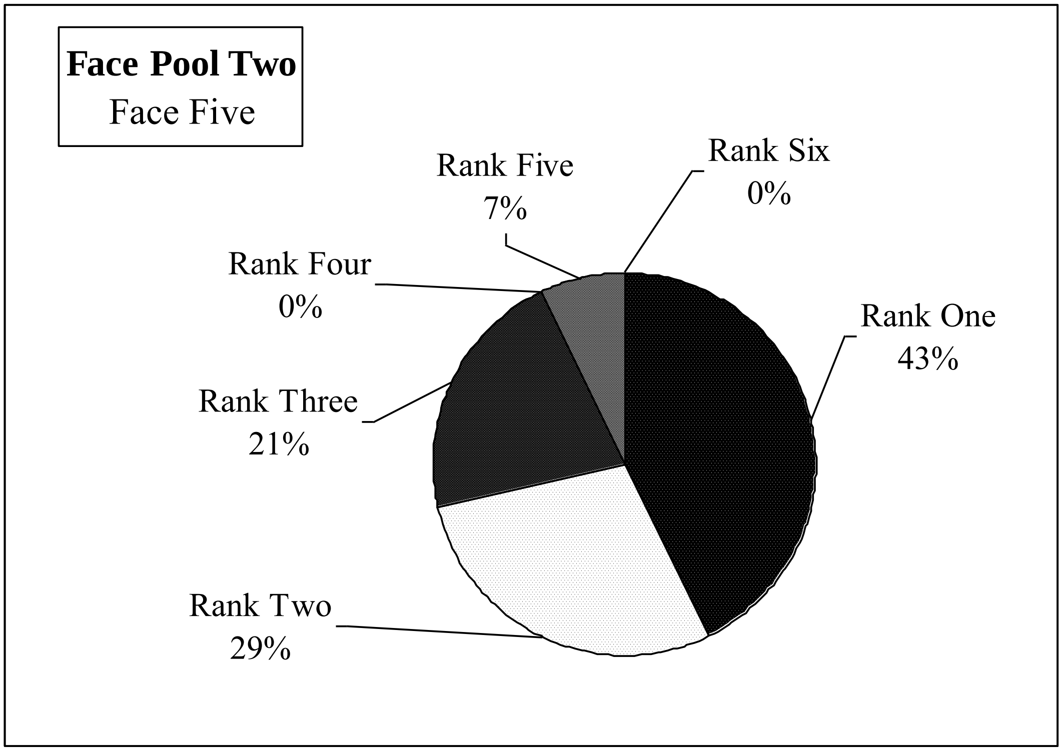

Figure 12e – Face Pool Two - Face Five - Expert resemblance rankings. [Median: 2, Mode: 1, Algorithm rank: 1].

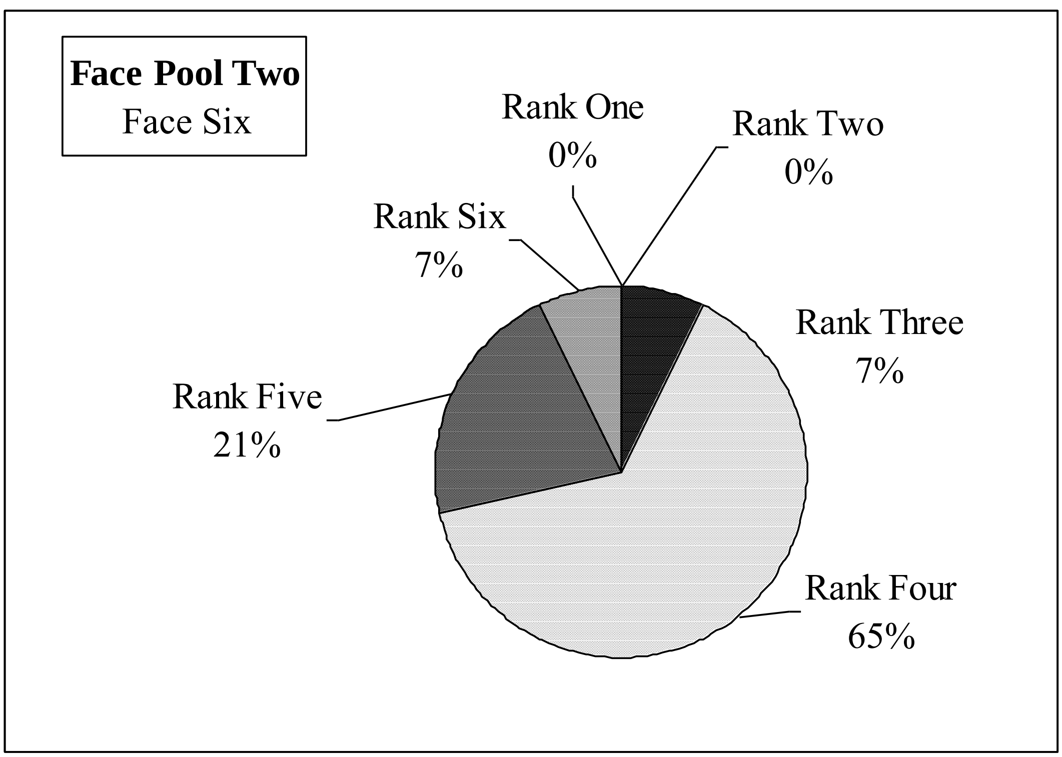

Figure 12f – Face Pool Two - Face Six - Expert resemblance rankings. [Median: 4, Mode: 4, Algorithm rank: ∞].

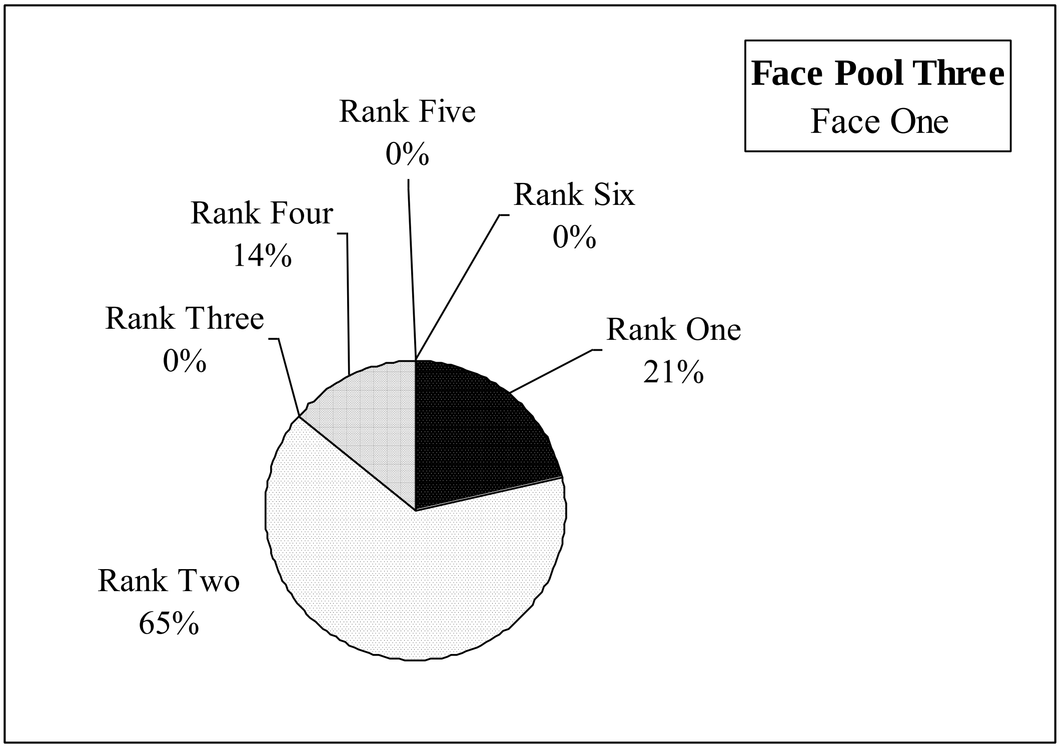

Figure 13a – Face Pool Three - Face One - Expert resemblance rankings. [Median: 2, Mode: 2, Algorithm rank: 1].

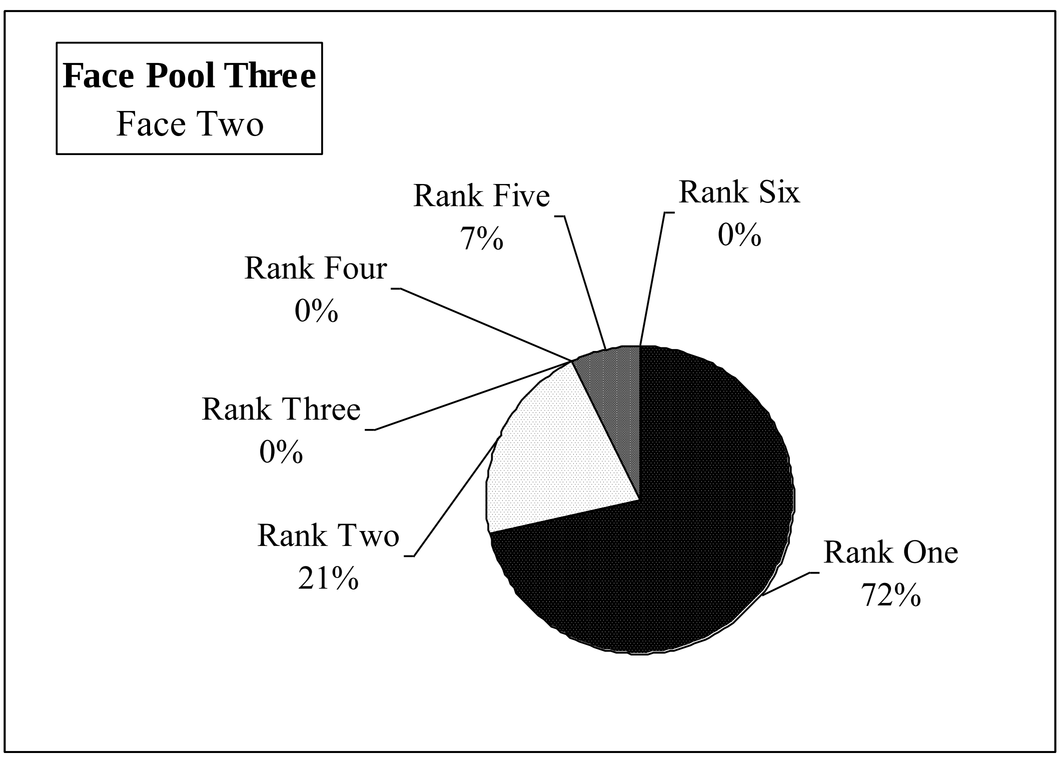

Figure 13b – Face Pool Three - Face Two - Expert resemblance rankings. [Median: 1, Mode: 1, Algorithm rank: 3].

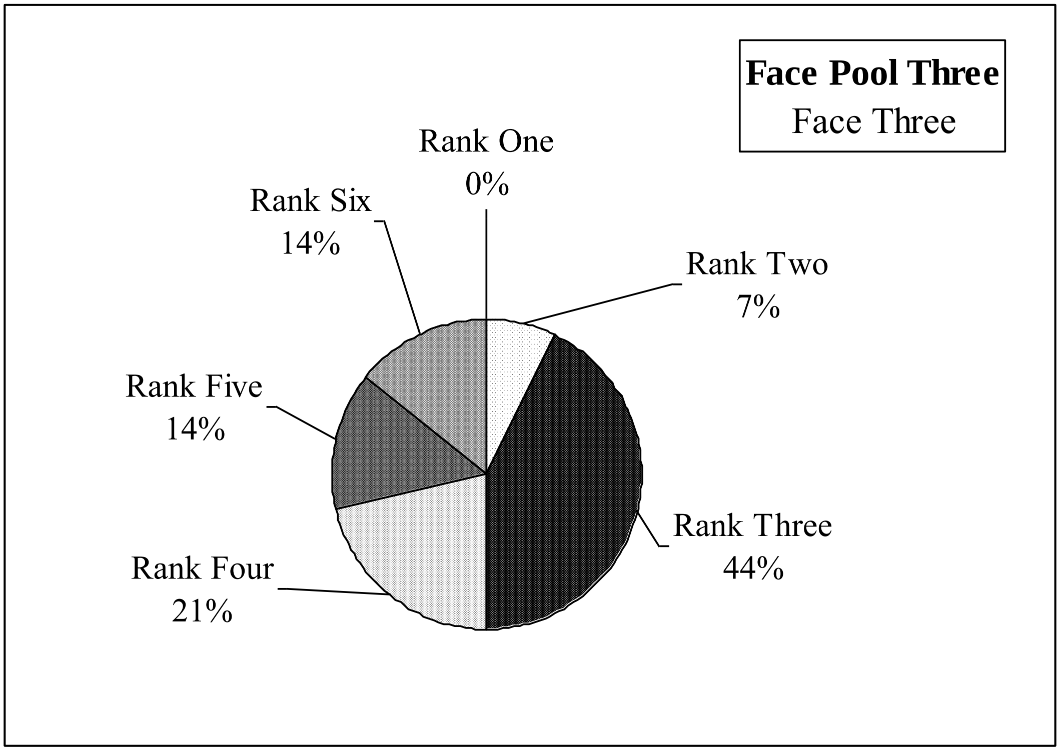

Figure 13c – Face Pool Three - Face Three - Expert resemblance rankings. [Median: 3.5, Mode: 3, Algorithm rank: ∞].

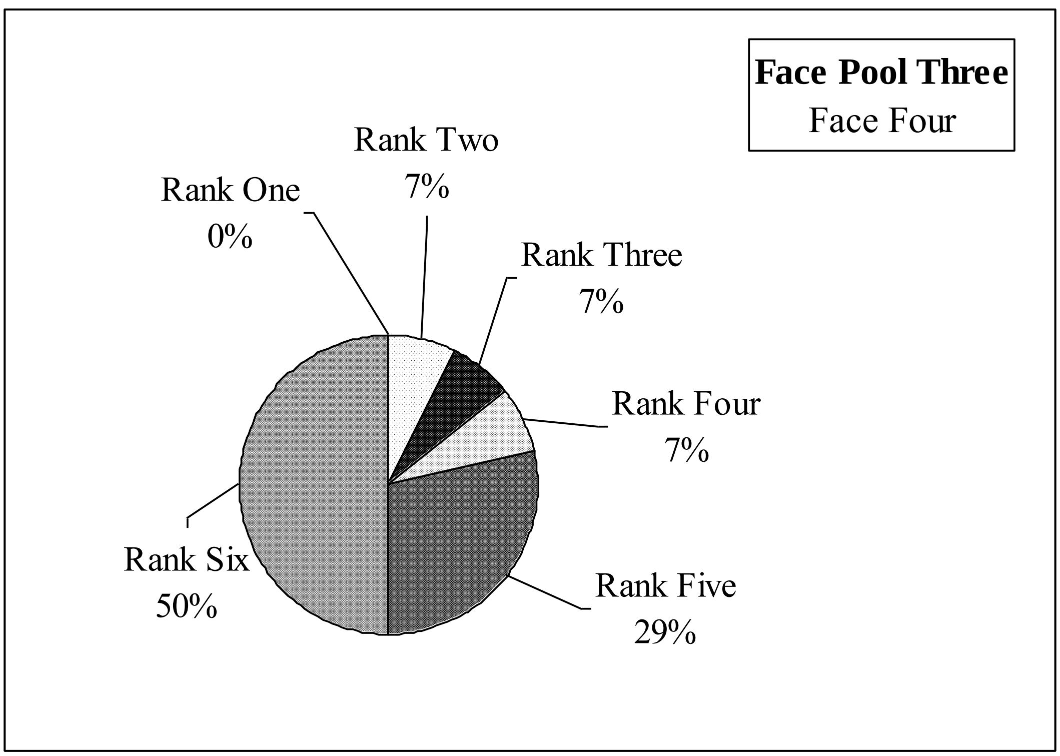

Figure 13d – Face Pool Three - Face Four - Expert resemblance rankings. [Median: 5.5, Mode: 6, Algorithm rank: ∞].

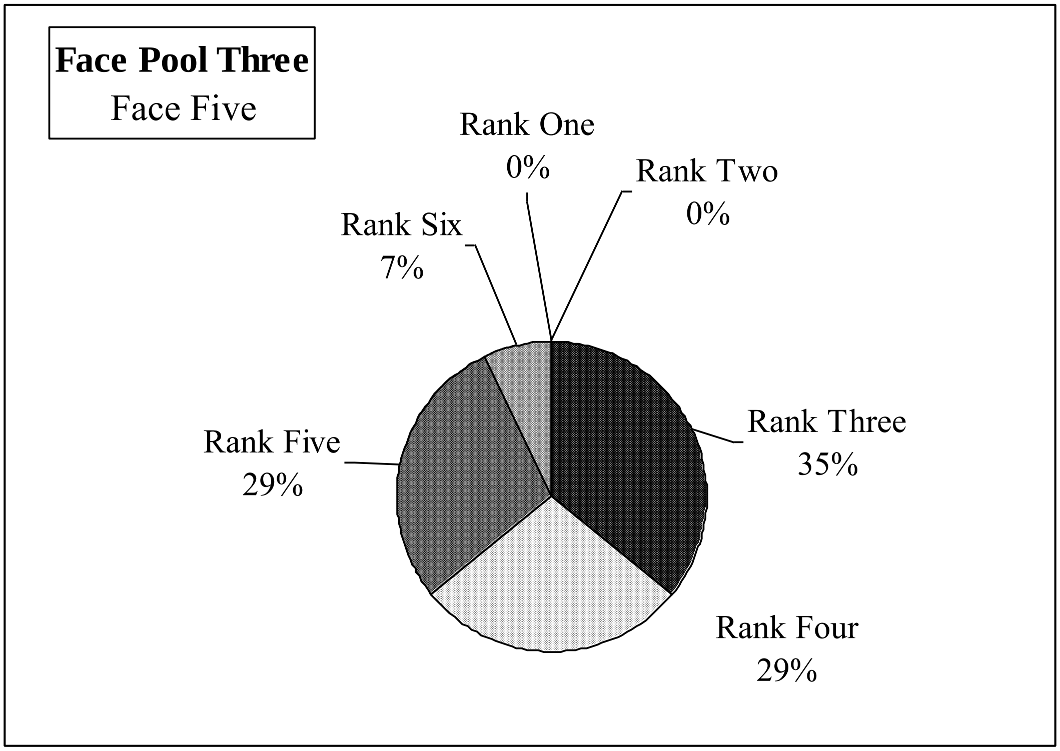

Figure 13e – Face Pool Three - Face Five - Expert resemblance rankings. [Median: 4, Mode: 3, Algorithm rank: 2].

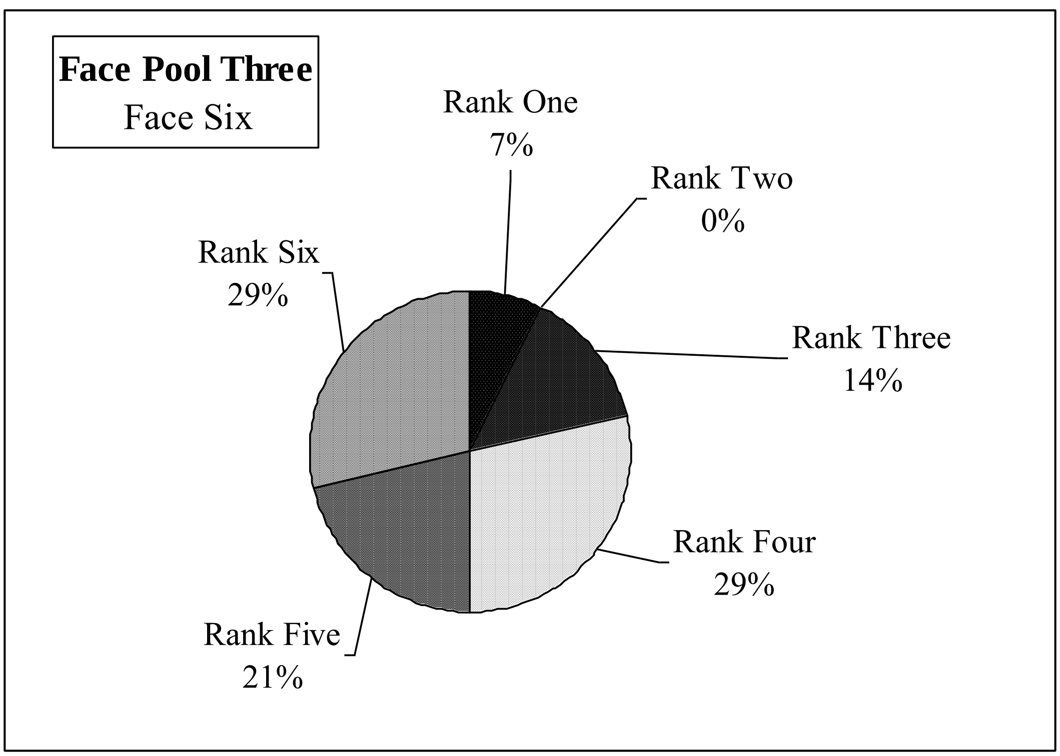

Figure 13f – Face Pool Three - Face Six - Expert resemblance rankings. [Median: 4.5, Mode: 4,6, Algorithm rank: ∞].

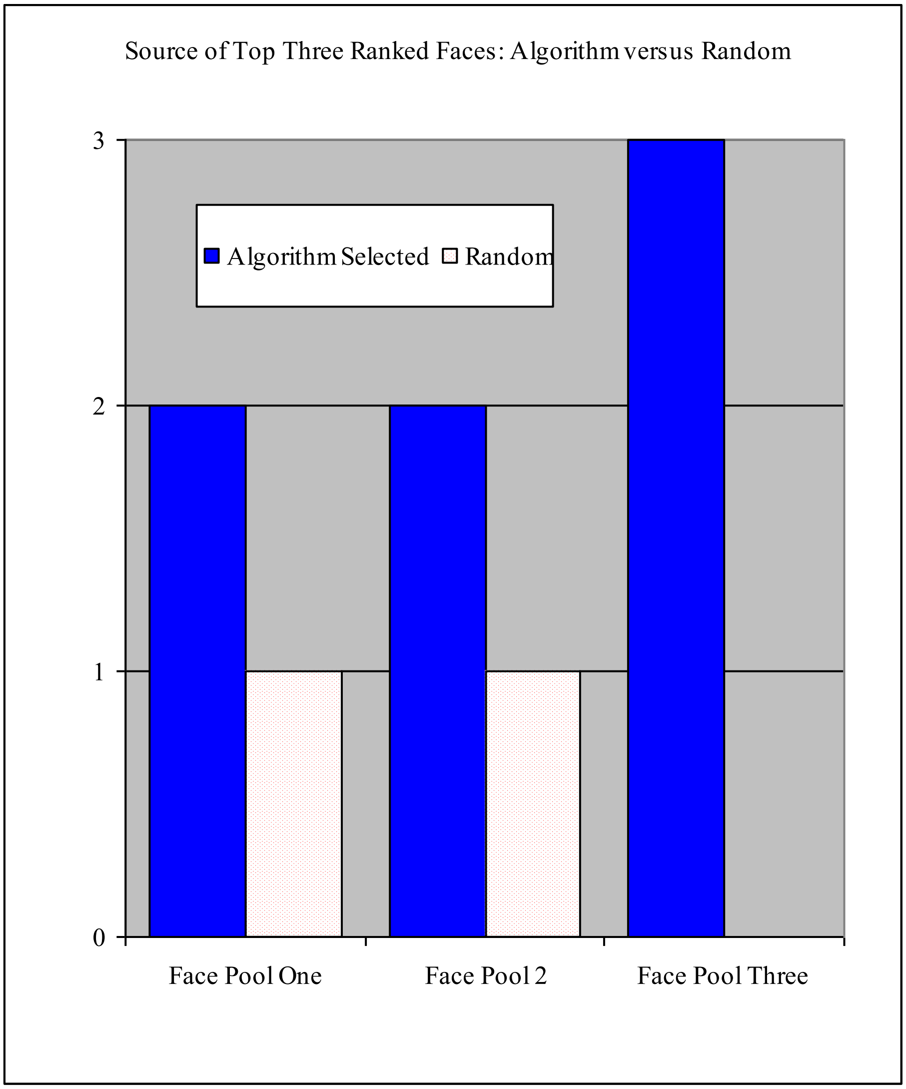

Figure 14 – Top ranked faces per face pool: algorithm-chosen versus random.

Sex Determination

The sex identification cephalometric data is presented in Table 10a. The equivalent measures in a sample of 50 Taiwanese females measured by Hsiao, Chang, & Liu (1996) is presented in Table 10b. A visual comparison of these values is presented in Figure 14.

	Study Measurements							
	Tracing 1							
	G-Sg-N	Sg-G-M	FSHt	G-M-S-N	MaWd	GPI	FSWd	MaHt
	1.05	0.47	28.12	92.74	22.41	4	11.33	6.54
	1.8	0.26	26.79	91.91	19.62	8	5.81	10.6
	1.77	0.59	24.88	92.44	17.61	7	11.43	6.46
	2.3	0.16	30.45	103.38	19.63	5	9.51	7.26
	1.46	0.1	28.9	93.92	15.42	5	9.2	7.04
	2.41	0.21	23.68	91.91	15.38	10	9.37	6.7
	2.69	0.67	30.66	97.59	19.19	6	12.19	6.42
	1.21	0.37	20.68	89.34	20.1	5	7.18	4.95
	1.12	0.63	15.72	81.6	15.58	5	8.2	2.47
	1.02	0.5	18.83	82.13	19.41	4	7.86	6.96
	2.43	0.14	25.55	98.95	16	9	11.38	6.17
	1.35	0.75	23.33	85.2	18.05	5	7.38	7.83
	1.24	0.39	19.14	85.91	14.11	6	5.04	3.54
	1.08	0.79	20.52	92.83	16.55	5	8.25	4.45
	2.12	0.36	22.11	90.28	22.37	9	7.71	5.31
	1.76	0.48	33.59	97.14	20.34	7	12.31	8.87
	1.53	0.49	26.86	89	18.11	6	7.26	5.46
	1.57	0.69	26.05	88.97	18.45	6	4.22	5.34
	1.54	0.09	28.72	89.38	18.65	6	9.57	6.44
	1.88	0.44	22.62	93.94	19.22	7	6.27	4.31
	1.78	0.71	24.43	98.48	22.79	8	10.4	5.27
	2.07	0.48	24.63	92.86	18.52	8	11.9	6.34
	3.53	0.17	17.69	93.95	16.57	12	7.11	4.39
	2.43	0.92	26.19	99.77	15.4	10	8.39	4.67
	1.94	0.76	25.46	88.42	21.22	7	9.77	6.09
	1.07	0.84	37.11	87.23	20.21	4	14.73	9.8
	0.49	0.29	34.17	88.23	15.42	2	12.29	3.51
mean:	1.73	0.47	25.44	91.76	18.38	6.52	9.11	6.04
σ:	0.65	0.24	5.11	5.28	2.40	2.23	2.53	1.85

Table 10a – Sex identification data recorded in this study (Hispanic females, n = 27).

	Norm Measurements (female, n=50) from Hsiao, Chang, & Liu (1996)							
	G-Sg-N	Sg-G-M	FSHt	G-M-S-N	MaWd	GPI	FSWd	MaHt
mean:	2.10	0.38	24.84	90.40	16.91	7.97	7.40	7.28
σ:	0.66	0.24	5.89	5.40	2.50	2.15	2.34	1.79

Table 10b – Sex identification data reported by Hsiao, Chang, & Liu (1996) (Taiwanese females, n = 50).

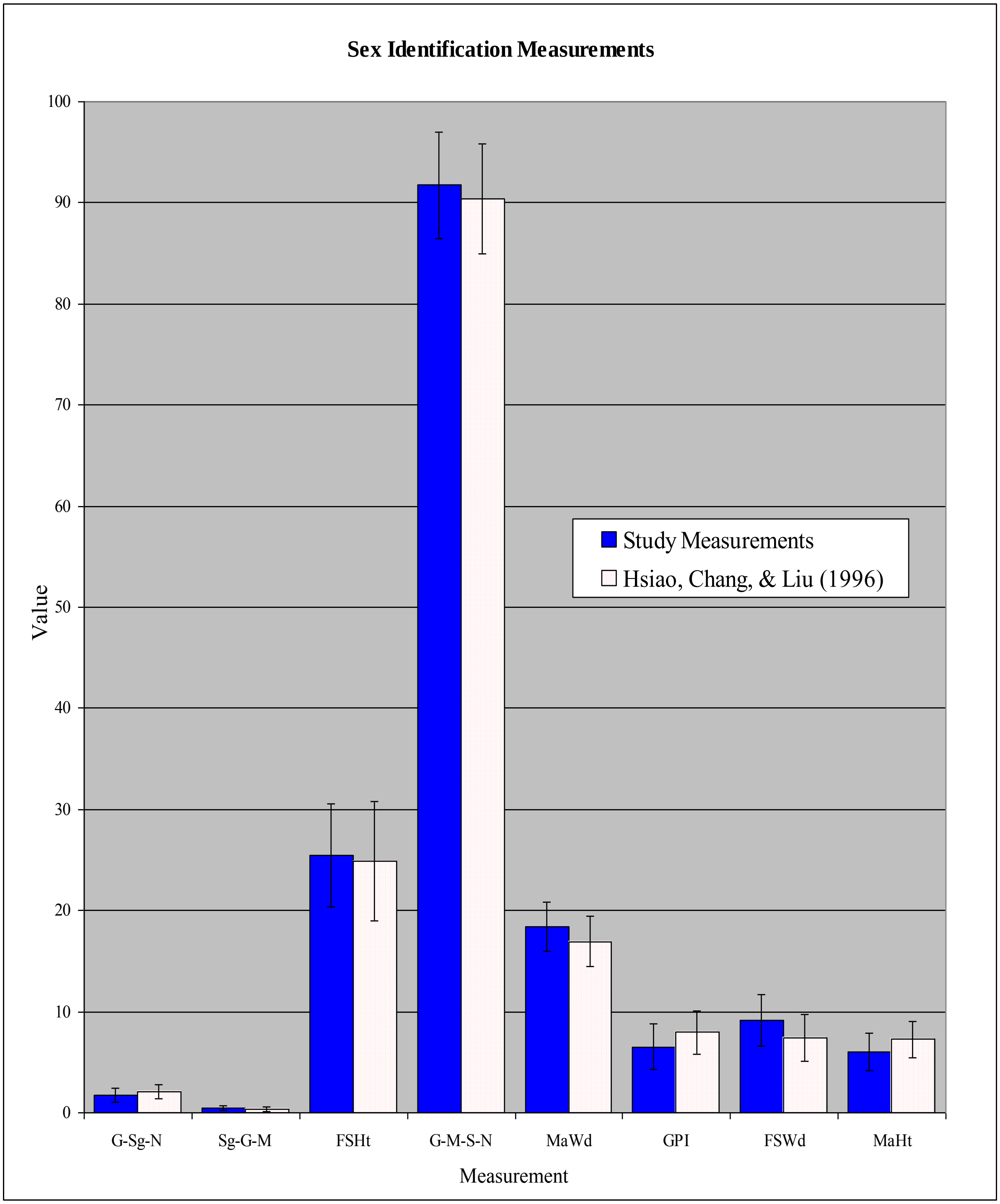

Figure 15 – Comparison of sex identification data with previously reported data.

Chapter 5: Discussion

Data Collection

It has been documented that CBCT radiographs are an accurate substitute for conventional lateral cephalometric radiographs for orthodontics and forensic investigations (Gribel, F., Gribel, M. N., Frazão, McNamara, & Manzi, 2011; Murphy, Drage, Carabott, & Adams, 2012). With the exception or one measurement all cephalometric measurements recorded in this study achieved strong reliability between separate tracings as indicated by intraclass correlation coefficient (ICC) testing. The measurement that did not achieve strong reliability was ANB with a reliability score of 0.893 (good reliability).

The diminished reliability of the measurement of ANB is potentially the result of its derivation from measurement of SNA and SNB. ANB is defined as the difference between SNA and SNB and its derivation in this study was through this relationship. Unfortunately this makes the error inherent in measurement of SNA and SNB additive and if these errors are both in the same direction relative to the true value of ANB, a larger error will be introduced. Care should be taken in future studies to ensure that ANB is derived from its actual anatomic landmarks (A point - nasion - B point).

In this study measurements that used the landmark articulare (Table 5a, page 25) were more susceptible to error. Articulare is defined as the point of intersection of the dorsal contour of the mandibular ramus and the cranial base and it is unique relative to other landmarks used in this study because it is considered a *constructed* cephalometric landmark. Articulare is not defined as a true anatomic landmark because the structures that define it do not actually contact in a real or three-dimensional skull and only appear to overlap in two-dimensional lateral radiography (Weaver, 2010). As a result articulare should not be included in a strictly CBCT-based cephalometric analysis (van Vlijmen et al., 2009). A solution for this finding is to switch to a lateral cephalometric CBCT view that emulates standard two-dimensional lateral cephalometric radiography in a CBCT cephalometric tracing software package when locating articulare. Care should be taken to orient the skull in proper natural head position when selecting articulare using this method to prevent parallax error.

Sex Identification

This study reliably produced CBCT derived measurements that were comparable to data from a sex identification method described by Hsiao, Chang, & Liu (1996) that used lateral cephalometric radiographs. Hsiao, Chang, & Liu (1996) first validated this method on a group of Taiwanese adults (male and female) and it was subsequently proven efficacious on adult Indian and European populations (Patil & Mody, 2005; Veyre-Goulet, Mercier, Robin, & Guerin, 2008). This project is the first to apply the method to a sample of Hispanic females [between the ages of 8 to 23 (mean: 13.5 years, standard deviation: 2.6 years)].

It is potentially circumstantial that the means and standard deviations of the cephalometric sex identification measurements in this study are comparable to those reported by Hsiao, Chang, & Liu (1996). As shown by Patil & Mody (2005) and Veyre-Goulet, Mercier, Robin, & Guerin (2008) different ethnic populations have unique mean values for these anatomic variables. Alternatively, this finding may indicate that there is uniformity in these cephalometric measures between the Hispanic female sample in this study and the sample of Taiwanese females used by Hsiao, Chang, & Liu (1996). Acquisition of their raw data will allow non-parametric statistical testing for correlation of these measurements. Additionally, further research may be directed at validating this method on a Hispanic sample by recording data for a matching set of Hispanic males and completing discriminant function analysis between male and female samples.

Facial Approximation

The method outlined in this study aimed to produce rapid facial approximations to aid forensic identification while employing minimal computation or graphical complexity. Furthermore, this project attempted to closely streamline a method of facial approximation with current modes of orthodontic record taking. The introduction of CBCT imaging into the orthodontic diagnostic record taking process has introduced commonality between the forensic facial reconstruction and orthodontic fields that should be fully explored.

The results of the facial approximation section of this study imply the ability of cephalometric measurements to create approximated soft tissue profiles from skull data alone. As depicted in Figure 13, in each face pool test the algorithm choices were among the three highest ranked faces. Nominal ranking data showed that the algorithm-selected top choice corresponded with mode values of rank one in Face Pools One and Two (Figure 8a, 8b). In Face Pool Three the algorithm-selected top choice corresponded with a mode expert assessed rank of two (the algorithm-selected third choice achieved a assessed mode rank of one). Overall the trend consisted of randomly selected face pool entries attaining an expert assessed mode rank of between four and six and the algorithm-selected choices achieving an expert assessed mode rank of between one and three. A more specific discussion of the results will address each component of the method directly (Figure 3, page 35).

Database Construction.

The lack of a deformation stage in this study's facial approximation method reduces complexity while increasing availability for layperson use in forensic investigation environments. However, this makes the process extremely dependent on the size and variability available in the database. As a result it is possible that as the database size increases the algorithm scores for the closest matches will decrease to values closer to zero. This situation will potentially create more significant results in research environments as the difference in algorithm scores between algorithm matches and random entries increase.

Inclusion of Body Mass Index (BMI) Information in Database. It has been established that a body mass index (BMI) can often be deduced based on any remaining soft tissue on the face and body, or based on any clothing available at the crime scene (Claes et al., 2010b). The relevance of BMI values to airway obstruction, sleep apnea, and orthodontic therapy has also been documented (Ono, Lowe, Ferguson, & Fleetham, 1996; Liu, Lowe, Fleetham, & Park, 2001). BMI calculation and recording of orthodontic patients is currently part of the diagnostic record taking process at the University of Las Vegas, Nevada School of Dental Medicine Orthodontic Department. Inclusion of this as a parameter in the database for cases where BMI of the missing person is known will produce approximations that display similar facial adipose levels.

Custom Database Creation for Alternative Methods. As described by Claes et al. (2010b) the craniofacial information (CFI) stage of modern facial approximation often employs a group of sample skull-soft tissue pairings in a database. This is used to estimate the relationship between these tissues for eventual craniofacial deformation (CFD). The method outlined in this study does not attempt a deformation stage. It is possible to use this method to create a custom database of anthropologic and cephalometrically similar skulls for an unknown skull and use this database to complete the reconstruction using another more complex reconstruction technique. Future research may explore the efficacy of using this procedure to create databases for use in alternative methods currently being investigated by facial approximation practitioners.

Integration into Orthodontic Record Taking. The materials and methods of this research project are purposefully similar to current orthodontic record taking and diagnosing practices. As facial reconstruction practitioners have already initiated, it is conceivable that orthodontic professionals may collectively create and continuously expand a large-scale facial approximation and identification database for use by facial reconstruction practitioners (Tilotta et al., 2009).

Search Algorithm

Currently assigned algorithm weights are shown in Table 6 (page 46). Further research may attempt to define more ideal weights. Weight assignment may potentially by improved through the application of regression analysis. A decision tree based learning algorithm can be applied to the members of a database relative to their level of similarity to a prompt face using an expert judge (leave-one-out cross validation scheme)

(Aha, Kibler, & Albert, 1991). The result of this process will be a ranking of all faces according to their assessed similarity to the target face. Principal component analysis can be applied to this ranking to extract the correlations between the various cephalometric measurements and this ranking and these relationships can be reflected in the algorithm weights (Jolliffe, 2005). This process can be repeated for different entries in the database (leave-one-out cross validation) and the resultant weights can be averaged.

Post-Match Modification

Despite ideal algorithmic weighting and ideal database size and structure it is unlikely to create overly precise approximations using this method. One method of improving this deficit is to define and apply the algorithm separately for different skull structures (e.g. zygomatic process, orbit, nasal, and jaw areas) and combine the results of the separate database search functions into one face. Using the terminology of Claes et al. (2010b) this would correspond to a *partial* craniofacial template as opposed to the currently described *holistic* template. An example of this is shown using two faces in Face Pool Two to create a superior match with more ideal jaw and nasal approximations (Figure 15) .

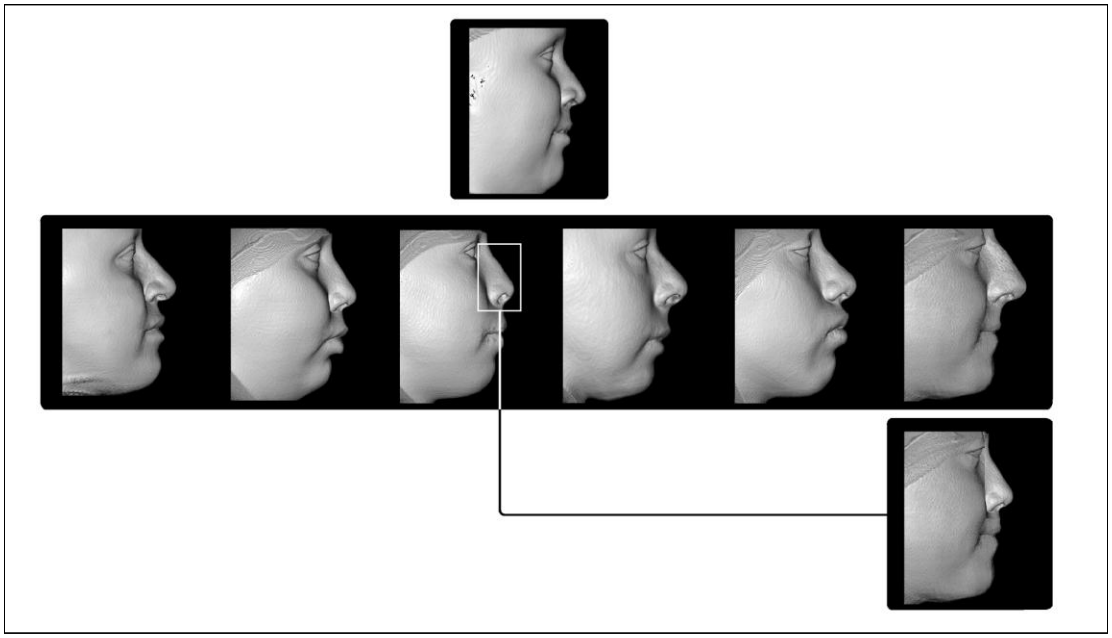

Figure 16 – Partial feature-based craniofacial matching and merging of results. Modification of Face Pool Two is shown displaying partial feature-based craniofacial matching and merging of results.

Accuracy Assessment

The methods of this study included a novel combination of face pool assessment and expert resemblance ratings, creating an assessment method referred to in this study as expert face pool resemblance ranking. The nominal data sample returned using this novel method does not lend well to rigorous statistical analysis because the lack of continuous data does not allow for tests of central tendency.

Due to institutional review board (IRB) limitations face pool assessment was not used in this study. Future studies may make modification to the search algorithm and database characteristics to produce potentially improved results, and include one such face as the prompt to a face pool. The true facial profile of the "unknown" leave-one-out cross validated skull may be placed in the face pool. Face pool evaluators may then be asked to select the face that most resembles the prompt. This is the gold standard of accuracy established in contemporary literature, and produces a data sample indicating how often each face in the face pool is selected that can be subjected to significance testing.

Chapter 6: Conclusions

1. Three-dimensional cone-beam computed tomography (CBCT) cephalometric measurements recorded for facial approximation and sex identification in this study were reliably measured and reproducible.
2. Although initial analysis implies that this facial approximation method is better at producing resemblance than random face selection, further testing needs to be completed with different assessment methods to more definitely attain an understanding of method accuracy.
3. Sex identification data recorded on this study's sample of Hispanic females appears to be relatively consistent with previously reported data samples. A matching sample of Hispanic males needs to be measured and compared to properly validate this method of sex identification.

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