SEX PREDICTION USING PALATAL SURFACE OF MAXILLARY PERMANENT LATERAL INCISORS

ETHEL LIM YI

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SEX PREDICTION USING PALATAL SURFACE OF MAXILLARY PERMANENT LATERAL INCISORS

by

ETHEL LIM YI

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CERTIFICATE

This is to certify that the dissertation entitled “Sex Prediction Using Palatal Surface of Maxillary Permanent Lateral Incisors” is the bona fide record of research work done by Ms. Ethel Lim Yi during the period from October 2024 to February 2025 under my supervision. I have read this dissertation and that in my opinion it confirms to acceptable standard of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Science in Forensic Science with Honours.

Supervisor,

....

Associate Professor Dr. Mohd Fadhli bin Khamis

Lecturer

School of Dental Sciences

Universiti Sains Malaysia

Health Campus

16150 Kubang Kerian

Kelantan, Malaysia

Date: 27 Feb 2025

DECLARATION

I hereby declare that this dissertation is the result of my own in investigation, except where otherwise stated and duly acknowledged. I also declare that it has not been previously or concurrently submitted of any other degree at Universiti Sains Malaysia or other institution.

Ethel Lim Yi

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LIST OF ABBREVIATIONS

±	Plus, or minus
α	Alpha
β	Beta
%	Percentage
mm	Millimetre
mm^2	Millimetre square
2D	Two dimensional
3D	Three dimensional
AM	Antemortem
BL	Buccolingual
CBCT	Cone beam computed tomography
CEJ	Cementoenamel junction
CI	Cervicoincisal
CI	Confidence interval
CT	Computed tomography
DEJ	Dentin-enamel junction
df	degree of freedom
DNA	Deoxyribonucleic acid
DPI	Dots per inch
DVI	Disaster victim identification
GM	Geometric morphometric
GMM	Geometry Morphometric Methods

HERS	Hertwig's epithelial root sheath
ICC	Intraclass correlation coefficient
INTERPOL	International Crime Polic Organisation
LED	Light emitting diode
LL	Labiolingual
MD	Mesiodistal
MLI	Maxillary Lateral Incisor
MRI	Magnetic resonance imaging
NGS	Next-generation sequencing
PLY	Polygon file format
PM	Postmortem
PMCT	Post-mortem computed tomography
PPSG	Pusat Pengajian Sain Pergigian
PSA	Palatal Surface Area
ROC	Receiver Operating Characteristics
SD	Standard deviation
Sig.	Significance
STL	Stereolithography
STRs	Short tandem repeats
USM	University Sains Malaysia
x	Number of size

RAMALAN JANTINA MENGGUNAKAN PERMUKAAN PALATUM GIGI INSISIFUS LATERAL MAKSILA KEKAL

ABSTRAK

Penentuan jantina merupakan aspek penting dalam antropologi forensik dan proses pengenalpastian identiti manusia, yang membantu mengecilkan skop pengecaman individu dalam penyiasatan forensik. Kajian ini bertujuan untuk menilai potensi penggunaan keluasan permukaan palatum (PSA) dan dimensi mesiodistal (MD) gigi incisor lateral maksila dalam meramalkan jantina dalam populasi Melayu (Malaysia). Sebanyak 100 model gigi (50 lelaki dan 50 perempuan) telah dianalisis menggunakan perisian pengimejan 3D (3-Matic-Mimics, Mareialise, Belgium), dan analisis statistik telah dijalankan bagi menentukan kewujudan dimorfisme seksual serta ketepatan ramalan jantina berdasarkan ciri-ciri odontometrik ini. Hasil kajian menunjukkan bahawa PSA gigi incisor lateral maksila mempunyai dimorfisme seksual yang signifikan secara statistik, yang mana lelaki mempunyai purata PSA yang lebih besar berbanding perempuan ($p < 0.05$). Walau bagaimanapun, dimensi MD tidak menunjukkan perbezaan yang ketara antara jantina ($p > 0.05$). Analisis regresi logistik mengenal pasti PSA sebagai peramal yang signifikan bagi klasifikasi jantina, tetapi ketepatan keseluruhan model hanya 61%, dengan ketepatan 60.0% untuk lelaki dan 62.0% untuk perempuan. Kawasan di bawah lengkung ciri operasi penerima (ROC) ialah 0.39, menunjukkan kebolehan diskriminasi model yang lemah. Kesimpulannya adalah PSA gigi atas lateral insisor hanya meramal jantina dengan ketepatan sederhana dan terhad aplikasinya untuk pengurusan kes forensik.

SEX PREDICTION USING PALATAL SURFACE OF MAXILLARY PERMANENT LATERAL INCISORS

ABSTRACT

Sex determination is a crucial aspect of forensic anthropology and human identification, aiding in narrowing down potential identities in forensic investigations. This study aimed to assess the potential of using the palatal surface area (PSA) and mesiodistal (MD) dimension of the maxillary lateral incisor for sex prediction within the Malay population (Malaysian). A total of 100 dental casts (50 males and 50 females) were analysed using 3D imaging software (3-Matic-Mimics, Materialise, Belgium), and statistical analyses were conducted to determine the presence of sexual dimorphism and the predictive accuracy of these dental features. The results indicated that the PSA of the maxillary lateral incisor exhibited statistically significant sexual dimorphism, with males having a larger mean PSA than females ($p < 0.05$). However, the MD dimension did not show a significant difference between sexes ($p > 0.05$). Logistic regression analysis identified PSA as a significant predictor for sex classification, but the overall classification accuracy of the model was 61%, with 60.0% accuracy for males and 62.0% for females. The area under the receiver operating characteristic (ROC) curve (0.39) further indicated a poor discriminative ability of the model. These findings suggest that the PSA of the maxillary lateral incisor only moderately predict sex, thus has limited application in forensic management.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Unique and sexually dimorphic structures play a crucial role in human identification. Understanding the link between tooth uniqueness, sexual dimorphism, and human identification is essential. Sex prediction is a pivotal component in forensic anthropology and human identification, as it provides crucial information that helps narrow down potential identities in forensic investigations. The determination of sex from skeletal remains, particularly through the examination of sexually dimorphic traits in the pelvis, skull, and long bones, allows forensic experts to estimate the sex of an individual with a high degree of accuracy (Nagare et al., 2018). This process is integral to the creation of a biological profile, which also includes age, ancestry, and stature, thereby assisting in the identification of unknown individuals (Byers, 2016). The ability to accurately determine sex is especially vital in cases of mass disasters, unidentified remains, and criminal investigations, where distinguishing between male and female remains can significantly streamline the identification process and focus investigative efforts (Ramakrishnan et al., 2015). Consequently, sex prediction serves as a foundational step in human identification, guiding further forensic analyses and contributing to the overall success of an investigation.

Research on sex prediction in the Malaysian population using dental measurements has demonstrated significant findings. Riaz et al. (2023) explored the cusp and crown areas of maxillary teeth in Malays using two-dimension (2D) digital models, discovering that males had significantly larger measurements than females. Their study developed a sex prediction model with 80% accuracy, highlighting the potential of these measurements in forensic applications. Similarly, Harudin et al. (2023) used three-dimension (3D) volumetric assessment of canines through post-mortem CT scans, finding that males generally had larger dental tissue volumes. Although their classification accuracy ranged from 60% to 74.1%, this approach was noted as a useful supplementary tool for sex determination. Earlier, Khamis et al. (2014) analysed mesiodistal and buccolingual crown dimensions across three major Malaysian ethnic groups. They found that the lower canine's mesiodistal diameter was the most sexually dimorphic, with varying degrees of dimorphism among Malays, Chinese, and Tamils. Discriminant function analysis provided classification rates between 70.2% and 78.5% for the composite group, confirming the reliability of odontometric analysis for sex prediction in this population.

Collectively, these studies underscore the effectiveness of various odontometric approaches in determining sex within diverse Malaysian ethnic groups. While two-dimensional measurements provide substantial accuracy, integrating three-dimensional analyses can enhance forensic identification processes, although they may serve best as supplementary tools. The continued exploration and combination of these methodologies hold promise for improving reliability and precision in forensic sex estimation practices in Malaysia.

1.2 Problem Statement

There has not been any publication on the correlation between sex estimation using the palatal surface area of lateral incisor tooth in the Malaysian population. Additionally, such information has not been published in a comprehensive study for other populations either. The distinctiveness of these occlusal traits in 3D dental models for human identification is not well-documented, particularly for the Malaysian population. To meet the requirements of the Daubert standard, these methods and their potential forensic applications need to be scientifically validated.

1.3 Justification of the study

Human identification is a cornerstone of forensic science, relying on sexually dimorphic biological traits. Teeth, with their resilience to postmortem changes, offer critical forensic insights. While odontometric studies have demonstrated the value of maxillary teeth in sex determination, most focus on two-dimensional analyses or isolated measurements, neglecting comprehensive evaluations.

1.4 Objectives

1.4.1 General:

To understand the association between palatal surface area and mesial-distal dimension of maxillary lateral incisor in both sexes of Malaysians.

1.4.2 Specific:

1. To determine the association between palatal surface area of maxillary lateral incisor and sex.
2. To determine the association between mesiodistal dimension of maxillary lateral incisor and sex.
3. To determine classification rates (accuracy) of sex prediction using palatal surface area and combination of mesiodistal dimensions of maxillary lateral incisor.

1.5 Research Question(s)

1. Can sex prediction model be determined using palatal surface area of maxillary lateral incisor?
2. Can sex prediction model be determined using palatal surface mesiodistal dimension of maxillary lateral incisor?
3. How accurately can sex be predicted using the palatal surface area and the mesiodistal dimensions of maxillary lateral incisor?

1.6 Null Hypothesis

1. There is no association between palatal surface area of maxillary lateral incisor teeth and sex.
2. There is no association between mesiodistal dimension of maxillary lateral incisor and sex.
3. The predictor variables (palatal surface area and the combination of mesiodistal dimensions of maxillary lateral incisor) do not significantly contribute to predicting sex.

CHAPTER 2

LITERATURE REVIEW

2.1 Tooth Development

Tooth development, also known as odontogenesis, is a complex biological process that begins during embryonic development and continues into adolescence. It involves the formation and maturation of teeth in a sequential and regulated manner. The process starts with the initiation stage, where the dental lamina forms as a thickened band of epithelial tissue in the jaw. This is followed by the bud stage, cap stage, early and late bell stage. Finally, the crown and root formation stages involve mineralization and eruption, where teeth emerge into the oral cavity. This intricate process is influenced by genetic, molecular, and environmental factors, ensuring the development of a functional dentition essential for mastication, speech, and aesthetics.

2.1.1 Bud stage

The bud stage is the initial phase of tooth development which starts in the 8th week of intrauterine life, where the epithelium intrusion the ectomesenchyme, leading to cell condensation due to increased mitotic activity. Tooth buds form at the dental lamina's ends separated from the ectomesenchyme by a basement membrane (S. Ali et al., 2021). The surrounding ectomesenchyme, named the dental follicle will forms cementum (periodontal ligament) and alveolar bone, while the dental papilla forms pulp and dentin. The enamel organ appears spherical with minimal differentiation. Tooth development depends on epithelial-mesenchymal interactions which begin at this stage, making it critical for proper tooth formation.

2.1.2 Cap stage

In this stage, the enamel organ grows and forms a concave shape. Around 12 weeks of intrauterine life, the inner enamel epithelium develops from cuboidal cells becoming columnar. This layer shapes the crown and later differentiates into ameloblasts, which form enamel (Rathee & Jain, 2023). The outer enamel epithelium formed from the enamel organ's outer layer will remains cuboidal to maintaining the organ's shape. The condensed mesenchymal cells beneath the inner enamel epithelium develop into the dental papilla, which later becomes the pulp. The enamel organ is surrounded by the dental follicle which forms the periodontal ligament. At 14 weeks, two new layers (stratum intermedium and stellate reticulum) formed. The stratum intermedium transports nutrients to ameloblasts, while the stellate reticulum protects underlying tissues and shapes the tooth (Rathee & Jain, 2023).

2.1.3 Early bell stage

In the bell stage, the enamel organ takes on a bell shape, marking the final crown formation (morphodifferentiation) and the differentiation of ameloblasts and odontoblasts (histodifferentiation) (S. Ali et al., 2021). The cervical loop where outer and inner enamel epithelium meet and will then become prominent. Between the stellate reticulum and inner enamel epithelium, a new layer called the stratum intermedium formed, working with the inner enamel epithelium to produce enamel.

At this stage, the enamel organ comprises four layers: outer enamel epithelium, inner enamel epithelium, stellate reticulum, and stratum intermedium. The dental lamina disintegrates, disconnecting the enamel organ from the oral epithelium, though remnants called epithelial rests of Serres persist. The enamel knot will disappear, and the enamel cord forms, aiding the transition from cap to bell stage. The tooth germ is enclosed by the dental follicle, with the cervical loop playing a key role in forming Hertwig's epithelial root sheath (HERS) for root development (Luan et al., 2006).

2.1.4 Late bell stage

In the late bell stage, the tooth germ grows larger and hard tissue formation begins. Dentinogenesis, the formation of dentin will occur first, followed by enamel formation (amelogenesis). Under the influence of the inner enamel epithelium, pre-ameloblasts induce nearby dental papilla cells to become odontoblasts, which secrete pre-dentin and then dentin. This stimulates pre-ameloblasts to transform into ameloblasts, which secrete enamel matrix that mineralizes into enamel (S. Ali et al., 2021).

Odontoblasts and ameloblasts migrate away from their secretion areas, with odontoblasts leaving behind processes. Tissue formation starts at future cusps or incisal edges and progresses downward. Root formation also begins at this stage, marked by the development of Hertwig's epithelial root sheath (HERS), which shapes the roots (Seow, 2014). On histological sections, enamel, dentin, ameloblasts, and odontoblasts are clearly visible. Disruptions at this stage can lead to abnormal or incomplete enamel and dentin formation.

2.2 General anatomy of dentition

Humans have two dentitions during their lifetime, essential for functions like mastication, speech, and facial aesthetics (Crăciunescu et al., 2023). Teeth are highly calcified structures which are supported in bony sockets called alveoli within the upper and lower jaws. There are four types of teeth: incisors, canines, premolars, and molars. The primary or deciduous dentition, consisting of 20 teeth (10 maxillary and 10 mandibular). Deciduous teeth begin forming prenatally at around 14 weeks and is complete by approximately 3 years of age. Each side of the jaw contains four incisors, two canines, and four molars.

On the other hand, the permanent dentition, comprising 32 teeth (16 maxillary and 16 mandibular) which develops gradually with roots completing formation around 14 to 15 years of age, except for third molars (wisdom teeth) which emerge between 18 to 25 years (Nelson & Ash, 2010). Each side of the jaw includes four incisors, two canines, four premolars, and six molars.

2.2.1 Component of tooth

A tooth consists of a visible crown and one or more roots anchored in the alveolar socket. It is composed of four main tissues: enamel, cementum, dentin, and pulp. The main component of a tooth that gives the crown and roots the basic shape and creates the walls of the pulp cavity in the crown and root area is dentine, a bone-like tissue.

2.2.1.1 Enamel

Enamel is the outermost layer of the tooth is structured in enamel rods, rod sheaths, and interrod cementing substance. Enamel rods are mostly aligned perpendicular to the dentin-enamel junction (DEJ), with twisting observed near the cervical area. The rod sheath, found at the interface of enamel rods and interrod enamel, is hypomineralized compared to the highly mineralized enamel which containing more protein. It ties enamel rods together, while interrod substance cements them. The DEJ features a pitted interface, where enamel rods fit into rounded pits of dentin, creating a strong bond (Crăciunescu et al., 2023; *Mosby's Dental Dictionary*, 2014).

2.2.1.2 Cementum

The dentine root is a bone-like structure that lies beneath the enamel tissue. It is made up of spongy bone-like tissue that is only found on the surface of the tooth and is covered in cementum. Also known as the cervical line, the cementoenamel junction (CEJ) is the point where the cement-delimited root and the enamel-delimited crown meet (Crăciunescu et al., 2023). Cementum is specifically designed to anchor and support the tooth within the bony socket. Both enamel and cementum cover the dentin, with three possible variations in their connection: cementum overlapping enamel (65%), a direct contact line between enamel and cementum (25%), or no contact, leaving dentin exposed (10%).

2.2.1.3 Dentin

As mentioned above, dentin is the largest tissue of a tooth which gives the basic shape of the crown and root and forms the walls of the pulp cavity in the crown and root area. The colour is light yellow in deciduous teeth and yellow in permanent teeth, less hard than enamel, and harder than the cementum. In contrast to the enamel, dentine is highly elastic, can support the non-resilient enamel, and is highly permeable. Dentine is structured into dentinal tubules that are ending beneath the enamel and contain the Tome's fibres also called processes of odontoblasts cells present in the dental pulp (Crăciunescu et al., 2023). For this reason, dentine is a living and sensitive hard tissue of the tooth. Dentine tubes have an "S" curved shape and start perpendicular to the pulp chamber surface but are straight under the cusps and in the root area. The dentine encloses the dental pulp, the soft tissue formed by blood vessels, nerves, and specialized tissue, all responsible for the tooth's vitality (*Mosby's Dental Dictionary*, 2014).

2.2.1.4 Dental pulp

The dental pulp resides within the pulp chamber of the crown, located near the cervical line and extending into the cervical third of the crown. It continues into the root via the pulp canal, collectively forming the pulp cavity. The pulp plays a crucial role in dentin formation, provides sensory feedback enabling the perception of stimuli, and delivers nutrients to the dentin through blood vessels and odontoblastic processes, maintaining the tooth's vitality. Additionally, the pulp has a defensive role, producing secondary dentin to preserve tooth vitality against damage from cavities, occlusal stress, or aging (Tjäderhane & Paju, 2019).

In younger teeth, the pulp chamber is larger and conforms to the shape of the crown, extending into the cusps as pulp horns. Over time, secondary dentin deposition reduces the size of the pulp chamber. Similarly, root canals and the apical foramen, which are wide in young teeth, narrow with age. Root canals can vary in shape, being straight or curved, and may include accessory lateral canals near the apical foramen or the pulp chamber floor.

The apical foramen, located at the root apex or its lateral side, serves as a small opening for blood vessels and nerves to enter the pulp cavity. A tooth may have multiple foramina, facilitating communication with the periodontal space. Endodontic and periodontal health are interconnected, with conditions in one influencing the other through the apical foramen or accessory canals (Tjäderhane & Paju, 2019).

2.2.2 Dental morphology

The crowns of anterior teeth have four axial surfaces and one incisal ridge, while premolars and molars feature five surfaces: four axial and one occlusal. The surfaces are named based on their anatomical position and relation to adjacent structures (Nelson & Ash, 2010). For upper and lower incisors and canines, the surfaces facing the lips are called labial surfaces. Surfaces closer to the median line of the face are referred to as mesial, while those farther from the median line are distal. Mesial and distal surfaces are also collectively termed proximal surfaces. Surfaces facing the tongue are known as lingual surfaces.

For premolars and molars, the surface terminology remains similar, except the surfaces facing the cheeks are called buccal surfaces. Collectively, buccal and labial surfaces are referred to as facial surfaces. The premolar and molar surfaces that make contact with the opposing teeth are called occlusal surfaces, while for incisors and canines is referred to as the incisal ridge (*Mosby's Dental Dictionary*, 2014; Nelson & Ash, 2010).

Teeth also have specific landmarks categorized as positive or negative. Positive landmarks include cusps, tubercles, cingulum, marginal ridges, triangular ridges, transverse ridges, oblique ridges, and lobes. Negative landmarks include fossae, sulci, pits, and developmental grooves (Crăciunescu et al., 2023).

Cusps are elevated structures on the crowns of premolars and molars, dividing their occlusal surfaces. Each cusp has a pyramidal shape with a quadrangular base, except for the mesiolingual cusp of the upper first molar. Tubercles are smaller elevations resembling cusps, formed by extra enamel (Nelson & Ash, 2010). The cingulum, located in the cervical third of the lingual surface of anterior teeth, adds bulk. Ridges are linear elevations named according to their position. Marginal ridges form rounded borders on the occlusal surface, with each premolar and molar having mesial and distal ridges.

Triangular ridges extend from cusp tips toward the centre of occlusal surfaces and are named after the corresponding cusps, such as the triangular ridge of the mesiobuccal cusp of the first mandibular molar. When two triangular ridges cross transversely, they form transverse ridges. Oblique ridges is unique to maxillary molars and are created by the union of the triangular ridges of the distobuccal and mesiolingual cusps. Lobes are primary structures in crown development, and mamelons are rounded protuberances on incisal ridges of newly erupted teeth are remnants of lobes that wear down with age (*Mosby's Dental Dictionary*, 2014; Nelson & Ash, 2010).

Fossae are concave areas found on the occlusal surfaces of premolars and molars and the lingual surfaces of incisors. Central fossae is present on occlusal surfaces which form where ridges and grooves converge. Triangular fossae are located mesial or distal to marginal ridges on lateral teeth and at the junction of the lingual fossae and marginal ridge with the cingulum on maxillary incisors. Pits are small depressions found at the intersections of developmental grooves (Nelson & Ash, 2010).

To accurately describe landmarks, the crown and root surfaces are divided into thirds following a three-part rule. For example, the buccal surface of the central upper incisor can be divided into incisal, middle, and cervical thirds in the cervical-incisal direction, and into mesial, middle, and distal thirds in the mesiodistal direction. This rule allows precise identification of landmarks, such as placing the mesioincisal angle of the maxillary central incisor in the incisal third (cervical-incisal direction) and mesial third (mesiodistal direction). The same rule applies to the root (Crăciunescu et al., 2023).

2.3 Anatomy of maxillary permanent lateral incisor

The maxillary lateral incisor complements the central incisor in function and has a crown that closely resembles it. However, the lateral incisor is smaller in all dimensions except for the length of its root. Due to its similarity in form to the maxillary central incisor, comparisons are often drawn between the two in descriptions. Unlike the central incisor, the lateral incisor exhibits considerable variation in its development, making it the most variable tooth in form aside from the third molar. Excessive variation can result in a developmental anomaly. A common example is a lateral incisor with a small, pointed shape, referred to as a peg-shaped lateral (Nelson & Ash, 2010).

Additionally, the presence of a palatogingival groove, also known as a palatoradicular groove, can predispose the tooth to localized periodontal disease (Nelson & Ash, 2010). Certain malformed lateral incisors may feature a prominent, pointed tubercle as part of the cingulum. Others may have deep developmental grooves extending lingually along the root, pronounced folds in the cingulum, twisted roots, distorted crowns, or similar abnormalities (Nelson & Ash, 2010).

2.3.1 Labial surface

When viewed from the labial surface the mesial outline of its crown often mirrors that of the central incisor but typically presents a more rounded mesioincisal angle (Nelson & Ash, 2010). The mesial crest of contour is generally situated at the junction of the middle and incisal thirds. In certain "square" crown forms, the mesioincisal angle may be nearly as sharp as that of the central incisor; however, a more rounded mesioincisal angle is more commonly observed. In contrast, the distal outline of the crown differs notably from the central incisor. It is consistently more rounded, with the crest of contour located more cervically, commonly near the centre of the middle third. Some crown variations exhibit a semicircular distal outline, extending gracefully from the cervical line to the centre of the incisal ridge, a semicircular shape extending from the cervical line to the centre of the incisal ridge (Kondo et al., 2014).

The labial surface of the crown is generally more convex than that of the central incisor, except in certain square or flat-faced forms. The maxillary lateral incisor is narrower mesiodistally, measuring approximately 2 mm less than the central incisor (Nelson & Ash, 2010). Its crown is also shorter cervicoincisally, typically by about 2 to 3 mm. Despite this, the root length of the lateral incisor is usually comparable to or slightly longer than that of the central incisor. The root length is proportionally greater relative to the crown length than in the central incisor, with the root often being about 1.5 times the crown length (Nelson & Ash, 2010).

The root tapers evenly from the cervical line to about two-thirds of its length, where it commonly curves sharply in a distal direction, terminating in a pointed apex. Although distal curvature is the most typical pattern, variations occur, including straight roots or those curving mesially. Research highlights that these variations in root curvature can impact clinical procedures such as endodontic treatment, as curvature affects access and instrumentation (L. Wang et al., 2022). The lateral incisor's significant variability in crown morphology, combined with its narrower dimensions, contributes to its unique role in dental aesthetics and occlusion.

2.3.2 Palatal surface

From the palatal surface perspective, the mesial and distal marginal ridges of the maxillary lateral incisor are distinctly pronounced (Nelson & Ash, 2010). The cingulum is typically prominent and often integrates with deep developmental grooves within the palatal fossa, where it merges with the cingulum. The linguoincisal ridge is well-developed, and the palatal fossa exhibits a more concave and well-defined shape compared to the central incisor (Nelson & Ash, 2010). It is similar to the central incisor, the crown tapers toward the palatal surface.

A notable feature is the presence of a deep developmental groove, often found adjacent to the cingulum, typically on the distal side (Nelson & Ash, 2010). This groove may extend onto the root, sometimes traversing its entire length. Additionally, the enamel in the deep areas of these developmental grooves is prone to irregularities or faults. These anatomical features, while significant in the natural tooth structure, holds significant implications for personal identification, age estimation, and pathology investigations. These unique anatomical characteristics can serve as identifying markers when analysing dental remains, as the distinctiveness of the grooves, ridges, and cingulum can be matched to an individual's dental records or known dental features.

2.3.3 Mesial surface

The mesial surface of the maxillary lateral incisor closely resembles that of the central incisor but is generally smaller in all dimensions except for root length. The crown is shorter, and the root is relatively longer. The labiolingual measurement of both the crown and root is approximately one millimetre less than that of the maxillary central incisor in the same mouth (Nelson & Ash, 2010). The curvature of the cervical line is pronounced in the direction of the incisal ridge; however, due to the smaller size of the crown, the actual extent of curvature is less than that found on the central incisor. The well-developed incisal ridge makes the incisal portion appear somewhat thicker than that of the central incisor. The root appears as a tapered cone from this surface, with a bluntly rounded apical end (Nelson & Ash, 2010). This varies among individuals, with the apical end sometimes being quite blunt, while at other times, it is pointed. In many cases, the labial outline of the root from mesial surface is straight. As in the central incisor, a line drawn through the centre of the root tends to bisect the incisal ridge of the crown.

2.3.4 Distal surface

The distal surface of the maxillary lateral incisor exhibits a crown that appears wider than its mesial counterpart which primarily due to the positioning of the crown on the root (Nelson & Ash, 2010). This results in a more pronounced distal marginal ridge and a broader labial surface. The curvature of the cervical line on the distal side is typically less pronounced than on the mesial side, often being approximately one millimetre less in depth (Nelson & Ash, 2010). Additionally, it is common to observe a developmental groove on the distal surface of the crown, which may extend onto the root for part or all its length. These grooves are considered developmental anomalies and can influence the tooth's functionality and susceptibility to pathology.

2.3.5 Incisal surface

The incisal view of the maxillary lateral incisor can either resemble the central incisor or a smaller canine, depending on its development (Nelson & Ash, 2010). When the lateral incisor follows the same developmental pattern as the central incisor, it looks similar in shape but smaller in size. However, if the lateral incisor has a larger cingulum and a more prominent incisal ridge, the labiolingual dimension may be greater than the mesiodistal dimension, causing it to look more like a small canine (Nelson & Ash, 2010). In general, maxillary lateral incisors are more convex on both the labial and lingual surfaces than central incisors. On the other hand, the maxillary central incisor appears bulkier from the incisal view, with broad contact areas on the mesial and distal sides. Its incisal surface typically has a triangular shape, though the lingual portion often has some irregularities.

2.4 Sex determination in forensic anthropology

Sex determination is a fundamental aspect of forensic anthropology, crucial for establishing the biological profile of unidentified human remains. Accurate sex estimation aids in narrowing down potential identities and is essential in medico-legal investigations. Traditional methods primarily involve morphological assessments of skeletal elements, with the pelvis and skull being the most sexually dimorphic and thus commonly analysed. However, in cases where these bones are fragmented or absent, forensic anthropologists have developed metric methods utilizing other skeletal components, such as long bones and dentition, to estimate sex (Nagare et al., 2018). Recent advancements have also seen the integration of molecular techniques, including DNA analysis, to enhance accuracy in sex determination. Despite technological progress, the reliability of these methods can be influenced by population-specific variations and preservation conditions of the remains, necessitating continuous research and validation across diverse populations.

Before the era of DNA analysis, forensic anthropologists primarily determined the sex of human skeletal remains. This determination is crucial for developing an accurate biological profile, as it influences the assessment of other factors like stature and age estimation. The sex is based on the observation that males and females exhibit differences in the size and shape of the skull and pelvis, a phenomenon known as sexual dimorphism (White & Folkens, 2005). By analysing these morphological features, forensic anthropologists can make informed assessments regarding the biological sex of the remains.

2.4.1 Skull

Sex determination is a fundamental aspect of forensic anthropology, playing a crucial role in identifying individuals from skeletal remains. Among various skeletal elements, the skull is considered the gold standard for sex prediction due to its structural robustness, resistance to post-mortem degradation, and pronounced sexual dimorphism. Researchers have employed both non-metric and metric methods to assess cranial features for sex estimation, each offering unique advantages and limitations.

Non-metric analysis relies on the visual assessment of cranial traits to differentiate between male and female skulls. Alves et al. (2020) examined specific features, including the frontal profile, superciliary arch, glabella, and mastoid process, in a sample of macerated Brazilian skulls. Their findings indicated that when these traits were assessed collectively, they achieved an accuracy of 90%, with the frontal profile emerging as the most reliable indicator. While non-metric methods are advantageous due to their ability to assess fragmented remains and their ease of application, they remain observer-dependent, requiring substantial expertise to ensure consistency.

In contrast, metric methods provide a quantitative and objective approach to sex estimation. Wang et al. (2024) highlighted advancements in three-dimensional (3D) imaging techniques, such as CT and MRI scans, which allow for precise geometric morphometric (GM) analysis. These technologies enable the separation of size and shape components in cranial morphology, improving sex classification accuracy. Additionally, they emphasized the importance of population-specific models, as cranial sexual dimorphism varies across ethnic groups. This need for localized reference datasets was also supported by Cappella et al. (2022),who developed a logistic regression model tailored to an Italian population, demonstrating the importance of incorporating ethnic variability into predictive models.

Several studies have focused on specific cranial structures that exhibit strong sexual dimorphism. Bhayya et al. (2018) conducted a craniometric assessment of the mastoid process using radiographic measurements, reporting a classification accuracy of 80%. Similarly, Passey et al. (2021) analysed the mastoid triangle in dry skulls from the North Indian population and confirmed its reliability for sex determination, achieving an 85% accuracy rate. These findings highlight the mastoid region as a key feature in forensic identification.

Del Bove et al. (2023) further expanded on cranial sex estimation by employing a landmark-based approach to map sexual dimorphism across the entire cranium. Their study reinforced the significance of cranial structures in distinguishing sex but did not specify an overall accuracy rate. Wei et al. (2024) utilized cone beam computed tomography (CBCT) to assess craniofacial bones in a central Chinese population, applying geometric morphometric techniques to achieve an impressive accuracy of over 90%.

2.4.2 Pelvis

The human pelvis is considered the most reliable skeletal element for sex determination in forensic anthropology due to its significant sexual dimorphism, stemming from its functional roles in locomotion and childbirth. Traditional morphological and metric methods, as well as advanced computational techniques, have been employed to enhance the accuracy of sex estimation.

Rogers & Saunders (1994) provided one of the earliest comprehensive evaluations of the morphological traits of the human pelvis for sex determination. They identified key dimorphic features such as the subpubic angle, sciatic notch, and ventral arc, reporting a high accuracy rate for sex determination based on visual assessments. Their findings highlighted the pelvis's potential as a primary skeletal element for identifying sex when the overall skeletal remains are fragmented or incomplete. However, the study also underscored the need for examiner expertise to minimize subjectivity in morphological evaluations.

In a shift toward more quantitative approaches, Gonzalez et al. (2009) utilized a geometric morphometric framework to assess sexual dimorphism in the pelvis. By analysing the shape of pelvic landmarks using three-dimensional coordinates, they achieved enhanced precision and reduced observer bias. This method enabled the separation of shape and size in dimorphism analyses, offering a robust and repeatable approach to sex estimation. They emphasized the applicability of geometric morphometrics for diverse populations, addressing the variability of pelvic morphology across different ethnic groups.

Modern computational techniques, as illustrated by Secgin et al. (2021), have further transformed the field. Their study utilized computed tomography (CT) images of the pelvis and applied a decision tree algorithm for automated sex prediction. This approach demonstrated a high accuracy rate, showcasing the utility of machine learning in forensic anthropology. The integration of CT imaging allows for precise measurement of pelvic dimensions, while decision tree algorithms enable automated and efficient sex classification, reducing the reliance on manual analysis.

Building on these advancements, Ives et al. (2024) introduced a novel method focused on pelvic scarring to estimate sex in adult individuals. Their study identified patterns of scarring associated with parturition in females as a distinguishing feature, with the potential to augment existing methods of sex determination. This technique is particularly useful in populations where traditional morphological features may overlap due to environmental or genetic factors. The study also emphasized the importance of population-specific research to enhance the applicability of pelvic-based methods in forensic contexts.

2.4.3 Long Bone

Long bones, including the humerus, femur, and forearm bones, are frequently used for sex determination in forensic anthropology due to their robustness, ease of preservation, and measurable dimorphic traits. Recent studies have combined traditional morphometric methods with advanced computational techniques to enhance the accuracy and applicability of these analyses across populations.

Harris & Case (2012) explored sexual dimorphism in the tarsal bones and its implications for sex determination. Although primarily focused on the tarsals, their findings provide insights into the broader applicability of long bones for forensic purposes. They demonstrated that specific dimensions of the tarsal bones exhibit statistically significant sexual dimorphism, highlighting their potential as supplementary skeletal elements for sex estimation. This study laid the foundation for understanding the role of smaller long bones in sex determination, especially when larger bones are unavailable.

Okai et al. (2019) focused on the predictive potential of percutaneous forearm bone lengths for estimating both height and sex. Their study introduced a regression-based model, demonstrating high accuracy in sex classification using simple, non-invasive measurements. This method offers practical utility in forensic investigations where skeletal remains are incomplete or when rapid assessments are required. The authors underscored the importance of incorporating both metric and non-metric traits for comprehensive analyses, particularly in contexts with limited resources.

Similarly, Knecht et al. (2023) expanded the scope of sex estimation by applying machine learning to the analysis of long bones. Their study utilized a large dataset of femoral and humeral measurements, employing various machine learning algorithms to develop predictive models. The integration of artificial intelligence allowed for the identification of complex patterns in the data, resulting in highly accurate sex estimation. This approach not only reduces observer bias but also highlights the potential of automated systems to handle large datasets efficiently. The study emphasized the need for population-specific training data to account for variability in sexual dimorphism across different demographic groups, ensuring the generalizability of the models.

2.4.4 DNA

DNA-based methods have significantly advanced sex determination in forensic anthropology and bioarchaeology, offering high accuracy even when skeletal remains are fragmented or degraded. Palmirotta et al. (1997) pioneered the application of multiplex polymerase chain reaction (PCR) assays for sex typing in DNA extracted from archaeological bones. Their study demonstrated the effectiveness of multiplex PCR in amplifying sex-specific genetic markers, even from degraded DNA samples. This breakthrough enabled accurate sex determination in ancient remains, highlighting the resilience of DNA-based methods in challenging conditions where traditional morphological features may be compromised.

Further advancements in DNA-based sex determination were highlighted by Ludeman et al. (2018), who validated the GlobalFiler™ PCR amplification kit, a six-dye multiplex assay designed for forensic casework. This kit amplifies short tandem repeats (STRs) and amelogenin markers, providing high sensitivity and specificity, which makes it ideal for forensic applications, even when DNA samples are degraded. Thomas (2020) expanded on these methods by reviewing emerging technologies such as Y-chromosome analysis and next-generation sequencing (NGS). These methods, which involve detecting differently sized amplicons through gel electrophoresis, indicate female presence with a single band (X chromosomes) and male presence with two bands (X and Y chromosomes).

2.4.5 Dentition

Besides, teeth are organs composed of the hardest mineralized tissue in the human body, which makes them highly resistant to decay and capable of withstanding physical, thermal, mechanical, chemical, or biological damage (Astete jofré et al., 2009). Therefore, sex determination analysis can be performed through morphological analysis of tooth, which can focus on either hard tissue such as odontometric and orthometric measurements or miscellaneous hard tissues of the oral and perioral regions. It can also involve the examination of soft tissues, including lip prints (cheiloscopy) and palatal rugae patterns (rugoscopy)(Ramakrishnan et al., 2015).

In this literature review will converge on the odontometric methods which involve mesiodistal dimensions and buccolingual dimension of teeth. Sexual dimorphism is evident in the shape and size of teeth, particularly in the mesiodistal and buccolingual dimensions. Tooth dimensions are a simple and reliable method for analysing sexual dimorphism, with studies indicating that the mesiodistal dimensions of male teeth are generally larger than those of female teeth (Khangura et al., 2011). According to Moss, it is due to greater enamel thickness in males, resulting from a long period of amelogenesis compared to females (Moss & Moss-Salentijn, 1977).

Soundarya et al. (2021) investigated sexual dimorphism in permanent maxillary and mandibular teeth using odontometric analysis. The study demonstrated that the mesiodistal (MD) width of the maxillary mesiodistal (MD) width, labiolingual (LL) width as well as cervicoincisal (CI) length of the crown in both maxillary and mandibular permanent incisors, canines and first molars. The findings revealed that males exhibited larger MD and CI dimensions compared to females, with the CI dimension of the mandibular first molar achieving an overall prediction accuracy of 72.5%. Notably, the accuracy for identifying males was 89.7%, though it was lower for females at 56.1%. Logistic regression analysis also confirmed the MD width of the maxillary canines and CI length of the mandibular first molars as significant parameters for sex determination.

Besides, the study of Khamis et al. (2014) provides a comprehensive analysis of odontometric sex variation in Malaysians, with a specific focus on the mesiodistal (MD) and buccolingual (BL) dimensions of permanent teeth. Their study highlights that certain tooth, particularly the lower canines, exhibit significant sexual dimorphism, making them valuable for sex prediction in forensic contexts. The research underscores the importance of population-specific data, revealing that the degree of sexual dimorphism varies among the three major ethnic groups in Malaysia—Malays, Chinese, and Tamils. This finding is crucial because it suggests that generalized models may not be applicable across different populations, emphasizing the need for tailored forensic approaches.

Despite the thorough examination of various odontometric parameters, the study by Khamis et al. (2014) does not extensively explore the mesiodistal dimensions of the palatal surfaces of incisors, which could be a valuable metric for sex determination. Most of the focus has been on the canines and other posterior teeth, leaving a gap in the literature regarding the potential of incisors, particularly in the context of the palatal surface. This gap suggests a need for further research to determine whether the mesiodistal dimensions of these surfaces could provide additional or even superior indicators of sexual dimorphism, potentially improving the accuracy of sex prediction models in forensic anthropology.

Also, most studies have focused on investigating the cusp and crown area measurement of maxillary posterior teeth, to analyse differences and correlations between sexes, employing a two-dimensional stereomicroscope (Riaz, Khamis, Ahmad, et al., 2023a). According to Riaz et al. (2023) males generally displaying larger cusps and crown areas than females in the Malay population of Malaysia. The research identifies the maxillary first premolar, second premolar, and first molar as the most sexually dimorphic tooth, particularly the mesiopalatal cusp. The logistic regression analysis was conducted using the backward stepwise Wald method which demonstrated strong accuracy with correctly predicting 80% of the selected cases and 71.2% of the unselected cases. The Hosmer-Lemeshow test yielded a not significance value of p =