

3D COMPUTERISED FORENSIC FACIAL RECONSTRUCTION
USING BLENDER

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3D COMPUTERISED FORENSIC FACIAL RECONSTRUCTION
USING BLENDER

by

LEE SY SHYAN

Dissertation submitted in partial fulfilment of the requirements for
the degree of Bachelor of Science (Honours) Forensic Science

FEBRUARY 2026

CERTIFICATE

This is to certify that the dissertation entitled '**3D COMPUTERISED FORENSIC FACIAL RECONSTRUCTION USING *BLENDER***' is the bona fide record of research work done by **MS. LEE SY SHYAN**, 163705, during the period of October 2025 to January 2026 under my supervision. I have read this dissertation and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfillment for the degree of Bachelor of Science (Honours) Forensic Science.

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DECLARATION PAGE

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at USM or other institutions. I acknowledged that the research work and collection of data belong to Universiti Sains Malaysia.

LEE SY SHYAN

Date: 29/1/2026

DEDICATION

I dedicate this dissertation to my beloved family, who have been a constant source of inspiration and strength, particularly during moments when I felt discouraged. Their unwavering moral, spiritual, emotional, and financial support made the completion of this study possible. I am deeply grateful for their love and sacrifices. I also dedicate this work to my friends and classmates for their encouragement, advice, and support throughout this academic journey. My sincere appreciation is extended to my supervisor for the continuous guidance, support, and valuable insights provided throughout the research process. The knowledge and direction shared made the research process more meaningful and intellectually enriching. I am truly grateful for the mentorship and dedication provided. Finally, I dedicate this work to those who have contributed to the advancement of forensic anthropology, facial reconstruction, and craniofacial identification. The foundational knowledge and methodologies established in previous studies were instrumental in shaping and guiding this research.

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LIST OF ABBREVIATIONS AND SYMBOLS

ANS	Anterior Nasal Spine
BMI	Body Mass Index
CBCT	Cone Beam Computed Tomography
CT	Computerised Tomography
CFR	Forensic Facial Reconstruction
C2M	Cloud-To-Mesh
DNA	Deoxyribonucleic acid
DVI	Disaster Victim Identification (DVI)
et al	et alia (“and other”)
FHP	Frankfort horizontal plane
FSTT	Facial Soft Tissue Thickness
ICP	Iterative Closest Point (ICP)
MFI	Mass Fatality Incidents (MFI)
MNW	Maximum Nasal Width (MNW)
MAW	Maximum Aperture Width (MAW)
MRI	Magnetic resonance imaging
PLY	Stanford Polygon (.ply)
UID	unidentified decedent
2D	Two-dimensional
3D	Three-dimensional
cm	centimetre
mm	millimetre

PEMBINAAN SEMULA WAJAH FORENSIK TIGA DIMENSI (3D) BERASASKAN KOMPUTER MENGGUNAKAN PERISIAN BLENDER

ABSTRAK

Kajian ini memfokuskan kepada rekonstruksi artistik wajah tiga dimensi (3D) daripada tengkorak manusia yang tidak dikenali, dengan meneliti hubungan antara morfologi kranial dan tisu lembut yang melapisi tengkorak serta membentuk rupa wajah. Rekonstruksi wajah merupakan satu pendekatan penting dalam pengenalpastian forensik apabila kaedah konvensional gagal dan maklumat antemortem tidak tersedia. Objektif utama kajian ini adalah untuk membangunkan dan menilai satu metodologi rekonstruksi wajah 3D berpendigitalan menggunakan perisian Blender serta menilai keberkesanannya melalui perbandingan tengkorak–wajah. Objektif tambahan kajian ini adalah untuk menilai tahap keserupaan wajah antara rekonstruksi wajah 3D dengan rekonstruksi wajah dua dimensi (2D) daripada kajian terdahulu (Kanesa, 2020; Nurul Hikmah, 2022). Rangka kerja rekonstruksi oleh Cicero Moraes telah digunakan sebagai metodologi utama dan seterusnya diubah suai dengan mengaplikasikan teknik terkini dan mantap bagi pemodelan ciri-ciri wajah individu, termasuk mata, hidung, telinga dan bibir, bagi meningkatkan ketepatan rekonstruksi. Kajian kawalan telah dijalankan terlebih dahulu menggunakan dua imbasan tomografi berkomputer (CT) tengkorak, dan wajah yang terhasil dibandingkan dengan gambar wajah sebenar bagi tujuan pengesahan dan penambahbaikan aliran kerja rekonstruksi. Metodologi yang telah diperkemas kemudiannya diaplikasikan ke atas lima tengkorak fizikal tidak dikenali sebagai sampel eksperimen. Aliran kerja rekonstruksi merangkumi pemerolehan dan analisis tengkorak, pendigitalan tengkorak, pengimportan ke dalam perisian Blender, peletakan penanda Ketebalan Tisu Lembut Wajah (Facial Soft Tissue Thickness, FSTT), pemodelan tisu, pemodelan ciri-ciri wajah individu, serta proses pemaparan akhir. Penilaian wajah rekonstruksi dilakukan

menggunakan kaedah superimposisi wajah, pemeriksaan mod pudar dan sapuan (fade and wipe), serta pemetaan wajah bagi menilai prestasi rekonstruksi. Perbandingan tambahan turut dilakukan dengan rekonstruksi wajah dua dimensi (2D) yang telah diterbitkan bagi menilai tahap keserupaan antara kaedah 2D dan 3D. Hasil kajian menunjukkan bahawa aliran kerja 3D yang dicadangkan membolehkan peletakan ciri-ciri wajah yang konsisten serta kawalan yang lebih baik terhadap perkadaran wajah dan morfologi permukaan. Penggunaan set data FSTT lengkap yang bersifat khusus populasi turut meningkatkan keselarasan anatomi. Walau bagaimanapun, perbezaan dalam pemeriksaan keserupaan wajah masih diperhatikan akibat variasi metodologi, kepelbagaian biologi, serta faktor berkaitan pengamal, termasuk subjektiviti artistik dan kesan silang kaum. Kesimpulannya, kajian ini membuktikan kebolehlaksanaan perisian Blender sebagai platform bagi rekonstruksi wajah forensik 3D dan menekankan kepentingan penyeragaman metodologi, penggunaan data khusus populasi, serta latihan pengamal dalam meningkatkan ketepatan dan kebolehpercayaan rekonstruksi.

3D COMPUTERISED FORENSIC FACIAL RECONSTRUCTION USING BLENDER

ABSTRACT

This research focuses on the three-dimensional (3D) artistic reconstruction of facial appearance from unknown human skulls, examining the relationship between cranial morphology and overlying soft tissues that define facial form. Facial reconstruction remains a critical approach in forensic identification when conventional methods fail, and no antemortem information is available. The primary aim of this study was to develop and evaluate a 3D digitised facial reconstruction methodology using Blender software and to assess its performance through skull–face comparison. An additional objective was to assess the facial similarity between the 3D reconstructed face and the 2D reconstructed face from previous studies (Kanessa, 2020; Nurul Hikmah, 2022). Cicero Moraes’s reconstruction framework was adopted as the primary methodology and was further modified using updated and established techniques for individual facial features, including the eyes, nose, ears, and lips, to improve reconstruction accuracy. A control study was first conducted using two computed tomography (CT) skull scans, and the resulting faces were compared with corresponding facial photographs to validate and refine the reconstruction workflow. The revised methodology was then applied to five unknown physical skulls as experimental samples. The reconstruction workflow comprised skull acquisition and analysis, skull digitisation, importation into *Blender*, placement of Facial Soft Tissue Thickness (FSTT) markers, tissue modelling, individual facial feature modelling, and final rendering. The reconstructed faces were evaluated using facial superimposition, fade and wipe mode examination, and facial mapping to assess the reconstruction performance. Additional comparisons were made with previously published two-dimensional (2D) facial reconstructions to examine the facial similarity between 2D and 3D methods. The results demonstrated that the proposed 3D workflow enabled consistent placement of facial features

and improved control over facial proportions and surface morphology. The use of a complete population-specific FSTT dataset enhanced anatomical coherence. Nevertheless, discrepancies were observed in facial similarity examination due to methodological variation, biological variability, and practitioner-related factors, including artistic subjectivity and the cross-race effect. In conclusion, this study demonstrates the viability of Blender as a platform for 3D forensic facial reconstruction and highlights the importance of methodological standardisation, population-specific data, and practitioner training in improving reconstruction accuracy and reliability.

CHAPTER 1: INTRODUCTION

1.1 Background of the study

This research explores the relationship between the skeletal structure of the skull and the overlying soft tissues of the face that define an individual's appearance. It focuses on the application of computer-aided forensic facial reconstruction (3D-CFR) as a valuable tool in unidentified human remains investigations, particularly in cases where traditional identification methods are limited or unavailable. The study primarily applies Cicero Moraes's method, which uses computer-aided forensic facial reconstruction through the open-source software Blender and his self-established protocol (Moraes & Miamoto, 2015). Cicero Moraes integrates his expertise in 3D modelling using Blender with forensic anthropology to produce accurate digital reconstructions by adapting traditional manual reconstruction techniques into a virtual environment. This study uniquely investigates the feasibility and reliability of implementing this method using a Malaysian population's facial soft tissue thickness (FSTT) database, addressing a critical gap in the availability of region-specific data for accurate reconstructions.

To provide a broader context, forensic facial reconstruction is a technique used to recreate a person's facial appearance from their skull for the purpose of identifying unknown human remains. Although this method is not regarded as the gold standard for human identification due to its complexity and degree of subjectivity, it remains highly valuable in specific situations, particularly when little or no personal information, such as DNA profiles, personal belongings, or complete skeletal remains, is available. It is especially useful in cases involving mass disasters, multiple burials, or unidentified remains. Besides, it is also a powerful investigative tool, which provides a visual representation that can generate leads and potentially lead to identification.

Forensic facial reconstruction can generally be categorised into two main approaches: two-dimensional (2D) and three-dimensional (3D) reconstruction. This study focuses on 3D computerised reconstruction, in which technology is integrated at every stage during the process. Both traditional and computerised approaches share the same fundamental principle: sculpting facial tissues over a physical or virtual replica of the skull based on average facial soft tissue thickness (FSTT) data. The key distinction is that the computerised method operates on a virtual copy of the skull, enabling precise digital adjustments and refinements to individual facial features. This allows for greater accuracy, reproducibility, and the potential for quantitative analysis compared to traditional clay-based methods.

In brief, the study starts with scanning the skull using techniques such as 3D surface scanning or CT imaging to create a digital model, then applying population-specific FSST data to generate a virtual face in the Blender 3D platform, as described in Cicero's manual (Moraes & Miamoto, 2015). As in all facial reconstruction techniques, FSTT data play a central role in shaping the initial face by guiding the placement of tissue depth markers. FSST is defined as the perpendicular distance from a specific anatomical landmark on the skull to the most superficial point of the corresponding soft tissue, measured in the standard Frankfort horizontal plane. Because FSTT values vary across populations, sexes, ages, and even lifestyles, selecting a reliable and population-appropriate dataset is essential for achieving an accurate and realistic reconstruction. Besides, instead of sticking to what Cicero has practised, several established methods on facial organs were applied in the process of 3D facial reconstruction, such as the nose projection technique using Rynn's method (Rynn, Wilkinson, & Peters, 2010) and other facial organs, such as lips, eyes, ears, etc.

With the rapid advancement of computer science and digital technologies, the field of facial reconstruction has evolved substantially since its early adoption in the late 20th century. Navic et al. (2023) summarise key developments in 3D computerised facial reconstruction over the past decade. These studies have shared a similar conceptual framework, emphasising the integration of craniofacial knowledge with computerised systems. Researchers continue to explore new methodologies and software solutions to improve accuracy, reproducibility, and user-friendliness. However, no universal protocol currently exists, as methodologies differ depending on the availability of FSTT data, the software used, and the reconstruction strategy. Moreover, studies have shown that the success rate and accuracy of reconstructions remain partly subjective, often depending on expert interpretation and validation tests.

1.2 Problem statement

In forensic identification, facial reconstruction plays a crucial role in estimating the possible facial appearance of unidentified individuals from their skeletal remains. However, various studies employ different Facial Soft Tissue Thickness (FSTT) databases and digital tools, leading to inconsistencies in reconstruction accuracy and reproducibility. Specifically, variations in software algorithms and the lack of standardised protocols result in discrepancies in facial feature estimations, particularly in the nose, eyes, and mouth. In Malaysia, comprehensive FSTT databases have been developed, but their application in full 3D virtual reconstructions remains limited.

Additionally, no established guideline outlines a systematic digital workflow using accessible open-source software such as Blender and MakeHuman. Moreover, the reliability of 3D computerised facial reconstructions compared to existing two-dimensional methods has not been thoroughly evaluated. Establishing such comparisons is crucial to validating the accuracy

and reliability of digital techniques in forensic contexts. Therefore, this study seeks to reconstruct faces from unknown skulls using the Malaysian FSTT database, formulate standardised virtual reconstruction guidelines, and assess the comparability between 3D and 2D reconstruction outcomes.

Facial reconstruction aims to recreate the *in vivo* appearance of an individual in a way that closely resembles the deceased person. The conceptual framework for the three-dimensional reconstruction of a face from unknown human skulls is illustrated in Figure 1.1.

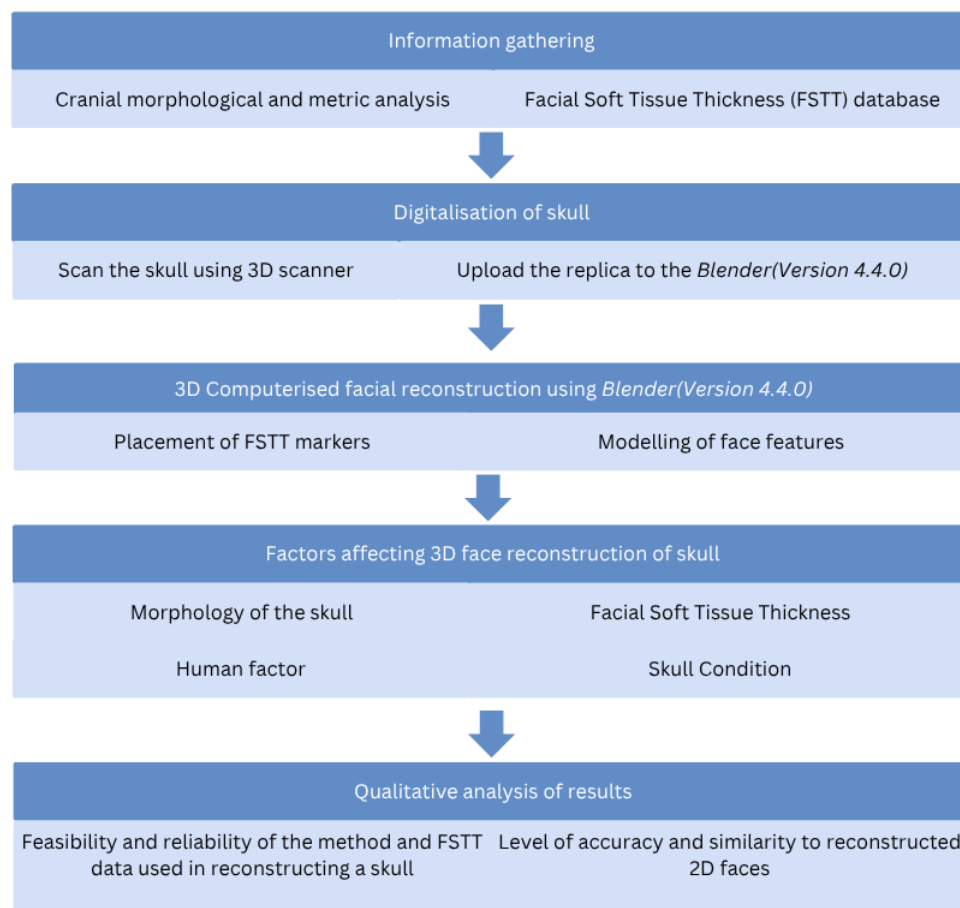


Figure 1.1 Conceptual framework of three-dimensional reconstruction of the face from the unknown human skulls.

1.3 Research question

1. What are the essential guidelines and workflow steps for performing computerised facial reconstruction using *Blender*, with the Malaysian population's FSST database?
2. Is it possible to recreate 3D faces from unknown skulls using the proposed methodology?
3. To what extent do the reconstructed 3D faces demonstrate a level of similarity that resembles the 2D facial reconstructions reported in previous studies?

1.4 Objectives of the Study

1.4.1 General Objective

To construct a three-dimensional facial representation from unknown human skulls using computerised reconstruction techniques, specifically in *Blender*.

1.4.2 Specific Objectives

1. To develop guidelines for 3D computerised facial reconstruction utilising *Blender*, using a known Malaysian population's FSST database.
2. To perform 3D computerised facial reconstruction on the experimental unknown skulls using the proposed methodology.
3. To evaluate the facial similarity between the reconstructed 3D faces and the two-dimensional reconstruction of faces from previous studies.

1.5 Significance of the Study

This study holds significant importance for forensic science, law enforcement, and the wider community by providing an efficient and accessible approach to facial reconstruction. Three-dimensional (3D) forensic facial reconstruction aims to recreate the appearance that most closely resembles the original face of the deceased, enabling the public or family members to

recognise the individual and ultimately leading to positive human identification. By developing a reliable and user-friendly method for 3D computerised facial reconstruction using facial soft tissue thickness (FSTT) databases, this research offers several key benefits: solving complex cases, enhancing accuracy through computer-based techniques, and contributing to both community welfare and forensic practice.

3D forensic facial reconstruction plays a crucial role in human identification, particularly when traditional methods such as DNA profiling, dental record comparison, or personal belongings are unavailable due to decomposition, insufficient remains, or the absence of reference data. According to Dr Arpad A. Vass, a forensic anthropology expert, human decomposition can begin as early as four minutes after death and progresses through four distinct stages (ServiceMaster BioClean, 2025). Once decomposition begins, biological evidence rapidly degrades and gradually loses its forensic value. Muscles and soft tissues decompose with the maggots' colonisation, resulting in the loss of identifiable facial features and tissues suitable for testing. Consequently, 3D facial reconstruction becomes particularly valuable in cases of mass disasters, serial burials, or cold cases where skeletal remains may be the only clue to a person's identity.

A well-executed 3D facial reconstruction allows investigators to recreate a face that closely resembles the deceased, which can then be released to the public or family members to facilitate recognition. The MH17 aeroplane crash serves as a notable example of its importance: the remains were scattered, burned, and fragmented, making visual identification impossible. Skull-based reconstruction provided one of the final opportunities to restore identity and deliver closure to grieving families. Similarly, in criminal investigations, the facial

reconstruction of ancient or long-buried remains can help reveal a victim's identity, generate new leads, and narrow down the suspect pool.

Furthermore, the use of computerised methods enhances the accuracy of reconstruction. This study highlights the advantages of integrating advanced computer technology into the reconstruction process. Traditional manual clay reconstruction, while valuable, is often subjective because it relies heavily on the skill, interpretation, and artistic intuition of the forensic artist. Such subjectivity can lead to inconsistencies between reconstructions produced by different artists, and the process itself can be time-consuming and labour-intensive. Computerised reconstruction overcomes many of these limitations by employing standardised FSTT data and algorithm-driven modelling. This approach significantly reduces personal bias and ensures that each reconstruction adheres to the same anatomical reference points, resulting in more reproducible outcomes. Because the software utilises precise digital measurements, it can capture subtle facial contours and proportional relationships that may be overlooked in a manual clay model. This enhanced precision allows the reconstructed face to more closely resemble the individual's true appearance, thereby improving the likelihood of public recognition.

One of the most meaningful contributions of this study lies in its potential to make facial reconstruction more widely accessible and practical, thereby strengthening forensic systems and supporting communities. The user-friendly nature of the developed method enables its application in both academic settings and real-world investigations. It provides a valuable training tool for future forensic scientists and law enforcement personnel, preparing them to handle cases involving unidentified remains with greater confidence. Importantly, this approach reduces dependency on trained forensic artists. Police departments, forensic

laboratories, and institutions without access to specialised artists can adopt this method with ease. Investigators with no artistic background can follow a clear, standardised protocol to produce accurate reconstructions, transforming what was once a subjective, ad hoc process into a consistent and reproducible forensic practice. This advancement enhances investigative efficiency, particularly in complex cases where fingerprints, DNA, or other means of identification are unavailable, such as mass disasters, severely decomposed remains, or unidentified skeletal material.

CHAPTER 2: LITERATURE REVIEW

2.1 Forensic 3D facial reconstruction

2.1.1 Introduction

Forensic facial reconstruction is the scientific art of recreating an individual's facial appearance from the skull, aiding in facial recognition and ultimately contributing to the identification of the deceased (Fernandes, Pereira, da, & Serra, 2013; George, 1987). It serves as a “method of last resort” in forensic personal identification when little or no other evidence, such as DNA, dental, or radiographic data, is available to identify the deceased (Verhoff, Kreutz, Ramsthaler, & Schiwy, 2006). This review will critically examine the history, techniques, and limitations of 3D computerised facial reconstruction, focusing on the challenges and opportunities presented by the implementation of this method with Malaysian population data.

Conventional identification techniques in forensic science, including DNA profiling, fingerprint analysis, and antemortem record comparison, are generally more effective and time-efficient than facial reconstruction. However, in extreme situations, these resources may be unavailable, necessitating Disaster Victim Identification (DVI). This is particularly relevant in mass fatality incidents (MFI) such as aeroplane crashes, serial murder burials spanning decades, and natural disasters like tsunamis, earthquakes, or severe floods. Within the forensic context, DVI refers to the formal process of identifying remains after a mass disaster, a circumstance in which forensic facial reconstruction can play a crucial role. The absence of comparative material often hinders investigations aimed at identifying unknown deceased individuals. The term “*unidentified decedent*” (*UID*) is used when a body cannot be identified, not necessarily due to destruction of identifiers, but often because of a lack of comparative records or poor preservation of remains.

In brief, forensic facial reconstruction involves the rebuilding of soft tissues on the skull to obtain an approximation of an individual's facial image. The ultimate goal of this process in a forensic context is to recreate an appearance that closely resembles the deceased, thereby stimulating recognition by the public or the family and ultimately contributing to identification (Tyrrell, Evison, Chamberlain, & Green, 1997).

Forensic facial reconstruction is generally categorised into two main approaches: two-dimensional (2D) and three-dimensional (3D) reconstruction. Both approaches can be conducted manually or through computerised means. In 2D reconstruction, a common method is digital drawing, in which a forensic artist, often working with an anthropologist, sketches facial features directly onto an image of the skull (Yadav, Panat, & Aggarwal, 2010). Another 2D technique, known as superimposition, uses algorithms to overlay skull images with portrait photo databases to identify the best visual match (Damas, Córdón, & Ibáñez, 2020). The 3D facial reconstruction approach, which is the focus of this study, encompasses both traditional manual methods, such as the American, Russian, or Manchester techniques, and 3D computerised facial reconstruction.

2.1.2 History of evolution

Three-dimensional (3D) traditional facial reconstruction originated in the 19th century and has been continuously refined to enhance its reliability through the application of anatomical knowledge. In its earliest form, wax was used for sculpting (Ullrich & Stephan, 2011). The field began with the Russian Method, developed by Russian anthropologist and archaeologist Mikhail Gerasimov (1907–1970). This method was primarily based on anatomical principles, in which only selected muscles and average soft tissue thickness values were modelled

anatomically (Ullrich & Stephan, 2016). The reconstruction process involved shaping muscles, glands, and cartilage onto the skull layer by layer. It is important to note that this approach was highly subjective and required extensive anatomical and anthropological expertise.

The American Method, later established by Krigman and his collaborators, introduced a distinct focus on soft tissue depth data. This technique emphasised the use of soft tissue thickness databases specific to an individual's sex, age, and ancestry to reconstruct the face (Verz, 2009). However, one of the major limitations of this method lies in its reliance on the accuracy of reference depth tables, which can be problematic since individuals vary in physical appearance even within the same ancestry.

The evolution of manual traditional 3D facial reconstruction culminated in the Combination Manchester Method (also known as the British Method), developed by Neave in 1977. This approach combined both the Russian and American methods by integrating considerations of facial musculature and soft tissue thickness, making it the most widely accepted traditional technique for facial reconstruction today. The same principles were later adapted for use in computerised 3D forensic facial reconstruction. In this method, soft tissue thickness data are used to define the general facial shape, while the facial and neck musculature are incorporated to refine anatomical detail and form (Verz, 2009; Greef & Willems, 2005).

With the advancement of 3D technology, computer-aided forensic facial reconstruction emerged to overcome the limitations and subjectivity inherent in traditional manual methods. A major breakthrough in this field was initiated by Vanezis et al. in the late 20th century (Vanezis, Blowes, Linney, & Tan, 1989). Vanezis was the first to employ a 3D computer graphics program to model a single-blind facial reconstruction from a human skull. Later, this

digital method was compared with traditional 3D techniques. As in all computer-based reconstructions, the skull was first digitised using a laser scanner and a video camera connected to a computer, producing a fully shaded 3D surface model. Various markers representing tissue depth were then placed on selected anatomical landmarks of the skull. Similar to the traditional approach, digital sculpting was performed by fitting a facial “mask” from a databank over the skull, allowing it to conform to the surface according to tissue depth measurements at specific points. Manual adjustments were then applied using virtual sculpting tools such as brushes. According to Vanezis, this novel technique provided greater speed and flexibility compared to manual methods but remained imperfect. He noted that further research was needed to improve tissue depth measurements, enhance facial feature averaging, and advance computer software capabilities (Vanezis & Vanezis, 2000).

Over the years, new methods and technologies have been developed to further advance 3D computerised facial reconstruction, incorporating approaches such as surface deformation (Quatrehomme, Cotin, Subsol, Delingette, & Garidel, 1997) and volume deformation (Nelson & Michael, 1998). Numerous studies have since integrated various 3D devices (e.g., touchscreens and haptic feedback systems) and advanced artificial intelligence (AI) applications into the reconstruction process. These innovations have proven successful in assisting facial recognition efforts in forensic, humanitarian, and archaeological contexts due to their flexibility, reproducibility, and rapid processing capabilities. Nevertheless, 3D computerised facial reconstruction remains an evolving field, and continuous research by new generations of scientists is essential to refine techniques and adapt applications for diverse population groups.

2.2 Three-dimensional computerised facial reconstruction

2.2.1 Classification

Three-dimensional (3D) computerised facial reconstruction can be further classified based on the technologies used, namely semi-automated and fully automated methods.

In semi-automated facial reconstruction, both manual and computerised processes are combined (Chaimongkhon et al., 2025). Commonly used software for this approach includes *3D Studio Max*, *Freeform*, *Blender*, *ZBrush*, and *Autodesk Maya*. These techniques involve layering facial muscles, soft tissues, and other anatomical features onto a 3D skull model, shaping the facial surface to correspond with facial soft tissue thickness (FSTT) dowels. More recent studies (Miranda, Wilkinson, Roughley, Beaini, & Melani, 2018; Baldasso et al., 2021) have adopted the wrapping homologous mesh model technique, in which mesh templates from free software (e.g., *MakeHuman*) are adjusted to fit dowel lengths representing average FSTT values determined by ancestry, gender, and age for the given 3D skull.

In contrast, automated facial reconstruction relies entirely on computer algorithms that integrate craniofacial and soft tissue thickness data to generate the facial model, often incorporating artificial intelligence tools such as *MATLAB*, *OpenGL*, *TIVMI*, and *Reface*. Jia et al. (2021) reported that automated reconstruction is considerably faster, averaging only one to two seconds without sacrificing accuracy. Generally, automated reconstruction techniques can be categorised into three main approaches: the soft tissue thickness data approach, the homologous mesh model approach, and the statistical model approach.

2.2.2 Method of Computerised 3D facial reconstruction

The process of computer-aided forensic facial soft tissue reconstruction can be divided into four main stages: information acquisition, digitisation of the underlying skeletal material, the modelling process, and plausibility verification. The Manchester Method is widely applied in modern facial reconstruction. Developed by Neave in 1977, it combines the objectivity of depth markers with the anatomical precision of individual muscle structures, making it a reliable and widely accepted technique (Gupta, Gupta, Vij, Vij, & Tyagi, 2015). This method provides a robust foundation for detailed facial reconstruction and is therefore an appropriate framework for the present study.

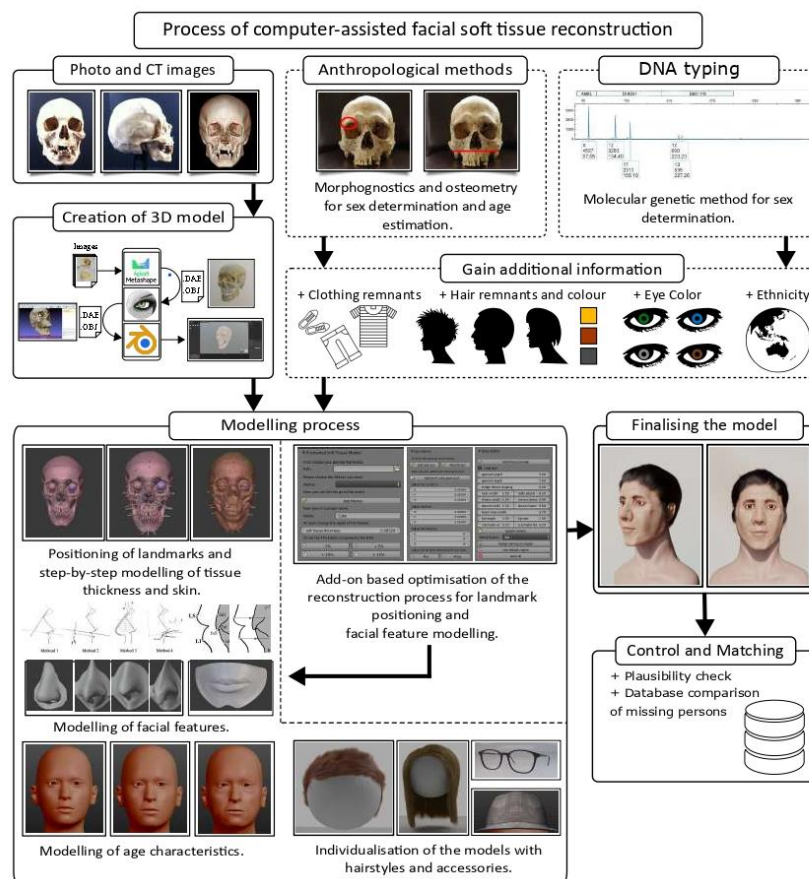


Figure 2.1 Process of the computer-aided forensic facial soft tissue reconstruction (Preuß, Becker, Rosenfelder, & Labudde, 2025)

Figure 2.1 shows the process of computer-assisted facial soft tissue reconstruction, which integrates multiple scientific and digital techniques to recreate a realistic facial approximation from skeletal remains. It begins with acquiring photo or CT images of the skull, followed by anthropological analysis, including morphognostic and osteometric assessments to estimate biological characteristics such as sex and age. In parallel, DNA typing may be used to confirm sex determination through molecular genetic methods. The next step involves the creation of a 3D skull model using specialised software that converts image data (e.g., DAE or OBJ formats) into a manipulable digital structure. Additional contextual information, such as hair colour, eye colour, ethnicity, and remnants of clothing, can be incorporated to improve the accuracy of the reconstruction. During the modelling process, anatomical landmarks are positioned, and facial soft tissue thickness (FSTT) values are applied to simulate skin depth and structure. Facial features and age characteristics are modelled step-by-step, often optimized through software add-ons to enhance precision in landmark positioning. The resulting models are then individualised with hairstyles and accessories to achieve a more lifelike appearance. In the finalisation stage, the reconstructed face undergoes a plausibility check and database comparison against records of missing persons to evaluate its reliability and potential for identification.

2.2.2.1 Extensive Research and Fact-Finding

Before the actual reconstruction begins, extensive research and fact-finding are required to gather as much information as possible about the subject. Fact-finding is typically conducted by frontline personnel, including investigating authorities and forensic experts, who handle the crime scene, evidence, and human remains. Crucial information is collected in the form of crime scene photographs and physical evidence, which are later processed into post-mortem

and forensic reports. These data contribute to establishing a biological profile of the individual and may also provide clues about the circumstances of death.

In cases involving unidentified decedents or mass fatality incidents, biological evidence may be insufficient to form a complete profile; however, even partial data can be valuable. Such information assists in selecting the appropriate population dataset for facial reconstruction. The biological profile generally includes the individual's sex, age, and ethnic origin (Verhoff, Kreutz, Ramsthaler, & Schiwy-Bochat, 2006). Standard procedures for anthropological assessment include morphognostic (visual assessment of form-based anatomical features) and osteometric (bone measurement) examinations of skeletal elements, particularly the skull, pelvis, and long bones. These analyses help determine sex by assessing and measuring sex-specific characteristics such as the shape of the eye sockets.

Once the biological profile has been established and suitable anatomical soft tissue markers and facial reconstruction methods have been identified, the practical process of computer-aided forensic facial soft tissue reconstruction can proceed.

2.2.2.2 Digitalisation of the skull

The target skull is first digitised into a 3D model using various imaging technologies. This represents a major difference from manual 3D facial reconstruction, as computerised reconstruction is performed on a digital replica rather than the physical skull. Common digitisation tools include photogrammetry, 3D laser scanning, computed tomography (CT), and cone beam computed tomography (CBCT). These methods produce high-quality 3D models that clearly visualise the bone structure of the skull. The resulting 3D models are then exported

in compatible file formats and uploaded to open-source 3D modelling and animation software, where the reconstruction process is carried out.

2.2.2.3 Placement of Anatomical Soft Tissue Markers

Using the selected software (eg, Blender), the reconstruction begins with the placement of anatomical soft tissue markers on the digital skull model. These markers, also known as landmarks, represent average facial soft tissue thickness (FSTT) values at specific anatomical points on the skull or face. Both the markers and the FSTT data are critical, as they determine reconstruction accuracy, where the markers indicate the points of tissue build-up, while FSTT values define tissue thickness.

In 3D computerised facial reconstruction studies, the number and terminology of FSTT landmarks vary depending on the research design, methodology, and selected FSTT reference table. Recent studies have identified 82 sites for soft tissue measurement on the skull. An example of these landmarks is presented by Caple and Stephan (2016) (Figure 2.2 and Table 2.1).

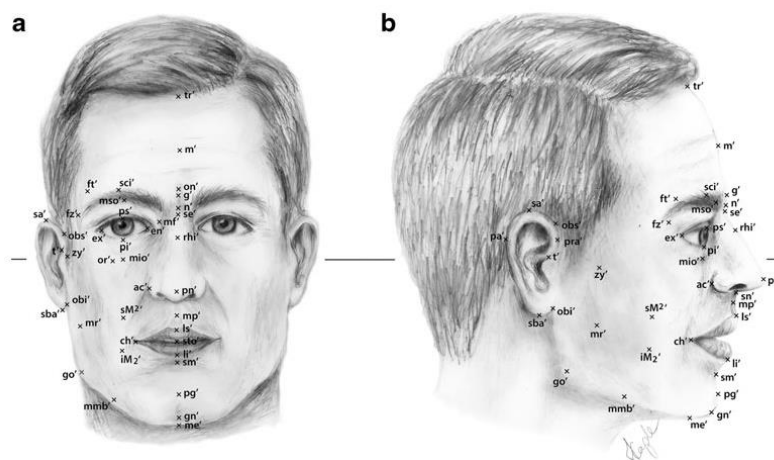


Figure 2.2 Eighty-two (38 midline and 44 bilateral) published hard tissue landmarks (Caple & Stephan, 2016). (a) Anterior view (b) Right lateral view.

Table 2.1: The craniometric landmarks, including their abbreviations, definitions, and various classifications (Caple & Stephan, 2016)

Landmark	3-D Notation	Definition	Bookstein Type
Median Points			
Alveolare	ale	Median point at the inferior tip of the bony septum between the upper central incisors. Equivalent to Infradentale superius.	II
Alveolon	alv	Median point, at the rear of the hard palate, of a line joining the posterior most alveolar margins.	II
Acanthion	a	Most anterior tip of the anterior nasal spine.	II
Apex	ap	Instrumentally determined median point on the superior surface of the cranial vault at the coronal plane connecting left and right po.	III
Basion	ba	Median plane at the anterior most extent of the foramen magnum.	II
Bregma	b	Where the sagittal and coronal sutures meet.	I
Genion	ge	Most projecting tip of the internal mental spine on the lingual surface of the mandible.	II
Glabella	g	Most projecting anterior median point on lower edge of the frontal bone.	II
Gnathion	gn	Median point halfway between pg and me.	III
Hormion	ho	Median point where the vomer and sphenoid bones meet.	I
Incision	inc	Point at the occlusal surface where the upper central incisors meet.	II
Infradentale	id	Median point at the superior tip of the septum between the mandibular central incisors.	II
Inion	i	Median point between the apices of the superior nuchal lines.	II
Klition	kl	Median endocranial point at the center of the highest extent of the posterior margin of the sella turcica.	II
Lamda	l	Point at which the two legs of the lambdoid suture and sagittal suture meet.	I
Linguale	li	Median most superior point of the mandibular symphysis, on the lingual surface.	II
Menton	me	Most inferior median point of the mental symphysis.	III
Metopion	m	Median point on the frontal bone as the greatest elevation from a cord between n and b.	III
Mid-philtrum	mp	Median point midway between ss and pr.	II

Nasion	n	Intersection of the nasofrontal sutures in the median plane.	I
Nasospinale	ns	Point where a line between the inferior most points of the nasal aperture crosses the median plane.	II
Obelion	ob	Median point where the sagittal suture intersects with a transverse line connecting parietal foramina.	II
Ophryon	on	Median point that intersects the smallest frontal bone chord width.	II
Opisthion	o	Median point on the anterior side of the foramen magnum's posterior rim.	II
Opisthocranion	op	Most posterior median point of the occipital bone (greatest length from g).	III
Orale	ol	Median most inferior point of the maxillary symphysis, on the lingual surface.	II
Pogonion	pg	Most anterior median point on the mental eminence of the mandible.	III
Prosphenion	ps	Median endocranial point at the center of the sphenoethmoidal suture.	I
Prosthion	pr	Median point between the central incisors on the anterior most margin of the maxillary alveolar rim.	II
Rhinion	rhi	Most rostral (end) point on the internasal suture.	I
Sphenobasion	sphba	Median point at the spheno-occipital synchondrosis.	I
Sphenoidale	sphen	Median endocranial point on the anterior clinoid process.	I
Staphylion	sta	Median point of a line between the posterior notches of the horizontal plates of the palatine bones.	I
Subspinale	ss	Deepest point seen in profile view below the anterior nasal spine.	II
Supragabellare	sg	Deepest part of the supragabella fossa in the median plane.	II
Supramentale	sm	Deepest median point in the groove superior to the mental eminence.	II
Supraorbitale	so	Median point at the height of the line joining the superior points of the orbital rims.	II
Vertex	v	Most superior point of the skull.	III
Bilateral Points			
Alare	al	Most lateral point on the nasal aperture.	III
Alar curvature pt	ac	Approximately 5 mm lateral to al.	II
Antegonion	ag	Apex of the antegonial notch.	II

Asterion	ast	Where the lambdoidal, parietomastoid, and occipitomastoid sutures meet.	I
Auriculare	au	On the zygomatic root, vertically above the external auditory meatus.	II
Condylion lat.	cdl	Most lateral point on the mandibular condyle.	III
Condylion med.	cdm	Most medial point on the mandibular condyle.	III
Coronale	co	Most lateral point on the coronal suture.	III
Coronion	cr	The tip of the coronoid process of the mandible.	II
Dacryon	d	Where the lacrimomaxillary suture meets the frontal bone.	I
Ectoconchion	ec	Lateral point on the orbit at a line that bisects it transversely.	II
Ectomolare	ecm	Most lateral point on the buccal alveolar margin (2nd molar).	III
Endomolare	enm	Most lateral point on the lingual alveolar margin (2nd molar).	III
Entomion	en	Where the squamous and parietomastoid sutures meet.	I
Euryon	eu	Most lateral point of the cranial vault.	III
Frontomolare orb.	fmo	Point on the orbital rim marked by the zygomaticofrontal suture.	II
Frontomolare temp.	fmt	Most lateral part of the zygomaticofrontal suture.	III
Frontotemporale	ft	Most anterior and medial point of the inferior temporal line.	II
Gonion	go	Point on the rounded margin of the angle of the mandible.	II
Infranasion	in	Intersection of the maxillonasal and nasofrontal sutures.	I
Infratemporale	it	Most medial point on the infratemporal crest of sphenoid.	II
Jugale	ju	Vertex of the posterior zygomatic angle.	II
Krotaphion	k	Posterior end of sphenoparietalis suture.	I
Lacrimale	la	Intersection of the posterior lacrimal crest and frontolacrimal suture.	I
Lingulare	lg	Superior most point of the lingula of the mandible.	II

Mastoidale	ms	Inferior most projecting point of the mastoid process tip.	II
Maxillofrontale	mf	Intersection of anterior lacrimal crest and frontomaxillary suture.	I
Medial orbit	mo	Point on the anterior lacrimal crest level with ectoconchion.	II
Mentale	ml	Most inferior point on the margin of the mandibular mental foramen.	II
Mid-infraorbital	mio	Point on the inferior orbital rim at vertical bisection.	II
Mid-mandibular brd	mmb	Point on the inferior border of the mandible midway between pg and go.	II
Mid-ramus	mr	Midpoint along the shortest antero-posterior depth of the ramus.	III
Mid-supraorbital	mso	Point on the superior orbital rim at vertical bisection.	II
Orbitale	or	Most inferior point on the inferior orbital rim.	II
Porion	po	Most superior point on the upper margin of the auditory meatus.	II
Pterion	pt	Region marked by the sphenoparietalis suture at its center.	I
Sphenion	sphn	Anterior end of the sphenoparietalis suture.	I
Stenion	ste	Most medial point on the spheno-squamosal suture.	II
Stephanion	st	Where the inferior temporal line crosses the coronal suture.	I
Temporale inf.	ti	Most superior point on the arc of the inferior temporal line.	III
Temporale sup.	ts	Most superior point on the arc of the superior temporal line.	III
Zygion	zy	Most lateral point on the zygomatic arch.	III
Zygomaxillare	zm	Most inferior point on the zygomaticomaxillary suture.	III
Zygoorbitale	zo	Intersection of the orbital margin and zygomaticomaxillary suture.	II

The number of selected midline landmarks generally ranges from 10 to 17, with nine (glabella, nasion, rhinion, mid-philtrum, prosthion, infradentale, pogonion, supramentale, and menton) being the most consistently used. The number of lateral landmarks differs across studies, but commonly includes jugale, orbitale, zygion, ectomolare, inframolare, and gonion (Navic P. , Inthasan, Chaimongkhon, & Mahakkanukrauh, 2023). Craniofacial landmarks are typically selected based on established systems and can be classified into three categories as defined by Bookstein (Bookstein, 1922): Type I are the anatomically defined points located on biological structures (e.g., nasion, rhinion, ectoconchion, maxillofrontale); Type II are the points located at the tip, lowest point, or at maxima/minima of curvature, often identified by palpation (e.g., glabella, mid-philtrum, frontotemporale, gonion); and Type III are the geometrically defined points determined by diameters, centroids, or intersections (e.g., menton, zygomaxillare, zygion, mid-ramus).

Over the past century, more than a hundred FSTT datasets and corresponding anatomical points have been published, and the number continues to increase (Stephan, Meikle, Freudenstein, Taylor, & Claes, 2019). The choice of reference dataset depends on the previously established biological profile, as FSTT values vary with factors such as gender, body mass index (BMI), and ancestry. Referring to a relevant dataset enhances the reliability and accuracy of the reconstruction outcome.

2.2.2.4 Reconstruction of Selected Facial Features and Modelling of the Soft Tissue and Skin

Following marker placement, the reconstruction proceeds with modelling of facial tissues and muscles, followed by the creation of facial organs and features such as the eyes, nose, and lips. There are several reconstruction techniques for each facial organ that have been published and gained recognition worldwide, particularly in the field of forensic facial reconstruction.

Among all the facial organs, the nose was one of the structures which were highly studied due to its contribution to the facial outlook. The nose is an important part of the face and provides a distinctive demeanour to an individual. Its central position, shape, size and symmetry play an essential role in the determination of the facial appearance and also facial convexity (Allam, Mpofu, Ghoneima, & Tuceryan, 2018). Prediction guidelines given by Rynn et.al (2009), Gerasimov (1955), Krogman & Işcan (1986), George (1987), Prokopec & Ubelaker (2002) and Macho (1986) were some of the older methods for nasal prediction.

Gerasimov pioneer in the development of the Russian/ European method, gave the two-tangent method. In his study, he states that the soft part of the nose is considered an "organic continuation of the nasal bones", thus, nose reconstruction is possible to be carried out with the nasal bone itself, with the absence of soft tissue on it. His method involves projecting two lines: one following the direction of the anterior nasal spine (ANS), and a second line tangent to the most distal portion of the nasal bones; their intersection indicates the tip of the nose (Gerasimov, 1955). In a study conducted by Rynn & Wilkinson (2006), this method was found highly accurate at predicting a point on the surface of the tip of the nose among the other six methods, excluding the Rynn method, which will be discussed below.

Wilton Krogman, on the other hand, gave a method where the pronasale could be predicted from the length of the anterior nasal spine, through 'The Threefold ANS' method. It involves tripling the length of the anterior nasal spine (ANS), measured from the vomer-maxillary junction (VMJ) to the acanthion, then adding this result to the mean tissue depth at subnasale in the direction projected from the ANS (Krogman & Işcan, 1986). However, this method was found to be inaccurate when tested on lateral cephalograms (Stephan, Henneberg, & Sampson,

2003; Rynn & Wilkinson, 2006). It appeared to overestimate nasal projection by an average of approximately 5 mm (Stephan, Henneberg, & Sampson, 2003). Apart from nasal projection, he suggested that soft tissue of nasal width could be predicted from the width of the bony nasal aperture, that is, the addition of 10 mm to the maximum width of nasal aperture for Caucasians and 16 mm for Negroids (Krogman & Işcan, 1986).

The Macho method, developed in 1986, was based on regression equations developed using seven craniometric measurements of the nasal aperture to external measurements of height, length, and depth of the nose (Macho, 1986). The method overestimated the height and depth of both male and female noses and the length of male noses in the tested sample. Only the length of female noses was accurately predicted (Rynn & Wilkinson, 2006).

The George method, given in 1987, was based on the aesthetic methods of facial surgery given by Goode. This proportion is 60.5% in males, and 56% in females (George, 1987). It also be found to be more accurate than methods by Gerasimov (1955) and Krogman & Işcan (1986) in Stephan et al. (2003)'s study. It showed a significant positive correlation, suggesting a link between the craniometric dimension and nasal projection, though the specific ratios overestimated projection in the tested sample.

Prokopec and Ubelaker (2002) gave a detailed description of a method for nose projection, which was initially proposed by Gerasimov to determine the profile of the nose (Prokopec & Ubelaker, 2002). It included a line drawn from rhinion, which was parallel to the nasion-prosthion plane, with the nasal aperture being subsequently divided into seven equidistant segments along the line. The distance from the line to the lateral surface of the aperture was measured and replicated anteriorly. Gerasimov believed that this demonstrated the nasal