

**3D SEX PREDICTION MODEL IN MALAYS USING LOWER
SECOND MOLAR**

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**3D SEX PREDICTION MODEL IN MALAYS USING LOWER
SECOND MOLAR**

by

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LIST OF SYMBOLS

α Alpha

β Beta

% Percentage

LIST OF ABBREVIATIONS

2D Two dimensional

3D Three dimensional

AI Artificial intelligence

ANN Artificial neural network

CBCT Cone beam computed tomography

CL/P Cleft lip and palate

DNA Deoxyribonucleic acid

DT Decision Tree

GH Growth hormone

GMM Geometric morphometric

ICD Intercuspal distance

IPD Interpit distance

LR Logistic Regression

ML Machine Learning

NB Naïve Bayes

OPG Orthopantomogram

PCR Polymerase chain reaction

PMCT Post-mortem computed tomography

RF Random Forest

SD Standard deviation

SVM Support Vector Machine

TLCG Total length of central groove

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MODEL PERAMALAN JANTINA 3D DALAM KALANGAN ORANG MELAYU MENGGUNAKAN GIGI MOLAR KEDUA BAWAH

ABSTRAK

Model peramalan jantina memainkan peranan penting dalam bidang forensik, terutamanya dalam Pengecaman Mangsa Bencana (DVI), dengan mengurangkan potensi kumpulan pengecaman kepada kira-kira separuh. Jantina juga merupakan komponen asas dalam profil biologi kerana ia menjadi asas kepada anggaran parameter lain seperti umur dan ketinggian. Sehingga kini, tiada kajian yang menyelidik peramalan jantina menggunakan ciri oklusal—khususnya jarak interkuspal (*intercuspal distance, ICD*), jarak interpititis (*interpit distance, IPD*), dan jumlah panjang alur tengah (*total length of central groove, TLCG*)—dalam populasi Melayu Timur Laut Malaysia. Oleh itu, kajian ini bertujuan untuk menilai hubungan antara ciri oklusal gigi molar kedua bawah dengan jantina dalam kalangan populasi tersebut. Pengukuran ICD, IPD, dan TLCG diperoleh secara tidak langsung daripada model acuan gigi 3D bagi 200 individu Melayu (100 lelaki dan 100 perempuan) menggunakan perisian *3-Matics*. Ujian-t sampel tidak bersandar dijalankan untuk menilai dimorfisme seksual antara jantina. Model peramalan jantina dibangunkan menggunakan empat pendekatan pembelajaran mesin, iaitu Regresi Logistik (LR), Mesin Vektor Sokongan (SVM), Random Forest (RF), dan Pokok Keputusan (DT). Keputusan menunjukkan bahawa nilai min ICD, IPD, dan TLCG secara umumnya lebih besar dalam kalangan lelaki berbanding perempuan, kecuali bagi jarak ML–MB. Antara model yang diuji, LR menunjukkan prestasi terbaik dengan nilai kawasan di bawah lengkung (AUC) sebanyak 0.70. Analisis LR secara langkah demi langkah mengenal pasti ML–MB ($p = 0.008$), MB–DB ($p = 0.014$), dan MB–DL ($p = 0.007$) sebagai peramal jantina yang signifikan. Dua daripada pemboleh ubah yang dikaji adalah lebih besar secara statistik pada lelaki berbanding perempuan, dengan peratusan

dimorfisme seksual antara 0.3% hingga 7.4% Model LR menghasilkan klasifikasi yang sederhana (ketepatan klasifikasi = 0.63, nilai AUC = 0.70), manakala model-model lain menghasilkan klasifikasi yang lemah.

3D SEX PREDICTION MODEL IN MALAYS USING LOWER SECOND MOLAR

ABSTRACT

Sex prediction models play a crucial role in forensic science, particularly in disaster victim identification (DVI), by reducing the potential identification pool by approximately half. Sex is also a fundamental component of the biological profile, as it forms the basis for estimating other parameters such as age and stature. To date, no studies have investigated sex prediction using occlusal traits—specifically intercuspal distance (ICD), interpit distance (IPD), and total length of the central groove (TLCG)—within the Northeastern Malay population of Malaysia. Therefore, this study aimed to evaluate the relationship between occlusal traits of the lower second molar and sex among the northeastern Malay population. Measurements of ICD, IPD, and TLCG were obtained indirectly from 3D dental casts of 200 Malay individuals (100 males and 100 females) using 3-Matics software. An independent t-test was conducted to assess sexual dimorphism between sexes. Sex prediction models were developed using four machine learning approaches: Logistic Regression (LR), Support Vector Machine (SVM), Random Forest (RF), and Decision Tree (DT). The results demonstrated that mean values of ICD, IPD, and TLCG were generally higher in males than in females, except for the ML–MB distance. Among the models tested, LR achieved the best performance, with an area under the curve value (AUC) of 0.70. Stepwise LR analysis identified ML–MB ($p = 0.008$), MB–DB ($p = 0.014$), and MB–DL ($p = 0.007$) as significant predictors of sex. Two of the variables studied were statistically significantly larger in males than females. The percentages of sexual dimorphism ranged from 0.3-7.4%. The highest sex prediction model was LR and yielded fair classification (classification accuracy = 0.63, AUC value = 0.70). Other models yielded poor classification.

Chapter 1 INTRODUCTION

1.1 Background

Sex prediction is one of the fundamental components in the biological profiling of human skeletal remains in forensic anthropology. Determining the sex of an individual assists in narrowing down the search parameters in identification processes and provides the basis for age, ancestry and stature estimation (Krishan et al., 2016). Historically, sex prediction relied on morphological analysis of skeletal elements such as pelvis, skull, and dental records (Krishan et al., 2016). These methods remain valuable but are limited by subjectivity, population specificity, and the condition of remains. In forensic and archaeological contexts, especially in tropical and humid climates such as Malaysia, these bones are often found in a fragmentary or deteriorated condition due to environment factors, post-mortem damage, or taphonomy changes. Consequently, there is a critical need for alternative method that are more durable and resistant to post-mortem degradation for accurate sex prediction.

DNA-based sex determination, particularly using PCR amplification of markers like amelogenin, SRY, and DYS14 is now standard, offering high accuracy even with compromised samples. Teeth and bone fragments are preferred sources due to their resilience. However, DNA-based sex determination requires laboratory facilities, can fail with degraded/contaminated samples, is costlier and more legally intensive (Bhoyar et al., 2024). 3D dental cast offers fast, non-destructive, portable, inexpensive to digitize and share, easily transmitted via the Internet, allows the dental practitioners to make accurate, rapid and convenient diagnosis and can be coupled with automated morphometrics or Artificial Intelligence (AI) for good accuracy (Baban & Mohammad, 2024).

A systematic review by Sabóia et al. (2013) highlights a significant geographic imbalance in sex estimation research within Southeast Asia. Out of fifteen relevant studies identified between 2014 and 2022, thirteen originated from Thailand, while only two were conducted in Malaysia. Notably, both Malaysian studies focused exclusively on the pelvis and cervical vertebrae. This scarcity of data underscores a critical research gap; if skeletal studies are this limited, the field of forensic odontology remains even more profoundly under-explored in the Malaysian context. Furthermore, the review concluded that sex prediction yields the highest accuracy when population-specific standards are employed. This is supported by Franklin & Flavel (2019), who observed that applying statistical models to individuals outside the original reference sample almost inevitably leads to a reduction in classification accuracy. Consequently, there is an urgent need to develop localized standards for the Malaysian population to ensure reliable forensic identification.

Sexual dimorphism refers to the physical differences that differentiate a male from a female of a species. Previous study revealed that permanent dentition exhibits sexual dimorphism even though it forms before the appearance of secondary sexual characteristics (Pilloud et al., 2024). Sexual dimorphism is noted in teeth throughout the dental arcade (Abaid et al., 2021). It can be observed in canines, molars, incisors, and premolars (Sabóia et al., 2013; Tabakcilar et al., 2021). Previous studies also hypothesized that under the influence of the Y-chromosome, mitotic activity in the tooth germs is enhanced, resulting in greater dentine thickness and larger crowns in males compared to female (Abaid et al., 2021). Therefore, the measurable difference in tooth size and morphology in teeth can be used as indicator for sex prediction. However, most existing studies in Malaysia have concentrated on maxillary anterior teeth like canines or maxillary posterior teeth like premolar and first molar (Harudin

et al., 2023;Riaz et al., 2024). This limitation poses challenges in applying existing models in cases where only mandibular posterior teeth were left, as dental morphometrics is known to vary across populations due to genetic factor (Garn et al., 1967), hormonal factor(Tabakcilar et al., 2021), and epigenetic factor(Lam et al., 2016).

Moreover, a large proportion of past studies on Malay population have relied on two-dimensional (2D) measurements techniques, such as manual caliper-based measurements (Kaeswaren & Weinheimer, 2019; Khamis et al., 2014), which may not capture subtle three-dimensional variations in dental morphology and low accuracy of prediction in the range of 75% to 80% (Riaz et al., 2024 ;Khamis et al., 2014). With the advancement of imaging technology, 3D morphometric analysis offers a more comprehensive and accurate approach to evaluate dental structures. Despite its growing use in other fields, there remains a lack of studies utilizing 3D analysis of posterior teeth, particularly the mandibular second molar (LM2), for sex prediction in the Malay population. Posterior teeth, especially molars, are known to exhibit stronger sexual dimorphism (Natarajan et al., 2025) due to their larger size, robust structure, and higher resistance to wear and post-mortem damage compared to anterior teeth.

The absence of population-specific and three-dimensional data for Malays creates a significant gap in forensic reference databases, limiting the accuracy of sex determination in cases involving Malaysian individuals. Therefore, there is a clear need to investigate sexual dimorphism in the posterior teeth of Malays using 3D imaging methods and to develop a population-specific predictive model. This study aims to address this gap by analyzing three-dimensional measurements, such as intercuspal distance (ICD), total length of central groove (TLCG), and interpit distance (IPD), to determine their potential as reliable indicators for sex

prediction. Establishing a 3D sex prediction model specific to the Malay population would contribute to the enhancement of accuracy of sex prediction and provide valuable reference data for future anthropological and forensic applications.

1.2 Problem statement

To date, there is no publication of sex prediction using occlusal traits, specifically, such as intercuspal distance, interpit distance and total length of central groove in Malaysian population. Therefore, this study aims to assess the relationship between the occlusal traits (intercuspal distance, interpit distance, and total length of central groove) of occlusal surfaces of mandibular second molar and sexes in Malay population.

In addition, the previous sex prediction accuracies in the Malay population were considered low to moderate, 77.9% (Khamis et al., 2014) and 80% (Riaz et al., 2024) respectively. This study aims to improve the accuracy of current sex prediction model for Malay population to more than 90% and achieve area under the curve index to more than 0.8 by incorporating 3D data analysis of intercuspal distance, interpit distance, and total length of central groove.

1.3 Objective

1.3.1 General objective

To determine the association between the occlusal traits (intercuspal distance, interpit distance, total length of central groove) of occlusal surfaces of lower second permanent teeth and sex in Malays population.

1.3.2 Specific objective

1.To evaluate sexual dimorphism of intercuspal distance, interpit distance, total length of central groove

2.To formulate sex prediction model, using intercuspal distance, interpit distance, total length of central groove as predictors

1.4 Significance of study

This study holds significant value in the field of forensic anthropology and odontology, as it aims to enhance methods of sex prediction using dental measurements. In many forensic and archaeological cases, skeletal remains are often incomplete or fragmented, making traditional indicators such as the pelvis or skull unavailable for analysis. Teeth, however, is among the most durable structures in the human body and can withstand decomposition, fire, and environmental damage. Thus, examining sexual dimorphism in the mandibular second molar provides an alternative and practical approach to determining sex when other skeletal elements are missing.

The study also addresses the importance of establishing population-specific standards for sex prediction. Dental morphology and dimensions can vary significantly among populations due to genetic, environmental, and dietary factors. Therefore, data derived from non-Malay populations may not accurately reflect the dental characteristics of the Malay population. By generating odontometric data specific to the Malay population, this research contributes to building a more reliable and locally relevant reference framework for forensic identification in Malaysia.

Furthermore, the findings of this research have broader implications for improving forensic investigation and human identification accuracy. Developing a reliable statistical model

based on dental measurement can assist forensic experts, anthropologists and law enforcement agencies in narrowing down identification parameters in both disaster victim identification and criminal cases. Beyond its forensic application, this study also contributes to the global understanding of sexual dimorphism in human dentition, enriching comparative data that can support future regional and cross-population studies.

In addition, the data obtained from this study can serve as a valuable foundation for future research involving AI and digital forensic applications. As forensic science increasingly integrates technology, accurate and comprehensive odontometric datasets are essential for training AI algorithms capable of performing automated sex prediction and identification. The measurements and statistical models derived from this research could be used to develop machine learning (ML) systems that analyze dental images, radiographs, or 3D scans with high precision and consistency. Furthermore, the findings can support the creation of digital modules or databases that store population-specific dental metrics, which would enhance the speed and reliability of digital identification processes in forensic investigations.

Chapter 2 LITERATURE REVIEW

2.1 Characteristic of teeth

Teeth, with its extra high durability, is one of the great humans remains that can be used in sex identification in Disaster Victim Identification (DVI). Teeth are composed of enamel, dentin and cementum with enamel being approximately 96% inorganic matters, 1-4% organic matter and 1-4% water (Sarna-Boś et al., 2022). The enamel covers the entire tooth crown and can reach several millimeters thickness. Enamel is the hardest tissue in the human body and has more structural hardness than bone remains, allowing them to survive longer periods and in better conditions in archaeological-logical context (Yepes López et al., 2019). Inorganic matters such as calcium and phosphate ions are the key components who provide hardness and mechanical resistance to the teeth. Teeth can resist physical, chemical, thermal, and biological postmortem damage. In addition, due to their small sizes, recovered teeth are generally unbroken compared to most bones. Moreover, human permanent dentition possesses morphological characteristics and dimensions that do not vary at the end of the growth and development period. Therefore, teeth, with their unique and strong characteristics, have high potential as indicator for sex prediction.

Tooth development proceeds through stages from initiation to maturation. The epithelium will differentiate into preameloblast. The preameloblast then become secretory ameloblasts and secrete enamel matrix. On the other hand, neural crest-derived cells will differentiate into odontoblasts. Odontoblast first appears at the sites of the future cusp tips and is responsible for secretion and mineralization of the dentine matrix. Early tooth development during the bud-to-cup transition requires signals from a transient signaling center named the primary enamel knot (EK). In monocuspid teeth such as incisors, and canines, only one EK develops.

In multi-cusped teeth like premolars and molars, secondary EKs act as signaling centers that define cusp tips (Yu & Klein, 2020). The EKs are non-proliferative and produce signaling molecules like fibroblast growth factors (FGF), bone morphogenetic proteins (BMP), β -catenin (Wnt), sonic hedgehog (Shh) that regulate the surrounding epithelium and mesenchyme to drive folding and shaping of cusps (Jernvall & Thesleff, 2012).

The spatial and temporal patterning of those knots influences where cusps will emerge (Kenessey et al., 2023). Grooves and pits are formed in the occlusal surface because of differential folding, invaginations, and growth constraints between cuspal regions. The deepest invaginations or converging folds may produce pits. Also, the lateral growth of the mesenchyme can push enamel organ loops outward, and in intercuspal regions the leftover epithelial tongues may appear, contributing to groove or pit formation (Yu & Klein, 2020; Seo et al., 2017). To sum up, pits, grooves, and cusp tip positions have been fixed during tooth development. Thus, their location and positions do not alter due to tooth eruption. However, these structures can be altered due to tooth wear, caries, and dental treatments or mutilation (Pinchi et al., 2015).

2.2 Factors affecting tooth development

Tooth development, or odontogenesis, is a complex embryonic process initiated and regulated by continuous epithelial-mesenchymal interactions. It is influenced by a combination of local and systemic factors, both of which can lead to developmental disturbances in tooth size, shape, structure, or number. In humans, odontogenesis begins early in prenatal development. The primary teeth start to form between 6th and 8th weeks of gestation, and the first permanent teeth buds appear around the 20th week in the utero

(Novacescu et al., 2025). If tooth development does not happen on time during these crucial periods, the affected teeth may not develop at all, leading to their congenital absence.

2.2.1 Local Factors Affecting Tooth Development

Local factors act directly on the development of tooth germs or surrounding tissues in a localized area of the jaw. Any trauma to the primary dentition may disturb the odontogenesis of the permanent dentition due to the close anatomical proximity of the apices of the primary teeth and germs of the permanent dentition. The most frequently involved teeth are the primary upper incisors. Two main mechanisms are used to describe how dental trauma on primary teeth can damage permanent successors. Firstly, a direct injury of the germ of the permanent tooth for the impact of the apex of the primary tooth's root and secondly, an indirect injury due to the pulp necrosis of the primary tooth and the consequent periapical infection (Bardellini et al., 2017). Common consequences observed in permanent dentition include enamel hypoplasia, crown dilaceration, arrest of root development, and eruption disturbances. These development disturbances will affect the morphology of the tooth (von Arx, 1993).

The pulpal inflammation or infection of a primary tooth and the spread of this condition to the periradicular tissues can lead to alterations in the dental germ of the permanent successor and to the surrounding structures. Bacterial invasion in the pulpal cavity and the action of its metabolic products together with pulp degradation can alter the unit of primary teeth in an irreversible way. Apical periodontitis of permanent dental germ interferes with formation, leading to injuries that can vary from enamel hypoplasia to arresting development of the permanent tooth. The severity of alteration in the development of a succedaneous permanent tooth germ depends on stage of calcification (Nolla's stage) and the degree of infection in

the primary tooth (Mariela Rodriguez Cordeiro & Jose de Carvalho Rocha, 2005). A study by Patil et al. (2023) confirms that chronic apical periodontitis of the primary dentition exerts a significant impact on the orientation of the emergence of permanent successors. The same study observed abnormalities in the shape of the permanent teeth on the affected side compared to the normal side, and these abnormalities were noticed in four-year-old participants, who had a history of infected, unrestored primary molars at the age of 2.5 to 3 years old.

Chemotherapy and have deleterious effects on dentition in children and adolescents. In a study by Najafi et al. (2011), disturbances in the root development of the mandibular teeth including short roots, arrested root development, V-shaped root and loose teeth were observed on a girl patient who once received chemotherapy and 2400-cGy radiation therapy treatment at the age of five for a lesion of Hodgkin's disease in the neck area. Pombo Lopes et al. (2024) conducted a systemic review and meta-analysis which found out that discoloration (53%), crown-root malformation or agenesis (36%), and enamel hypoplasia (32%) were the most common dental anomalies observed in childhood cancer survivors, followed by root development alterations, unerupted teeth, microdontia, hypodontia, and macrodontia.

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2.2.2 Systemic Factors Affecting Tooth Development

Systemic factors affect the body as a whole and influence the formation, mineralization, and eruption of all teeth to varying degrees. Among the systemic factors, the endocrine system plays a critical role, as hormones regulate cellular differentiation, proliferation, and bone remodeling necessary for tooth formation and emergence. Recent literature reinforces the connection between hormonal balance and dental outcomes, primarily observing delays in eruption time and developmental anomalies with endocrine disorders.

Growth hormone (GH) is synthesized by hypophysis and is an important hormone affecting postnatal growth. It can cause gigantism in children of 0-6 years old and acromegaly in grown-ups if it is over synthesized. Children or adults with gigantism have normal dentition, but different sizes or shapes of teeth compared to others. On the other hand, in a study by Torlińska-Walkowiak et al. (2025) observed delay in tooth eruption observed in the short-statured children, particularly the first permanent molars and incisors.

Thyroid gland hormones such as triiodothyronine (T3), thyroxine (T4), and calcitonin hormones regulate the metabolism speed of the body (Tabakcilar et al., 2021). Hyperthyroidism occurs when thyroid hormones are over secreted and will lead to increased metabolic rates. High metabolic rates will lead to accelerated tooth eruption, maxillary and mandibular osteoporosis. In contrast, hypothyroidism is a medical condition where thyroid hormones are insufficiently secreted and leads to decreased metabolic rate and osteoblastic

activity and can therefore cause dental abnormalities such as enamel hypoplasia, micrognathia, and delayed tooth eruption (Papadopoulou et al., 2024).

Syndromic diseases such as Down Syndrome and cleidocranial dysplasia are well documented examples which contribute to delayed tooth eruption (Wang et al., 2015), supernumerary teeth, and misalignment. These anomalies arise due to genetic mutations that impact craniofacial development and bone growth (Ahmed et al., 2025).

Cleft lip and palate (CL/P) is a multifactorial condition in which environment and genetic factors play a major role in its etiology. Past studies revealed that CL/P will cause some dental anomalies such as variations in tooth size, morphology, and position. In a study by Mendes et al. (2023), significant differences in tooth crown size, specifically mesiodistal length and buccolingual width between patients with CL/P and controls was observed. Differences between cleft and non-cleft sides was also being observed in individuals with CL/P. In a study conducted by Kaplan et al. (2020), where mesiodistal values of upper central incisors and first molar were significantly greater in unilateral CL/P patients on the non-cleft side.

Research indicates that diet and nutrition are critical determinants of tooth development, influencing the odontogenesis to the timing of eruption and the quality of enamel mineralization. Deficiencies in key micronutrients, particularly during prenatal and early childhood stages, can lead to irreversible structural defects. The development of hard tissues such as dentine, enamel and cementum requires specific vitamins and minerals to ensure proper crystal structure and density. According to Swapna & Abdulsalam (2021), vitamin D acts as a hormone that regulates calcium and phosphate absorption with the help of intestinal

absorption regulation. Severe deficiency can lead to “rachitic tooth”, which is characterized by highly defective and hypomineralized enamel and dentine, that increases susceptibility to fractures and decay (Botelho et al., 2020). Vitamin A plays an important role in development and maintenance of oral epithelium and periodontium (Chandan & Rao, 2023). According to Gondivkar et al. (2019), deficiency of vitamin A may result in gingivitis and gingival hypoplasia. The severe deficiency of both vitamin A and D is related to enamel hypoplasia.

2.3 Post Developmental Tooth Change

After a tooth erupts in the oral cavity, its morphology and crown dimensions undergo changes primarily due to pathological conditions, wear, dental treatments, or deliberate mutilation as observed in traditional practices.

Tooth wear is a multifactorial condition and directly affects cusp height, groove length, and pit depth. Tooth wear is generally divided into four major types: attrition, abrasion, erosion or corrosion, and abfraction. Attrition refers to mechanical wear from tooth-to-tooth contact. Attrition flattens or removes cusp tips which indirectly alter intercusp distance (Plongniras et al., 2025). Abrasion is mechanical wear caused by foreign objects. Erosion or abrasion refers to the chemical dissolution of tooth structure by acids that do not involve bacteria (Pollock et al., 2024). Abfraction is the microfracture of enamel and dentine due to occlusal stress and flexural forces. Normal wear may smooth or erase pits, diminishing the anatomical features and heavy wear changes occlusal morphology (Bronkhorst et al., 2023).

Dental caries is defined as a localized chemical dissolution of tooth surface resulting from metabolic events taking place in a biofilm covering the affected area. Dental caries usually develops at relatively protected sites in the dentition where biofilms are allowed to accumulate and mature over time. Such sites include pits, grooves, and fissures in occlusal

surfaces, especially during eruption, and approximal surfaces cervical to the contact point or area and along the gingival margin. These can further deepen pits, grooves, and reduce cusp height through demineralization and cavitation (Pang et al., 2021). Dental treatments such as restoration using amalgam and lesion composites on occlusal surfaces of the tooth may also alter or obscure the important landmarks.

Similarly, in certain tribes, teeth may be mutilated as part of their cultures or aesthetics (Kgabi et al., 2024). Tooth mutilation, also known as dental art, is a modification of teeth that alters the surface shape of teeth without any medical indication and has been practiced for thousands of years in the continents of America, East Asia, Southeast Asia, and Africa (Rahmi et al., 2024). Infant oral mutilation is commonly practiced in eastern African countries, and this contributes to trauma that dramatically affect tooth size and morphology, where dimension of enamel, dentine and cementum were all reduced (Zachariadou et al., 2023).

2.4 Sexual dimorphism and factors affecting it

Sexual dimorphism refers to the systemic morphological differences between males and females of the same species and is of great importance in forensic dentistry (Abaid et al., 2021). Sexual dimorphism in dentition is widely observed across populations, with males generally exhibiting larger teeth, especially canines and molars.

Sexual dimorphism in permanent teeth primarily due to differences in dental tissue proportions. According to Sorenti et al. (2019), male molars generally possess significantly greater proportion of dentine than females, both absolutely and proportionally, while females tend to have thicker enamel than males. These differences are most pronounced in canines

and molars. Similar findings were also observed by Fernée et al. (2020). To sum up, the dentine component, rather than enamel, is the main contributor to size differences, and this pattern is consistent across various populations. This finding was confirmed by research on comparison between European and African populations, done by Blasco-Moreno et al. (2024).

Genetic control plays a significant role in tooth size. Sex-linked genes on the Y chromosome promotes dentine, enamel and overall tooth growth whereas X chromosome only influences enamel formation (Abaid et al., 2021). A study on sexual dimorphism between twin and family showed that crown dimensions have a high heritability, with additive genetic variation accounting for a large proportion of the phenotypic variation. Hormonal factors, specifically intrauterine exposure to male hormones also contributed to increased tooth size in males, as supported by studies on twins and individuals with sex chromosome abnormalities (Ajmal et al., 2023) (Paschos, 2013) (Garn et al., 1967).

2.5 Sex prediction methods

It has been universally acknowledged that primary identifiers are the most dependable method for confirming identification. According to INTERPOL (2023), these identifiers include “Friction Ridge Analysis”, “Forensic Odontology” and “DNA”. Forensic odontology is a subfield of dentistry that focuses primarily on identifying a person’s identity by analyzing the distinctive anatomical structure of the oral cavity (Mehmood et al., 2022). Forensic odontology has been extensively applied in Disaster Victim Identification (DVI) to identify victims of mass casualty incidents, either man-made or natural. According to INTERPOL (2025), DVI teams are employed in so-called open and closed disasters. Forensic odontology

is especially useful in open disasters like earthquakes, tsunamis and landslides where identification of the victims is difficult due to large number of casualties involved. It helps narrowing down the pool of potential identities by 50% and makes subsequent identification procedures easier (Acharya & Babu, 2025).

Skull, consists of cranium and mandible, presents an interesting set of traits for studying morphological variation in relation to the sexes or other factors, such as genetics, developmental processes, and environmental influences (Wang et al., 2024). Sexual dimorphism of the skull female skull. Sexual dimorphism also demonstrated in terms of shape. Males tend to develop a more prognathic and dolichocephalic cranium compared to females (Profico et al., 2017).

The human mandible has been considered useful for sex prediction, especially in cases when pelvis and cranium are absent. Toneva et al. (2023) found that mandibular size differed significantly and achieved a sex classification accuracy rate of 87%. Nevertheless, mandibular morphology is susceptible to secular changes and inconsistent among populations.

Sex identification using dental features is primarily categorized into metric, non-metric, radiographic or imaging and biochemical methods. Non-metric methods rely on the presence or absence of specific morphological features from soft and hard tissues. Soft tissue analysis includes cheiloscopy and rugoscopy study, whereas hard tissue analysis examines dental and skeletal anatomy. Compared to metric methods, non-metrics analysis may be more prone to interpreter subjectivity (Heng et al., 2022).

In contrast, the metric method, more known as forensic odontometric is based on quantitative tooth measurements, either directly or indirectly, offering greater precision and reproducibility, which allows for validation of the results. Post-mortem remains with teeth present can undergo metric analysis without sustaining too much harm to the remains. Odontometric methods provide moderate to high accuracy between 51-95.9% for sex prediction, with accuracy varying by both tooth type, population and method (Herrera-Escudero et al., 2024).

Advanced imaging techniques like Cone Beam Computed Tomography (CBCT) and Orthopantomograms (OPGs) also are increasing utilized to accurately measure odontometric and craniofacial features, such as the mandibular ramus height and gonial angle, without damaging the remains (Acharya & Babu, 2025).

Biochemical method, which use Polymerase Chain Reaction (PCR) targeting human markers like amelogenin, SRY, and DYS14 to identify sex. These markers consistently offer the highest accuracy rates for sex determination, especially in severely degraded or burnt remains where morphological traits are compromised. Studies demonstrated that accuracy of sex prediction using amelogenin can reach 99% for combined modern and archaeological reference samples (Gamble et al., 2024). Nonetheless, the accuracy drops when the samples were contaminated as demonstrated in a study by Reddy et al. (2011), where four females were wrongly identified as male out of 15 female samples, giving only 73.3% accuracy. Although it is regarded as the gold standard, its routine application in forensic practice is often constrained by cost, logistical challenges, and the requirement for specialized equipment.

Odontometric analysis basically involves taking the linear measurements of crown, root, and arch dimensions. Its growing use is being highlighted in recent studies for sex prediction in forensic odontology, especially when skeletal remains are fragmented or degraded. It is preferred over morphological methods because it is rapid, affordable, and easier to apply. Besides, dental morphological traits have not been found to be as sexually dimorphic as tooth size variables.

In a scoping review by Herrera-Escudero et al. (2024) accurate approaches for estimating sexual dimorphism. Among these, odontometric techniques were the most implemented, utilizing intraoral measurements, dental plaster models, digital scanning or software-based analyses, with reported accuracies ranging from 51% to 95.9%. Overall metric methods demonstrated higher accuracy than non-metric methods, which showed prediction rates of approximately 58% but lower accuracy than biochemical methods, which can achieve precision of up to 100%.

2.6 Tooth selection

Recent systemic reviews and literature overviews have consistently emphasized that teeth show considerable percentage of sexual dimorphism. Canines and molars are being reported as most sexually dimorphic teeth group.

Molars are the second most sexually dimorphic teeth after canines in sex prediction study (Albernaz Neves et al., 2022). Molars show consistent dimorphism with good preservation potential and are more resistant to wear or damage, useful for fragmented remains. Also, they possess **larger surface to volume ratios for measurements**, specifically mesiodistal and buccolingual dimensions. Mandibular second molar produced high correct classification rate

using support vector machine (SVM), with 85% for females and 92% for males. These accuracies outperformed mandibular first molar, 76% for females and 81% for males and the second premolar, 84% for females and 76% for males (Natarajan et al., 2025).

Also, in a study by Khamis et al. (2014) which focused on odontometric sex variation in Malaysians, mesiodistal and buccolingual of mandibular second molar showed 2.7% and 3.6% percent dimorphism, which is considered high as compared to other teeth. According to Ajmal et al. (2023), molars have the edge over canines, which have a greater propensity of being impacted and thus are not accessible for odontometric analysis. Besides, molars are the first permanent teeth to erupt in the mouth; hence, they are easily accessible for sex estimation at an early age when compared with other permanent teeth, allowing the model to be applied to wider range of ages.

Moreover, second molars are less affected by early attrition since they erupt later than many anterior teeth and premolars, with mandibular second molar around 12-13 years old (Khan et al., 2020). So, in young adult samples, molars may show less cumulative attrition than incisors or first molars that have been erupted much earlier. This increases the chance of occlusal surfaces being protected well for morphometric measurements.

Second molars are double-rooted teeth, which make it more firmly attached to the dental arch and less susceptible to postmortem loss than single-rooted teeth like canines and incisors (Franco et al., 2021). Since they are located at the posterior of the mouth, they are better protected by tongue and masseter muscle than the canines. They also demonstrated good prediction of accuracy among canines, incisors, and premolars (Ram et al., 2025). Most importantly, there is a lack of studies using mandibular second molars

2.7 Sex prediction in forensic odontology

Tooth width and arch dimensions have been measured on dental casts by direct methods, such as hand-held calipers. Recent technological advancements now allow dental casts to be converted into digital dental models.

Traditional 2D radiographs are being replaced by three-dimensional (3D) imaging technologies as this decreases the storage costs, allows for easy access, and enables analysis of digital dental imagery by advanced software. Cone-beam computed chromatography is now a standard trend for evaluating 3D dental and maxillofacial structures. This is because CBCT allows for precise measurement of anatomical features and root morphology, which vary significantly between sexes(Radu et al., 2025). Harudin et al. (2023) have utilized three-dimensional (3D) imaging technique such as post-mortem computed tomography (PMCT) images as study samples for sexual dimorphism using canines based on volumetric measurements. Overall, males have larger dental tissue than females ($p<0.05$). The overall sex classification accuracy ranged from 60% -74%.

Recent advances in forensic odontology have also seen a rapid integration of 3D morphometric techniques and artificial intelligence (AI) for sex prediction, with a focus on improving accuracy, reproducibility, and applicability across diverse populations. Studies have demonstrated that 3D geometric morphometric (GMM) applied to dental casts or CT scans of teeth can achieve sex classification accuracies ranging from 56% to over 90%, depending on the population and tooth type analyzed (Oliva et al., 2022) (Liu et al., 2021). A study by Aisyah Aminah Rosli et al. (2025) utilized GMM analysis to evaluate sexual dimorphism of the children mandible aged 3-12 years old of the Malay ethnic group and

found that the accuracy for sex classification was only 62-65.55%. The findings indicated that GMM shows less effective in determining sex in prepuberty population due to the absence of secondary sexual traits.

The integration of AI and ML enhances the accuracy of biological profiling, particularly in identifying human remains from mass disasters or criminal cases. While traditional methods rely heavily on subjective expert observation, contemporary studies are shifting toward automated, quantitative frameworks to minimize human bias and improve reliability.

Patil et al. (2020) conducted a comparative study on gender classification based on mandibular morphometric parameters utilizing Artificial Neural Networks (ANN) and compared it with logistic regression and discriminant analysis. The findings indicated that ANN demonstrated the highest accuracy (75%) compared to discriminant analysis (69.1%) and logistic regression (69.9%). The results revealed that ANN is a good gender prediction tool, and its application is promising as it automates and eases the method of identifying unknown gender.

Esmailyfard et al. (2021) conducted a study on sex classification of first molar teeth in CBCT images using data mining. The authors compared three popular ML methods: Random Forest (RF), Support Vector Machine (SVM) and Naïve Bayesian (NB) to identify the most effective method for accurate sex determination. Their findings revealed that NB outperformed the other methods. NB offered the highest accuracy (89.35%), sensitivity (88.73%), precision (86.42%) and specificity (91.44%).

These studies demonstrated that the field of forensic odontology is undergoing a significant transformation, moving from traditional manual measurement toward digital automation. More studies should be done in the future to confirm the reliability of the method. While most of the authors concluded their findings on a positive note, they emphasized that population-specific models needed to be developed as tooth size and mandibular shape vary across population. (Heng et al., 2022).

2.8 Definition of Malay population

According to Article 160 of the Federal Constitution of Malaysia, “Malay” means a person who professes the religion of Islam, speaks the Malay language and conforms to Malay customs. Several studies have explored sexual dimorphism in the Malay population through dental measurements. However, none have focused on the occlusal traits of the lower second molar. (Harudin et al., 2023; Kaeswaren & Weinheimer, 2019; Khamis et al., 2014).

Chapter 3 METHODOLOGY

3.1 Research design

This was a cross-sectional, retrospectively selected dental casts from the archives.

3.2 Study area

The study was carried out in the Digital Imaging Room in the School of Dental Sciences, Universiti Sains Malaysia.

3.3 Study population

The population for this study was consisted of individuals from the Malay ethnic group in the Northeastern Malaysia. The participants included patients attending the dental clinic whose dental casts were retrieved from the archives of the School of Dental Sciences, USM. The Malay origin ethnic group and sex were confirmed based on the dental records. Ethical approval was obtained from Human Research Ethics Committee of the Universiti Sains Malaysia (USM/JEPeM/KK/25111024).

3.4 Sample selection

The sample was selected based on predefined inclusion and exclusion criteria. The dental casts were selected if it met all the inclusion criteria and rejected if it met any of the exclusion criteria.

Table 3.1: Inclusion and exclusion criteria for sample selection

Inclusion Criteria	Exclusion criteria
• Participants with Malay ethnicity and Malaysian nationality • Completely erupted permanent mandibular second molar tooth • Males and females • Minimal tooth wear (second degree of wear: small, rounded facets; cusp peaks still identifiable) (Molnar, 1971)	• Any treatment-related to pathology, abnormality, or effects of trauma that could obscure the observation of its morphology. • Restored second molar • Sample with systemic medical disease (e.g. Pituitary dwarfism, Treacher Collins syndrome (TCS), Cleft lip, Down's syndrome and Vitamins deficiency) • Damaged dental casts with mold or fungus or fractured and distorted scanned digital model

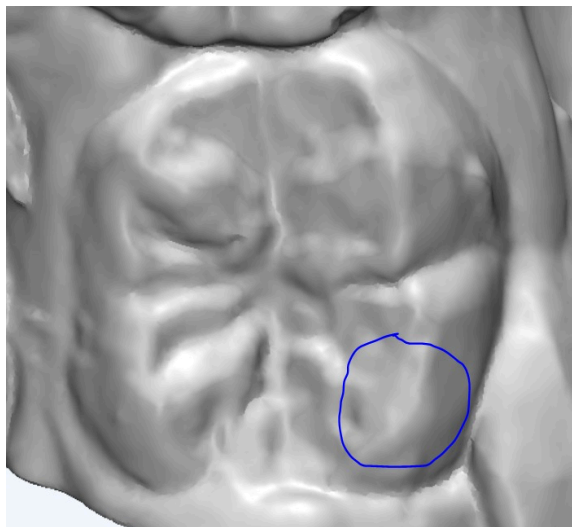


Figure 3.1: MFK 4 with 2nd category of tooth wear.