# Sexual dimorphism and population variation of a selection of vertebrae in a South African sample

by

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## ABSTRACT

In the discipline of forensic anthropology, numerous methods exist to establish a biological profile. However, many methods rely on established standards created from a limited number of skeletal elements. If these skeletal elements are not recovered or are fragmentary, the established methods cannot be applied, and the biological profile cannot be estimated accurately. As such, further exploration into the variation of numerous alternative skeletal elements and their potential use in forensic analyses is required. The purpose of this study was to explore the osteometric variation of a selection of vertebrae to examine the population affinity and sexual dimorphism in a South African sample. Additionally, this study aimed to establish if a universal discriminant analysis can be used to estimate population affinity and sex without the prior determination of the specific number of vertebrae within the vertebral column.

The current study consisted of two components, centred firstly around the exploration of vertebral variation and secondly on its use in predictive models. The variation exploration component quantified the osteometric variation among vertebrae to determine if there are statistically significant differences among vertebrae to see if non-specific, universal formulae - regardless of the specific number of a vertebra (e.g., T1, T2 etc.) - can be created. Secondly, the classification component aimed to apply the vertebral differences to develop classification standards to estimate population affinity and sex in a sample of black and white South Africans.

For the variation exploration component of the study, a series of 20 measurements were collected to assess the variation within and among the cervical, thoracic, and lumbar vertebrae of a sample of 30 black South African males. Out of the original 20 measurements, 14 were observed to be sufficiently repeatable and were retained for the creation of predictive models. The vertebrae within each type were compared using ANOVA and Tukey's HSD, which revealed that the atypical vertebrae (i.e., C7, T1, T12) were significantly different from the typical vertebrae within each vertebral region. As such, the atypical vertebrae are too different from the remaining vertebrae in each of the relevant subgroups and are not useful for non-specific, universal formulae.

For the classification component, a selection of cervical, thoracic and lumbar vertebrae of 180 black and white South African adult males and females were measured. Both univariate models, as well as multivariate models (combining all of the measurements), were created for

each vertebra to assess how accurately the vertebrae can predict population affinity and sex when using linear discriminant analysis. Finally, combined models were also created using the measurement means for all vertebrae in each subtype (i.e., a universal cervical model, universal upper thoracic model, universal lower thoracic model, and universal lumbar model).

The univariate models using each measurement collected for each sub-type of vertebra separately, resulted in classification accuracies of 50% to 90% for population affinity and 35% to 92% for sex when considering all vertebrae. Overall, the cervical vertebrae (C3-C6) presented with the highest accuracies for sex estimation but yielded poor results for population affinity estimation, where both the thoracic (T2-T11) and lumbar (L1-L4) vertebrae performed comparably well. Among the measurements, the vertebral body, spinous process and transverse process lengths and height measurements performed the best across all vertebrae. The universal univariate models assessing each measurement collected for the combined cervical, thoracic and lumbar vertebrae within each sub-type presented with classification accuracies ranging between 78% and 82% for population affinity and between 73% and 84% for sex estimation, where the upper thoracic vertebrae (T2-T6) and lower thoracic vertebrae (T7-T11) performed the best. Multivariate models using all of the measurements per sub-type vertebrae resulted in classification accuracies between 73% and 94% for population affinity and 70% and 89% for sex estimation. Finally, the universal multivariate model assessed all the vertebrae together (cervical, thoracic and lumbar vertebrae), and demonstrated classification accuracies between 81.7% and 87.2% for population affinity estimation, and 81.7% and 87.2% for sex estimation, where the lower thoracic (T7-T11) vertebrae performed the worst for both biological parameters.

Ultimately the best results were achieved using the multivariate models, as the inclusion of more variables maximises group differences. Combined models that made use of means irrespective of vertebra number yielded good accuracies. Therefore, a universal formula to estimate population affinity and sex can be used without *a priori* knowledge of the vertebral number. Both univariate and multivariate approaches achieve fairly high classification accuracies. The satisfactory performance of the univariate models also allows for the estimation of population affinity and sex from fragmentary or incomplete vertebrae.

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our backs
tell stories
no books have
the spine to
carry

-Rupi Kaur

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# CHAPTER 1: INTRODUCTION

Forensic anthropologists reconstruct biological profiles from incomplete or skeletonised remains. A biological profile serves to assist medico-legal investigators in possibly identifying an unknown individual and includes parameters such as age, stature, sex and population affinity (Ousley *et al.*, 2009; Krüger *et al.*, 2015; Liebenberg, 2015; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019). Several methods exist to estimate population affinity and sex for South Africa using various skeletal elements (L'Abbé *et al.*, 2013; Liebenberg, 2015; Krüger *et al.*, 2018; Liebenberg *et al.*, 2019). Current methods typically concentrate on larger skeletal elements, specifically, the pelvis, skull and long bones. But skeletal remains are often incomplete or taphonomically altered when recovered in a forensic context. Therefore, other skeletal elements should also be investigated to establish classification standards (Pastor, 2005; Krüger, 2015; Torimitsu *et al.*, 2016; Liebenberg *et al.*, 2019).

To further explore additional skeletal elements, several studies have also assessed smaller elements of the axial skeleton for population affinity and sex estimation. The axial skeleton and its associated muscles provide support, allow movement and disperse load-bearing forces throughout the body (Marino, 1995; Wescott, 2000; Yu *et al.*, 2008; Kibii *et al.*, 2010; Marlow and Pastor, 2011; Bethard and Seet, 2013; Gama *et al.*, 2015; Ostrofsky and Churchill, 2015; Ramadan *et al.*, 2017; Hora and Sladek, 2018; Oura *et al.*, 2018; Jeong *et al.*, 2019; Rozendaal *et al.*, 2020).

Previous studies have implemented a variety of methods to estimate population affinity and sex from specific vertebrae (Berry *et al.*, 1987; Marino, 1995; Cheng *et al.*, 1998; Kibii *et al.*, 2010; Gama *et al.*, 2015; Torimitsu *et al.*, 2016; Montasser *et al.*, 2017; Ramadan *et al.*, 2017; Hora and Sladek, 2018; Jeong *et al.*, 2019; Rozendaal *et al.*, 2020). For example, some authors achieved high classification accuracies (64% - 92.9%) using the first and second cervical, twelfth thoracic or first lumbar vertebrae (Marlow *et al.*, 2011; Ostrofsky *et al.*, 2015; Torimitsu *et al.*, 2016; Hora and Sladek, 2018). While many studies have reported marked sex differences in the specific vertebrae, research on population variation, particularly in the South African population, is limited (Kibii *et al.*, 2010; Ostrofsky *et al.*, 2015; Ünlütürk, 2016).

The purpose of the study was, therefore, to assess the osteometric variation within and among a selection of vertebrae to determine their value for estimating population affinity and sex. More specifically, different vertebrae were compared to see if it would be possible to create

universal standards irrespective of the specific vertebral number and to test how the predictive power of universal standards compares to vertebra-specific standards when employing both univariate and multivariate models.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Forensic Anthropology and the Biological Profile

Forensic anthropologists frequently receive decomposed remains that require specialised analyses to facilitate personal identification. Several methods that evaluate the size and shape of the human skeleton exist to estimate a biological profile using various skeletal elements, including osteometric and morphoscopic approaches. The osteometric approach involves taking measurements from human remains compared to the morphoscopic approach, which involves visually assessing the morphological variants of human remains (typically the skull and the pelvis). The estimation of population affinity and sexual dimorphism is an essential aspect of the biological profile used to assist in identifying unknown individuals from complete or fragmentary remains (Ousley *et al.*, 2009; Krüger *et al.*, 2015; Liebenberg, 2015; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019).

Population affinity refers to skeletal characteristics that differ among populations and are correlated to several factors, such as genetics, genetic history (species' genetic variation and the relationships between different populations), environment, socioeconomic status, and social boundaries (inequalities in social opportunities and access to resources), all of which can influence skeletal or biological variations (Sauer, 1992; Posel, 2001; Bergström *et al.*, 2020; Ross and Pilloud, 2021; Winburn and Algee-Hewitt, 2021). The observable traits, such as skin colour, facial characteristics, skeletal morphology and behavioural attributes, are interpreted into a social labelling system used by law enforcement to identify unknown individuals (Ousley *et al.*, 2009; Klales *et al.*, 2012; Klales and Kenyhercz, 2015; Krüger *et al.*, 2015; Liebenberg, 2015). For population affinity estimation, the osteometric approach has yielded better accuracies than the morphological or morphoscopic approach (Hefner, 2009; L'Abbé *et al.*, 2011; Ousley and Jantz, 2012; Stull *et al.*, 2014). The cranium has traditionally been recognised as the most accurate skeletal element for population affinity estimation, with classification accuracies ranging between 73% and 89% for South African population groups (L'Abbé *et al.*, 2013; Stull *et al.*, 2014). More recently, the postcranial skeleton has shown to be just as valuable for population affinity estimation, with accuracies of 85% when assessing black, white and coloured South Africans (Liebenberg, 2015).

Sexual dimorphism refers to the size and shape variation between males and females. Bone growth is a continuous process that persists into early adulthood and is influenced by genetics,

environment, and hormones. The presence and concentration of sex hormones (oestrogen and testosterone) have variable effects on bone growth, resulting in general differences in overall body size and proportions between male and female individuals (Cabo *et al.*, 2012; Wells, 2012; Krüger, 2015). In low concentrations, oestrogen can promote the secretion of growth hormones stimulating growth spurts in both sexes. However, at higher concentrations, oestrogen cause epiphyses to fuse and thereby halt the growth of long bones. The stimulation of endosteal and trabecular bone growth, as well as the increase in tensile bone strength, is also regulated by oestrogen (Juul, 2001; Cabo *et al.*, 2012; Krüger, 2015). On the other hand, testosterone promotes cortical bone growth in male adolescents and increases cortical diameter as osteoblastic activity is stimulated and osteoblast apoptosis is inhibited. In males, both oestrogen and testosterone work together to stimulate periosteal bone and cortical bone growth during puberty. As a result, testosterone builds wider and stronger bones in males, with increased bone mass in certain skeletal regions, such as the lumbar vertebrae, resulting in sexual dimorphism (Bonjour *et al.*, 1991; Callewaert *et al.*, 2010; Krüger, 2015).

Sexual dimorphism is population-specific and the degree to which males and females differ from one another can vary among and within groups or populations (Barrier and L'abbé, 2008; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019). Therefore, population-specific standards are important for classifying the sex of unknown individuals (Seeman, 2001; Pastor, 2005; Steyn and Patriquin, 2009; Krüger *et al.*, 2015; Liebenberg *et al.*, 2019). For sex estimation, both morphoscopic and osteometric methods have been shown to be accurate. While measurements from long bones are more reliable and achieve higher accuracies (up to 94%) in estimating sex than the skull, morphological differences of the pelvis and skull are very useful when long bones are not available for analysis. While the pelvis yields accuracies of up to 90%, long bone analysis have yielded accuracies between 86% and 96% (Phenice, 1969; Walker, 2008; Spradley and Jantz, 2011; Klales *et al.*, 2012).

Numerous studies have been conducted on the South African population regarding population affinity and sex estimation, improving the ability of forensic anthropologists to create biological profiles (L'Abbé EN ; Elliott and Collard, 2009; Ousley *et al.*, 2009; Spradley *et al.*, 2011; Klales *et al.*, 2012; Klales *et al.*, 2015; Krüger *et al.*, 2015; Liebenberg *et al.*, 2015; Hefner, 2016; Spradley and Jantz, 2016; Krüger *et al.*, 2017). Unfortunately, the estimation of population affinity and sex commonly relies on fragile elements (such as the pubic bone or craniofacial bones), often lost or destroyed in forensic and archaeological contexts. In the post-

mortem context, remains may present with taphonomic changes, such as faunal damage, thermal alterations and weathering, frequently resulting in fragmentation of the bones. In some cases, only limited or fragmentary elements are recovered, making new techniques necessary to attempt a possible identification (Marlow *et al.*, 2011; Gama *et al.*, 2015; Torimitsu *et al.*, 2016). Therefore, other skeletal elements, such as the vertebrae, should be investigated to establish classification standards for instances when fragmentary or incomplete remains are recovered (Pastor, 2005; Krüger, 2015; Torimitsu *et al.*, 2016; Liebenberg *et al.*, 2019). Vertebrae are often fairly well preserved, with minimal damage and weathering with the exception of the transverse processes and spinous processes. Since the vertebral column is comprised of so many vertebrae, the possibility of at least some vertebrae being available and intact is great, even if the remains have substantial damage and weathering, as thick layers of muscles and ligaments surround the vertebrae.

## 2.2 General Vertebral Morphology and Bone Growth

During embryological development, vertebrae develop through the formation of somites within the axial skeleton. Somites are segmented units that develop along the neural tube and become individualised into different vertebrae types by the action of *Hox* genes (Carapuço *et al.*, 2005). The human vertebral formula (as determined by the complex of *Hox* genes) consists of seven cervical vertebrae, twelve thoracic vertebrae, five lumbar vertebrae, five sacral vertebrae and three to four coccygeal vertebrae. The general components that make up vertebrae include a vertebral body and posterior vertebral arch (Sadler and Langman, 2010; Drake *et al.*, 2016). The vertebral body is the main weight-bearing part of the vertebra, separated in the vertebral column by the intervertebral disc. The body size is dependent on the type of vertebra, where the amount of weight distribution differs in the different regions of the spine. For example, the cervical vertebrae are the smallest and are specialised to support and allow movement of the skull. In contrast, the lumbar vertebrae are the largest and are structurally specialised to support the weight of the upper body (torso) (Waxenbaum and Futterman, 2018).

The vertebral arch forms the lateral and posterior aspects of the vertebral foramen, where the surrounding elements form the vertebral canal. The vertebral canal is firmly anchored to the posterior aspect of the vertebral body by two pedicles. A flat sheet of bone extends from each pedicle to meet at the midpoint, forming the roof of the vertebral arch. Posteriorly and inferiorly, a spinous process extends from the lamina junction, which serves as a ligament and muscle attachment site. Transverse processes extend from the pedicles and lamina and are a

site for articulating the ribs to the thoracic vertebrae. Additionally, superior and inferior articular processes project from the junction between the lamina and pedicles, which are articulation sites for the sequential vertebrae (Drake *et al.*, 2016).

Overall, the seven cervical vertebrae are typically small and square-shaped, presenting with characteristic round transverse foramina (found on the transverse processes), triangular vertebral foramina and short and bifid (split) spinous processes. The first and second cervical vertebrae (atlas and axis, respectively) are considered atypical vertebrae that are specialised to carry and move the head. The twelve thoracic vertebrae are characterised by their articulation facets, more specifically demifacets, located on the lateral aspect of the vertebral bodies for articulation with the ribs. The thoracic vertebrae are somewhat heart-shaped and present with a circular vertebral foramen. The five lumbar vertebrae are distinguishable from the other vertebrae due to their weight-bearing capacity making them considerably larger, with kidney-shaped bodies and large, blunt spinous processes (White and Folkens, 2005; Sadler *et al.*, 2010; Drake *et al.*, 2016).

### 2.3 Extrinsic and Intrinsic Influences on Vertebral Variation

Various factors affect vertebral morphology, including sex, age, growth and development, pathology, and physical activity. Sexual dimorphism has been noted in the growth and development of vertebrae (Cheng *et al.*, 1998; Wescott, 2000; Pastor, 2005; Soegiharto *et al.*, 2008; Yu *et al.*, 2008; Marlow *et al.*, 2011; Gama *et al.*, 2015; Ostrofsky *et al.*, 2015; Torimitsu *et al.*, 2016; Montasser *et al.*, 2017; Ramadan *et al.*, 2017; Oura *et al.*, 2018; Rozendaal *et al.*, 2020). The vertebrae of females are relatively taller and thinner in the coronal plane than in males. The female vertebral body height is greater than males, while the male vertebral body transverse diameter is greater than females. From the age of eight to about 21 years of age (i.e., when maturity is reached), the thoracic and lumbar vertebrae (specifically from the sixth thoracic to the fifth lumbar vertebrae) increase substantially in size and dimensions in males compared to females (Bellemare *et al.*, 2003).

Furthermore, sexual dimorphism in spinal growth produces a thinner thoracolumbar spine in the coronal plane of females compared to males, indicating sexual dimorphism in the shape of the vertebral body due to differential growth rates between males and females during puberty (Taylor and Twomey, 1984). Given the differences caused by testosterone, male vertebrae have been found to be 25% larger than those of females (Bellemare *et al.*, 2003). Previous studies

have reported that the vertebral column is heavily associated with sex differences in the thoracic cage related to the respiratory system. More specifically, males have larger muscles connected to their transverse processes than females (Bellemare *et al.*, 2006; Bastir *et al.*, 2014; Weaver *et al.*, 2014).

Many changes occur within the skeleton through either growth or degeneration, which can affect the rates at which these processes occur between males and females. Several studies have noted sexually dimorphic patterns in the ageing process of vertebrae (Atkinson, 1967; Mosekilde, 2000; Albert *et al.*, 2010; Aylott *et al.*, 2012; Baidas, 2012; Albert and Maier, 2013; Chiara *et al.*, 2016; Ramadan *et al.*, 2017). Age-related changes of the vertebrae have been observed, especially among lumbar vertebrae, although all vertebrae may be affected. With increased age, the transverse diameter of the endplates and vertebral body increases. Conversely, a decrease in anterior and posterior vertebral height is seen, which produces a wedge-shaped vertebral appearance with age (Snodgrass, 2004a; Garoufi *et al.*, 2020). Essentially, vertebrae become flatter and wider with age. In addition to the dimensional changes of the body, osteophyte development is commonly observed along the articular surfaces. Osteophytes refer to lipping around the articular surfaces, also known as bony spurs. The bony spurs develop due to various internal and external factors, including physical activity (i.e., strenuous labour, sport, and mechanical exertion), age and degenerative diseases. In a normal vertebral column, osteophyte development occurs after the epiphyseal ring fusion, and as the bony spurs appear, osteophytes increase with age in both severity and frequency (Snodgrass, 2004b; Van der Merwe *et al.*, 2006b; Klaassen *et al.*, 2011; Ezra *et al.*, 2019).

Previous studies have also suggested that the lumbar vertebrae show a pattern of sexual dimorphism, which may be due to the different load-bearing capacities between male and female individuals (Berry *et al.*, 1987; Cheng *et al.*, 1998; Ostrofsky *et al.*, 2015; Oura *et al.*, 2018). Load-bearing capacity, such as physical activity, affects bone mass, microarchitecture, and size throughout life, relates to differences in gait between males and females, which effects the pelvic shape, leading to possible sexual dimorphism. An increase in load-bearing capacity of the vertebrae has, in addition, been associated with an increase in vertebral dimensions and bone mass (Junno *et al.*, 2013; Oura *et al.*, 2016). Additionally, studies demonstrated that males in their twenties are more likely to have a higher bone mass and strength peak than females in their twenties, which may translate to osteometric differences (Pastor, 2005; Yu *et al.*, 2008; Torimitsu *et al.*, 2016).

A number of studies have found that osteophytes form in different patterns in females and males, with females showing greater variation (Allbright, 2007; Garoufi *et al.*, 2020). Van der Merwe *et al.* (2006a) focused on osteophyte formation in the South African population, which indicated that cervical and lumbar vertebrae had more significant osteophyte development with greater variation in males. Although age is a factor in osteophyte development, the main reason for the appearance of bony spurs is extensive pressure exerted on the vertebrae, which weakens and progresses due to age (Van der Merwe *et al.*, 2006a; Klaassen *et al.*, 2011). Another factor to consider is premature degeneration, which occurs either from an increase in load-bearing capacity, early degenerative disease onset (e.g., second osteoporosis) or trauma to the vertebrae (Scher, 1990; Kerttula *et al.*, 2000; Junno *et al.*, 2013).

### 2.4 Practical Application and Previous Studies Assessing Vertebrae

Research investigating population affinity and sex has assessed various methods, including morphological, metric, and scoring methods, to estimate population affinity and sex using vertebrae (Cheng *et al.*, 1998; Wescott, 2000; Pastor, 2005; Soegiharto *et al.*, 2008; Yu *et al.*, 2008; Marlow *et al.*, 2011; Gama *et al.*, 2015; Ostrofsky *et al.*, 2015; Torimitsu *et al.*, 2016; Montasser *et al.*, 2017; Ramadan *et al.*, 2017; Oura *et al.*, 2018; Rozendaal *et al.*, 2020). However, previous studies did not create standards for vertebral measurements based on the results and typically concentrated on larger skeletal elements (i.e., pelvis, skull and long bones). Even though vertebrae can be distinguished from one another by type, identifying the exact vertebral number (e.g. fourth thoracic vertebrae) may be difficult and time-consuming, especially if the vertebrae are fragmentary and no consecutive vertebrae are present (Cheng *et al.*, 1998; Kibii *et al.*, 2010; Gama *et al.*, 2015; Torimitsu *et al.*, 2016). The lack of anthropological research on vertebrae limits the accuracy and reliability of standards, as previous studies employing vertebrae focus on cadaveric or scan materials rather than skeletal elements. The development of standards for vertebrae may assess variations among and within the different vertebrae exploring whether standards are interchangeable or if vertebrae type-specific standards need to be created (Hora and Sladek, 2018). Therefore, universal, non-specific formulae for vertebrae can be beneficial as standards could be applied interchangeably across vertebrae without first establishing the vertebral type or number.

Numerous studies have evaluated the variation of the first and second cervical vertebrae using multiple measurements, which achieved accuracies between 70.91% and 92.9% for sex estimation (Marino, 1995; Wescott, 2000; Marlow *et al.*, 2011; Gama *et al.*, 2015; Torimitsu

*et al.*, 2016; Rozendaal *et al.*, 2020). A variety of studies (Marlow *et al.*, 2011; Bethard *et al.*, 2013) validated the method published by Wescott (2000) to estimate sex from the first and second cervical vertebrae. Overall, sex differences were observed between males and females, with males having larger vertebral body dimensions than females (Wescott, 2000; Marlow *et al.*, 2011; Bethard *et al.*, 2013).

Similarly, several studies focused on the lower thoracic and upper lumbar vertebrae in various population groups to estimate sex and noted accuracies between 64% and 90% (Yu *et al.*, 2008; Ostrofsky *et al.*, 2015; Hora and Sladek, 2018; Oura *et al.*, 2018; Garoufi *et al.*, 2020). Overall, males were found to present with larger measurement means than females when assessing the lumbar vertebrae. Furthermore, the lumbar vertebrae yielded greater classification accuracies than the studies using thoracic and cervical vertebrae.

Limited research has been done on vertebrae of the South African population to estimate population affinity and sex (Kibii *et al.*, 2010; Ostrofsky *et al.*, 2015; Ünlütürk, 2016). Kibii *et al.* (2010) focused on the seventh cervical vertebrae of South African Zulu (black), white, and coloured individuals to explore morphometric variation. The study found that sexual dimorphism was observable in vertebrae, with males having substantially greater dimensions than females (Kibii *et al.*, 2010). Ostrofsky *et al.* (2015) focused on the morphological differences using the lumbar region to estimate the sex of 98 black South Africans. Their results yielded accuracies ranging from 64.6% to 83.5%, with the vertebral body generating the highest accuracy (Ostrofsky *et al.*, 2015). Ünlütürk (2016) examined the vertebrae of black and white South Africans to estimate population affinity. The sample was composed of complete vertebrae from 144 individuals. The analysis provided a correct classification rate of 85% to 88%. Compared to the classification rates noted with skeletal elements such as the skull and the pelvis, the results reported by Ünlütürk (2016) are comparable. However, as the sample decreased due to missing or damaged vertebrae, the analyses had to counteract a lot of missing data, where more sacral measurements than vertebral measurements were taken with a limited amount of measurements (five) taken from the vertebrae (Ünlütürk, 2016).

In previous studies, authors usually focused on the atypical or transitional vertebrae, so limited evidence of comparable differences in and among the different typical vertebrae exists, and authors typically did not compare the specific types of vertebrae to one another but rather focused on atypical vertebrae (first cervical, second cervical and fifth lumbar vertebrae), and studies were often limited to sex estimation. Furthermore, little to no research is available on

the vertebral variations among the various South African population groups, and limited studies have created established standards for population affinity and sex estimation among typical vertebrae (Wescott, 2000; Pastor, 2005; Yu *et al.*, 2008; Kibii *et al.*, 2010; Marlow *et al.*, 2011; Gama *et al.*, 2015; Ostrofsky *et al.*, 2015; Torimitsu *et al.*, 2016; Ünlütürk, 2016; Jeong *et al.*, 2019; Garoufi *et al.*, 2020; Rozendaal *et al.*, 2020).

# CHAPTER 3: EXPLORATION OF VERTEBRAL VARIATION

To effectively explore sexual dimorphism and population affinity in the vertebrae of modern South Africans, this study consisted of two components. First, the variation exploration component and second, the classification component. The variation exploration component evaluated the size variation among vertebrae, both within and among vertebral types (cervical, thoracic, and lumbar vertebrae), to determine the possibility of creating universal vertebral standards for population affinity and sex estimation. Furthermore, measurement error was assessed to demonstrate the degree of measurement repeatability. Evaluation of measurement error and variability is important when creating standards based on metric data, as measurements need to be repeatable and valid.

## 3.1 South African Population Groups

South Africa is a country with a diverse and vast heritage that consists of various ancestries with varying geographical origins (i.e., indigenous San, Khoe-Khoe African, European, Asian and Indian). The 2021 South African mid-year population estimates reported that black South Africans comprised 80.9% of South Africa's population, while white South Africans and coloured South Africans comprised 7.7% and 8.8% of the population, respectively (www.statssa.gov.za).

South Africans were classified into strict social categories during the segregation era (1948 to 1990). South African social segregation (*Apartheid* era) imposed legal separation, which allowed limited gene flow amongst the South African population groups. South Africans are mainly classified into four groups: white South Africans, black South Africans, coloured South Africans and Indians and other Asian South Africans (Christopher, 1992; Bickford-Smith, 1995; Christopher, 2001; Ribot, 2004).

Black South Africans are said to have originated as a result of the southward migration of Bantu-speaking individuals from western-central Africa into southern Africa (Ribot, 2004; Franklin *et al.*, 2007; Franklin *et al.*, 2010). In South Africa, the descendants of the Bantu-speakers further subdivided with time into different ethnic groups; this includes Nguni (Xhosa, Zulu, Northern Ndebele, Southern Ndebele and Swazi), Sotho (Pedi and Basotho), Tswana, Venda and Tsonga (Hall and Morris, 1983; Savage, 1986; Larson and Ribot, 2004; Ribot, 2004). White South Africans are mainly descendants of European settlers who arrived during

multiple colonisation periods, specifically settlers from the Netherlands, Belgium, Germany, France, Portugal, and Britain (Steyn and İşcan, 1997; İşcan and Steyn, 1999).

## 3.2 Skeletal Sample

The sample for this component of the study consists of the cervical, thoracic and lumbar vertebrae (except C1, C2, and L5) of 30 black South African adult males. The skeletal remains were obtained from the Pretoria Bone Collection (PBC), which is housed in the Department of Anatomy at the University of Pretoria. Because this component focused only on variation among the different vertebrae, by looking at a single population and sex group (black South African adult males), any variation observed should inherently be due to differences in the vertebral structure and morphology rather than differences attributed to population and sex variation.

Individuals that presented with extensive pathology (e.g., osteophytosis or vertebral compression), vertebral deformity (e.g., scoliosis, spondylolysis, or sacralisation), an indication of spinal surgical procedures, or post-mortem damage were excluded from this study component, however, individuals that presented with minimal pathology were included in the sample. Additionally, individuals that did not present with all 24 vertebrae were excluded.

## 3.3 Methods

### 3.3.1 Osteometric Analysis

A series of 20 measurements (Table 3.1, Appendix I) were chosen to assess the variation of cervical, thoracic, and lumbar vertebrae. Measurements were collected using a digital sliding caliper according to definitions collected from several previous studies (Cheng *et al.*, 1998; Marlow *et al.*, 2011; Gama *et al.*, 2015; Oura *et al.*, 2018). Osteometric data was collected on all cervical, thoracic, and lumbar vertebrae except the first and second cervical vertebrae and the fifth lumbar vertebrae. Refer to Table 3.1 for the measurement abbreviations and Appendix I for detailed measurement definitions.

**Table 3.1:** Measurement abbreviations. Refer to Appendix I and II for more information regarding the measurements.

| | | | |
|---|---|---|---|
| **Maximum Superior Sagittal Length** | XSLs | **Pedicle Height** | PH |
| **Maximum Anterior Height** | XAH | **Pedicle Width** | PW |
| **Maximum Centroid Height** | XCH | **Maximum Pedicle Length** | XPL |
| **Maximum Posterior Height** | XPH | **Transverse Process Length** | TPL |
| **Maximum Superior Articular Length** | XALs | **Maximum Transverse Process Width** | XTPW |
| **Maximum Inferior Articular Length** | XALi | **Maximum Superior Articular Process Width** | XAPWs |
| **Maximum Superior Articular Width** | XAWs | **Maximum Inferior Articular Width** | XAPWi |
| **Maximum Inferior Articular Width** | XAWi | **Articular Process Height** | APH |
| **Foramen Sagittal Length** | FSL | **Maximum Spinous Process Length** | XSPL |
| **Foramen Coronal Width** | FCW | **Maximum Inferior Sagittal Length** | XSLi |

### 3.3.2 Statistical Analysis

The intra- and inter-observer error rates were tested to evaluate the repeatability of the 20 measurements. For the intra-observer error rate, the measurements were performed twice by the principal investigator. For the inter-observer error rate, the measurements were performed twice by two different observers, the principal investigator and a second observer. To measure observer error, absolute and relative technical error of measurements (TEM and %TEM, respectively) were calculated, which are useful in comparing sets of repeated measurements (Ulijaszek and Lourie, 2005; Geeta *et al.*, 2009). TEM uses a co-efficient to determine the precision, quality, and accuracy of the measurements and provides an absolute value (in mm) to indicate discrepancies among sets of measurements. Additionally, %TEM offers a relative value of measurement discrepancies by also taking the size of the measurement into account.

Multiple statistical analyses were conducted using R (version 4.0.5) and the RStudio environment (R Core Team, 2020). Pearson's correlations were used to indicate the strength of the linear relationship between the measurements. A linear correlation coefficient greater than zero indicates a positive relationship. In contrast, a value less than zero signifies a negative relationship (Taylor, 1990; Asuero *et al.*, 2006; Torimitsu *et al.*, 2016; Schober *et al.*, 2018). A Holm's adjustment was added to reduce Type I errors that can occur with multiple comparisons (Holm, 1979; Kalnins, 2018). The correlation coefficients were displayed using the *corrplot* package in R to assist in interpreting the relationships among the measurements and search for multicollinearity using shapes and colours as illustrations. The ellipses show both the sign and magnitude of the correlation value using shades of red and blue (Friendly, 2002). The different shades of red and blue indicate the various negative and positive correlations, with the width and shade/spectrum of the ellipse demonstrating the magnitude of the correlation between the measurements. A smaller ellipse indicates a stronger correlation,

and a larger ellipse indicates a weaker correlation. For visualisation of the correlation, variables were ordered to display the patterns of relations using angular order of the eigenvector (AOE). AOE relationships between vectors indicate correlations among variables, and therefore, an order based on the angular relationships naturally places the most similar variables together. Variables are ordered based on the angles formed by the first two or three eigenvectors (Friendly, 2002). As a result, all variables are contained within a 90-degree segment of the p-space, and most correlations are positive or near zero. Additionally, a significance test was added, and any non-significant correlation coefficients were omitted from the plot (Friendly, 2002; Kumari, 2008; Wei *et al.*, 2017).

ANOVA was used to test for significant differences between variables. First, ANOVA was used to test for differences among the different vertebrae within a single type (e.g., comparing the same measurements collected from C3, C4, C5 and C6). Subsequently, ANOVA was also used to test for significant differences among the subtypes (i.e. comparing the same measurements among the cervical, thoracic and lumbar vertebrae) (Fenech, 1979; Madrigal, 2012). ANOVA assumes a normal distribution of the data, as well as homogeneity of variance, which means the variance among the groups or samples should be approximately equal. Additionally, ANOVA assumes that the measurements and variables are independent of each other (Stahle and Wold, 1989; Tabachnick and Fidell, 2019). Additionally, Tukey's HSD test was applied *post hoc* to identify where the specific differences occurred.

### 3.4 Results: Measurement Repeatability

A series of measurements (Appendix I) were compiled from previous studies and assessed to gauge the repeatability of the measurements. In the current study, both the intra- and inter-observer errors demonstrated widespread variation with many measurements presenting with high error rates. Overall, the intra- and inter-observer error rates ranged between 0.00mm and 3.54mm (TEM); 0.00% and 29.79% (%TEM) and between 0.00mm and 7.29mm (TEM) and 0.00% and 27.03% (%TEM), respectively (Table 3.2 – 3.5). The intra-observer error rate was overall lower than the inter-observer error rate, except for the measurements of the lower thoracic vertebrae, where the upper range of the error for inter-observer error rate was lower than the intra-observer errors. The measurements collected from the lower thoracic and lumbar vertebrae were overall noted to be the most repeatable (Table 3.3 – 3.5).

The measurements with the highest TEM and %TEM for both inter- and intra-observer error rates varied, but the maximum centroid height, maximum articular process height, maximum superior articular length, maximum superior articular width, pedicle height, pedicle width, foramen sagittal length, foramen coronal width consistently presented with large observer errors. A cut-off point of 7% was selected, and any measurement with a %TEM greater than 7% was considered unreliable and was therefore excluded from further classification analyses.

**Table 3.2:** Absolute technical error of measurement (TEM) and relative technical error of measurement (%TEM) assessing the intra- and inter-observer error rates for the cervical vertebrae (C3 – C7). Refer to Appendix I for measurement names and definitions. Bold indicates the highest %TEM.

| | Inter | | | | | | | | | | Intra | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C3 | | C4 | | C5 | | C6 | | C7 | | C3 | | C4 | | C5 | | C6 | | C7 | |
| | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM |
| **XSLs** | 0.45 | 2.57 | 0.45 | 2.69 | 0.45 | 2.66 | 0.32 | 1.85 | 0.32 | 1.81 | 0.71 | 4.14 | 0.45 | 2.69 | 0.45 | 2.66 | 0.45 | 2.60 | 0.00 | 0.00 |
| **XCH** | 0.84 | **7.68** | 1.00 | **9.26** | 0.84 | **8.28** | 1.10 | **10.74** | 1.45 | **11.59** | 1.00 | **9.26** | 1.34 | **12.42** | 0.95 | **9.39** | 1.22 | **11.66** | 1.48 | **11.59** |
| **XAH** | 0.45 | 3.44 | 0.63 | 4.72 | 1.05 | **8.67** | 0.84 | 6.59 | 0.84 | 5.62 | 0.55 | 4.12 | 0.45 | 3.34 | 0.77 | 6.35 | 0.84 | 6.49 | 0.84 | 5.62 |
| **XPH** | 0.32 | 2.24 | 0.32 | 2.34 | 0.32 | 2.41 | 0.55 | 4.31 | 1.14 | **7.97** | 0.45 | 3.11 | 0.55 | 3.94 | 0.32 | 2.41 | 1.00 | **7.58** | 0.95 | 6.28 |
| **XALs** | 1.10 | **7.40** | 1.61 | **11.36** | 1.14 | **8.32** | 1.82 | **12.70** | 1.00 | 6.85 | 1.05 | **7.55** | 1.00 | **7.58** | 0.45 | 3.44 | 1.38 | **9.92** | 0.55 | 3.83 |
| **XALi** | 1.10 | **7.11** | 1.22 | **7.90** | 1.00 | 6.41 | 1.14 | **7.36** | 0.89 | 6.13 | 0.45 | 3.06 | 0.45 | 3.02 | 0.63 | 4.11 | 0.45 | 3.02 | 0.63 | 4.45 |
| **XAWs** | 1.18 | 6.10 | 1.38 | **7.07** | 2.14 | **10.41** | 2.37 | **10.96** | 2.37 | **9.94** | 0.77 | 4.12 | 0.63 | 3.36 | 0.95 | 4.92 | 1.22 | 5.92 | 1.34 | 6.10 |
| **XAWi** | 0.77 | 4.30 | 1.10 | 6.02 | 1.26 | 6.73 | 1.73 | **8.41** | 1.58 | 6.45 | 0.77 | 4.50 | 0.77 | 4.35 | 0.77 | 4.26 | 0.77 | 3.87 | 0.84 | 3.56 |
| **FSL** | 0.95 | 6.28 | 1.00 | 6.67 | 1.14 | **7.36** | 0.55 | 3.44 | 1.18 | **7.58** | 0.55 | 3.78 | 0.63 | 4.33 | 1.00 | 6.58 | 0.55 | 3.49 | 0.95 | 6.12 |
| **FCW** | 2.17 | **9.15** | 2.10 | **8.53** | 1.95 | **7.86** | 1.67 | 6.44 | 1.61 | 6.35 | 0.55 | 2.43 | 1.00 | 4.31 | 0.89 | 3.73 | 0.45 | 1.77 | 1.00 | 4.07 |
| **PH** | 0.32 | 4.45 | 0.45 | 6.04 | 0.84 | **11.16** | 0.55 | **7.94** | 0.45 | 5.32 | 0.71 | **9.69** | 0.63 | 8.32 | 0.84 | **11.16** | 0.84 | **12.49** | 1.05 | **12.34** |
| **PW** | 0.84 | **15.79** | 1.00 | **20.00** | 0.63 | **10.90** | 0.63 | **10.54** | 0.71 | **10.88** | 0.84 | **15.21** | 0.77 | **14.34** | 0.63 | **10.90** | 0.63 | **10.54** | 0.84 | **12.87** |
| **XPL** | 1.00 | **20.83** | 0.84 | **17.07** | 1.05 | **21.40** | 0.77 | **14.34** | 1.26 | **22.59** | 0.32 | **7.35** | 0.84 | **19.46** | 0.77 | **17.60** | 0.45 | **8.94** | 0.32 | 6.45 |
| **TPL** | 1.45 | 4.46 | 0.71 | 2.15 | 0.71 | 2.03 | 1.48 | 4.12 | 0.71 | 1.86 | 1.48 | 4.58 | 1.41 | 4.29 | 0.55 | 1.57 | 1.52 | 4.25 | 1.52 | 4.00 |
| **XTPW** | 1.26 | 2.40 | 0.95 | 1.74 | 6.32 | **11.40** | 0.00 | 0.00 | 0.32 | 0.47 | 1.26 | 2.40 | 1.76 | 3.30 | 1.00 | 1.72 | 1.26 | 2.05 | 2.86 | 4.04 |
| **XAPWs** | 1.30 | 2.76 | 1.34 | 2.73 | 0.89 | 1.77 | 0.55 | 1.02 | 0.55 | 1.03 | 1.30 | 2.76 | 1.61 | 3.26 | 1.34 | 2.64 | 0.55 | 1.03 | 0.45 | 0.84 |
| **XAPWi** | 1.18 | 2.38 | 1.41 | 2.76 | 1.30 | 2.43 | 0.77 | 1.46 | 2.28 | 4.51 | 0.77 | 1.57 | 1.55 | 3.00 | 1.45 | 2.72 | 0.45 | 0.84 | 3.45 | 6.91 |
| **APH** | 1.10 | 5.02 | 1.00 | 4.55 | 0.55 | 2.46 | 1.26 | 5.55 | 4.28 | **15.22** | 0.71 | 3.32 | 1.55 | **7.17** | 1.22 | 5.40 | 2.57 | **10.98** | 1.41 | 5.24 |
| **XSPL** | 0.71 | 4.23 | 0.71 | 4.75 | 0.55 | 3.20 | 0.32 | 1.29 | 0.63 | 1.96 | 0.71 | 4.29 | 1.05 | **7.04** | 2.32 | **13.06** | 1.00 | 4.13 | 1.92 | 5.92 |
| **XSLi** | 0.77 | 4.40 | 0.84 | 4.73 | 0.32 | 1.77 | 0.45 | 2.54 | 0.00 | 0.00 | 0.55 | 3.09 | 0.84 | 4.73 | 0.32 | 1.77 | 0.45 | 2.54 | 0.45 | 2.69 |
| **min** | 0.32 | 2.24 | 0.32 | 1.74 | 0.32 | 1.77 | 0.00 | 0.00 | 0.00 | 0.00 | 0.32 | 1.57 | 0.45 | 2.69 | 0.32 | 1.57 | 0.45 | 0.84 | 0.00 | 0.00 |
| **max** | 2.17 | 20.83 | 2.10 | 20.00 | 6.32 | 21.40 | 2.37 | 14.34 | 4.28 | 22.59 | 1.48 | 15.21 | 1.76 | 19.46 | 2.32 | 17.60 | 2.57 | 12.49 | 3.45 | 12.87 |
| **mean** | 0.96 | 6.15 | 1.00 | 6.65 | 1.22 | 6.88 | 0.94 | 6.08 | 1.18 | 6.71 | 0.77 | 5.02 | 0.96 | 6.21 | 0.88 | 5.82 | 0.90 | 5.71 | 1.14 | 5.65 |

**Table 3.3:** Absolute technical error of measurement (TEM) and relative technical error of measurement (%TEM) assessing the intra- and inter-observer error rates for the upper thoracic vertebrae (T1 – T6). Refer to Appendix I for measurement names and definitions. Bold indicates the highest %TEM.

| | Inter | | | | | | | | | | | | Intra | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T1 | | T2 | | T3 | | T4 | | T5 | | T6 | | T1 | | T2 | | T3 | | T4 | | T5 | | T6 | |
| | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM |
| **XSLs** | 0.32 | 1.89 | 0.32 | 1.75 | 0.95 | 4.96 | 0.71 | 3.29 | 1.05 | 4.62 | 0.55 | 2.25 | 0.63 | 3.79 | 0.55 | 2.96 | 0.89 | 4.43 | 1.14 | 5.21 | 0.55 | 2.37 | 0.45 | 1.83 |
| **XCH** | 2.19 | **15.32** | 3.08 | **18.24** | 1.14 | 7.08 | 1.26 | 7.81 | 1.64 | **10.33** | 1.76 | **10.54** | 1.52 | **10.46** | 1.18 | 7.40 | 1.18 | 7.40 | 1.52 | **9.42** | 1.14 | 6.99 | 1.52 | **8.97** |
| **XAH** | 2.45 | **14.85** | 2.26 | **11.70** | 0.95 | 5.30 | 0.45 | 2.51 | 0.55 | 3.09 | 0.55 | 3.03 | 0.55 | 3.26 | 0.55 | 2.93 | 0.71 | 3.95 | 0.32 | 1.77 | 0.55 | 3.09 | 0.45 | 2.46 |
| **XPH** | 1.14 | 6.71 | 0.95 | 5.13 | 0.55 | 2.90 | 0.45 | 2.38 | 0.71 | 3.70 | 0.45 | 2.31 | 0.77 | 4.45 | 0.77 | 4.08 | 0.55 | 2.90 | 0.45 | 2.38 | 0.45 | 2.33 | 0.45 | 2.31 |
| **XALs** | 1.18 | 7.99 | 1.38 | 8.89 | 0.84 | 4.89 | 1.45 | 7.67 | 2.02 | **10.18** | 1.61 | 7.61 | 0.84 | 5.81 | 0.55 | 3.78 | 1.45 | 8.57 | 0.45 | 2.48 | 0.63 | 3.36 | 0.45 | 2.21 |
| **XALi** | 0.89 | 5.92 | 1.05 | 6.06 | 0.63 | 3.44 | 1.55 | 7.82 | 1.61 | 7.68 | 1.26 | 5.80 | 0.77 | 5.23 | 1.30 | 8.00 | 0.77 | 4.21 | 0.55 | 2.87 | 0.45 | 2.21 | 0.95 | 4.54 |
| **XAWs** | 1.26 | 5.23 | 1.38 | 5.74 | 0.84 | 3.59 | 1.38 | 6.13 | 1.48 | 6.18 | 1.34 | 5.41 | 1.48 | 6.31 | 1.48 | 6.31 | 0.84 | 3.69 | 0.71 | 3.17 | 0.89 | 3.86 | 0.84 | 3.47 |
| **XAWi** | 2.55 | 9.96 | 2.59 | 10.31 | 0.55 | 2.25 | 1.05 | 4.18 | 1.10 | 4.31 | 1.58 | 6.10 | 1.18 | 4.77 | 1.05 | 4.21 | 0.84 | 3.47 | 1.05 | 4.25 | 0.77 | 3.10 | 0.63 | 2.49 |
| **FSL** | 1.22 | 7.38 | 1.55 | 8.95 | 1.58 | 9.04 | 2.32 | 13.67 | 1.84 | **10.98** | 2.28 | **13.26** | 0.63 | 3.90 | 0.84 | 4.89 | 1.10 | 6.44 | 1.00 | 6.25 | 1.48 | **9.16** | 1.18 | 7.40 |
| **FCW** | 3.44 | **16.20** | 3.73 | **18.46** | 1.48 | 7.97 | 1.18 | 6.72 | 1.14 | 6.75 | 1.34 | 8.08 | 1.48 | 7.65 | 0.89 | 4.71 | 1.26 | 7.11 | 0.84 | 4.95 | 0.71 | 4.29 | 0.84 | 5.33 |
| **PH** | 2.63 | **25.50** | 2.63 | **21.18** | 0.77 | 6.15 | 0.55 | 4.53 | 1.05 | 9.28 | 1.00 | 8.20 | 0.77 | 7.52 | 0.71 | 5.75 | 0.63 | 5.02 | 0.63 | 5.27 | 1.34 | **11.77** | 0.63 | 5.27 |
| **PW** | 0.89 | 11.04 | 0.95 | **13.75** | 0.84 | **14.18** | 0.84 | **17.07** | 0.55 | **10.33** | 1.05 | **19.79** | 0.71 | 8.95 | 0.77 | **12.49** | 0.84 | **16.41** | 0.71 | **15.04** | 0.89 | **17.89** | 0.84 | **17.80** |
| **XPL** | 1.18 | **24.15** | 0.84 | **19.46** | 0.77 | **15.49** | 0.84 | **16.41** | 0.55 | **10.33** | 1.26 | **23.42** | 0.77 | **16.14** | 0.32 | 7.71 | 1.14 | **25.34** | 0.84 | **17.07** | 0.71 | **13.86** | 0.45 | 8.60 |
| **TPL** | 0.63 | 1.71 | 0.84 | 2.41 | 1.22 | 3.89 | 1.41 | 4.78 | 0.95 | 3.05 | 1.70 | 5.44 | 1.05 | 2.86 | 2.26 | 6.62 | 1.22 | 3.96 | 1.58 | 5.36 | 0.89 | 2.94 | 0.89 | 2.92 |
| **XTPW** | 1.00 | 1.32 | 1.05 | 1.51 | 1.45 | 2.29 | 0.63 | 1.05 | 0.45 | 0.73 | 0.55 | 0.89 | 2.55 | 3.41 | 2.55 | 3.74 | 0.45 | 0.71 | 1.00 | 1.67 | 0.00 | 0.00 | 0.55 | 0.89 |
| **XAPWs** | 0.45 | 0.89 | 0.45 | 1.14 | 0.77 | 2.18 | 0.45 | 1.32 | 0.45 | 1.41 | 0.32 | 1.01 | 4.54 | 9.11 | 1.34 | 3.42 | 0.71 | 2.00 | 0.55 | 1.62 | 1.48 | 4.72 | 0.00 | 0.00 |
| **XAPWi** | 1.22 | 2.99 | 1.58 | 4.24 | 1.38 | 3.97 | 1.73 | 5.35 | 1.45 | 4.49 | 2.28 | 7.13 | 1.67 | 4.06 | 0.55 | 1.44 | 1.05 | 2.99 | 0.77 | 2.33 | 0.32 | 0.96 | 1.05 | 3.19 |
| **APH** | 0.55 | 1.92 | 2.88 | 8.70 | 0.32 | 1.00 | 0.77 | 2.42 | 1.00 | 3.16 | 1.10 | 3.28 | 1.64 | 5.63 | 0.55 | 1.69 | 0.45 | 1.42 | 0.77 | 2.46 | 0.45 | 1.42 | 0.89 | 2.66 |
| **XSPL** | 0.00 | 0.00 | 0.32 | 0.83 | 0.77 | 1.91 | 0.71 | 1.70 | 1.61 | 3.70 | 1.58 | 3.66 | 0.32 | 0.86 | 0.71 | 1.86 | 0.84 | 2.05 | 0.95 | 2.27 | 2.05 | 4.69 | 1.58 | 3.66 |
| **XSLi** | 0.32 | 1.81 | 0.32 | 1.62 | 1.10 | 5.22 | 0.45 | 2.00 | 0.32 | 1.56 | 0.55 | 2.22 | 0.32 | 1.79 | 0.45 | 2.28 | 0.55 | 2.55 | 0.45 | 1.98 | 0.45 | 1.86 | 0.55 | 2.20 |
| **min** | 0.00 | 0.00 | 0.32 | 0.83 | 0.32 | 1.00 | 0.45 | 1.05 | 0.45 | 0.73 | 0.32 | 0.89 | 0.32 | 0.86 | 0.32 | 1.44 | 0.45 | 0.71 | 0.32 | 1.62 | 0.00 | 0.00 | 0.00 | 0.00 |
| **max** | 3.44 | 25.50 | 3.73 | 21.18 | 1.58 | 15.49 | 2.32 | 17.07 | 2.02 | 10.98 | 2.28 | 23.42 | 4.54 | 16.14 | 2.55 | 12.49 | 1.45 | 25.34 | 1.58 | 17.07 | 2.05 | 17.89 | 1.58 | 17.80 |
| **mean** | 1.28 | 8.14 | 1.51 | 8.50 | 0.95 | 5.38 | 1.01 | 5.94 | 1.08 | 5.78 | 1.24 | 7.22 | 1.26 | 6.01 | 1.00 | 4.95 | 0.89 | 5.90 | 0.83 | 5.04 | 0.83 | 5.21 | 0.77 | 4.53 |

**Table 3.4:** Absolute technical error of measurement (TEM) and relative technical error of measurement (%TEM) assessing the intra- and inter-observer error rates for the lower thoracic vertebrae (T7 – T12). Refer to Appendix I for measurement names and definitions. Bold indicates the highest %TEM.

| | Inter | | | | | | | | | | | | Intra | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | T7 | | T8 | | T9 | | T10 | | T11 | | T12 | | T7 | | T8 | | T9 | | T10 | | T11 | | T12 | |
| | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM | TEM | % TEM |
| **XSLs** | 0.55 | 2.16 | 0.55 | 2.07 | 0.63 | 2.33 | 0.45 | 1.63 | 0.32 | 1.17 | 0.32 | 1.12 | 0.45 | 1.76 | 0.32 | 1.19 | 0.77 | 2.85 | 0.32 | 1.15 | 0.32 | 1.17 | 0.45 | 1.57 |
| **XCH** | 1.14 | 6.52 | 0.63 | 3.61 | 1.64 | 8.82 | 1.00 | 5.19 | 1.82 | 8.78 | 1.92 | 8.63 | 1.64 | **9.19** | 1.10 | 6.15 | 1.61 | **8.40** | 0.89 | 4.52 | 1.30 | 6.24 | 1.95 | **8.70** |
| **XAH** | 0.63 | 3.44 | 0.63 | 3.29 | 0.63 | 3.04 | 0.45 | 2.05 | 0.32 | 1.42 | 0.00 | 0.00 | 0.45 | 2.43 | 0.45 | 2.35 | 0.63 | 3.04 | 0.45 | 2.05 | 0.32 | 1.42 | 0.00 | 0.00 |
| **XPH** | 0.32 | 1.51 | 0.32 | 1.50 | 1.00 | 4.59 | 1.00 | 4.42 | 0.45 | 1.86 | 0.00 | 0.00 | 0.00 | 0.00 | 0.32 | 1.53 | 1.00 | 4.59 | 0.77 | 3.46 | 0.45 | 1.86 | 0.32 | 1.22 |
| **XALs** | 1.38 | 6.18 | 1.30 | 5.60 | 1.34 | 5.50 | 1.64 | 6.65 | 1.76 | 7.19 | 1.87 | 7.39 | 0.89 | 4.14 | 0.00 | 0.00 | 1.18 | 5.10 | 0.77 | 3.34 | 0.63 | 2.73 | 0.71 | 2.98 |
| **XALi** | 1.64 | 6.67 | 1.70 | 7.07 | 2.07 | **8.40** | 1.73 | 6.98 | 3.56 | 13.76 | 1.64 | 6.25 | 1.34 | 5.99 | 0.55 | 2.37 | 1.58 | 6.79 | 0.71 | 3.03 | 0.71 | 2.93 | 0.32 | 1.25 |
| **XAWs** | 1.64 | 6.25 | 0.89 | 3.22 | 1.34 | 4.72 | 1.92 | 6.27 | 1.52 | 4.58 | 1.61 | 4.16 | 1.05 | 4.08 | 0.55 | 2.01 | 1.00 | 3.55 | 1.14 | 3.81 | 1.14 | 3.49 | 1.38 | 3.66 |
| **XAWi** | 1.18 | 4.17 | 1.22 | 4.21 | 0.84 | 2.71 | 1.97 | 5.86 | 1.45 | 3.82 | 1.34 | 3.30 | 1.34 | 4.90 | 0.77 | 2.75 | 0.55 | 1.80 | 2.45 | **7.61** | 0.32 | 0.85 | 1.00 | 2.50 |
| **FSL** | 1.70 | **10.45** | 2.41 | **14.87** | 1.73 | **10.43** | 2.10 | 12.79 | 1.73 | 9.62 | 3.27 | 16.95 | 1.48 | **9.39** | 1.26 | **8.32** | 1.22 | 7.90 | 1.61 | **10.21** | 1.22 | **7.16** | 2.39 | **13.05** |
| **FCW** | 0.77 | 4.78 | 0.77 | 4.67 | 0.55 | 3.24 | 0.55 | 3.20 | 0.71 | 3.78 | 1.90 | 8.47 | 0.32 | 1.96 | 0.55 | 3.44 | 0.71 | 4.18 | 1.41 | **8.22** | 0.63 | 3.44 | 1.22 | 5.80 |
| **PH** | 0.45 | 3.49 | 1.10 | 8.43 | 0.84 | 5.85 | 0.84 | 5.33 | 0.45 | 2.63 | 0.45 | 2.51 | 1.61 | **12.22** | 0.84 | 6.59 | 1.34 | **9.32** | 0.71 | 4.50 | 0.32 | 1.87 | 0.32 | 1.79 |
| **PW** | 0.84 | **14.18** | 0.84 | **12.13** | 1.00 | **13.51** | 1.34 | 16.77 | 1.22 | 14.41 | 1.41 | 14.73 | 1.55 | **29.79** | 1.87 | **32.82** | 1.61 | **24.43** | 1.00 | **13.89** | 0.89 | **11.47** | 1.38 | **15.84** |
| **XPL** | 0.71 | **11.98** | 1.30 | **20.06** | 1.70 | **27.03** | 0.55 | 9.61 | 1.10 | 21.07 | 0.77 | 11.74 | 0.77 | **13.83** | 1.14 | **20.73** | 0.95 | **17.25** | 0.45 | **8.28** | 0.71 | **13.86** | 0.63 | **9.88** |
| **TPL** | 1.18 | 3.87 | 0.95 | 3.15 | 1.18 | 4.02 | 0.84 | 2.90 | 0.32 | 1.20 | 0.55 | 2.01 | 0.55 | 1.84 | 0.84 | 2.80 | 0.95 | 3.26 | 1.00 | 3.52 | 0.32 | 1.21 | 0.84 | 3.13 |
| **XTPW** | 1.34 | 2.23 | 1.41 | 2.39 | 1.84 | 3.19 | 1.22 | 2.20 | 1.22 | 2.37 | 0.45 | 0.83 | 1.30 | 2.17 | 1.38 | 2.31 | 2.26 | 3.91 | 0.77 | 1.39 | 0.77 | 1.50 | 0.45 | 0.83 |
| **XAPWs** | 0.55 | 1.80 | 0.55 | 1.74 | 1.30 | 3.82 | 1.10 | 3.06 | 0.45 | 1.20 | 0.71 | 1.88 | 0.55 | 1.81 | 0.77 | 2.48 | 0.95 | 2.78 | 1.05 | 2.92 | 0.55 | 1.48 | 0.84 | 2.23 |
| **XAPWi** | 2.07 | 6.26 | 2.49 | **7.32** | 1.18 | 3.22 | 0.77 | 2.06 | 3.18 | 8.39 | 0.71 | 2.27 | 1.95 | 5.77 | 1.64 | 4.74 | 0.55 | 1.48 | 0.55 | 1.45 | 0.32 | 0.86 | 0.55 | 1.76 |
| **APH** | 0.77 | 2.21 | 1.14 | 3.21 | 0.63 | 1.79 | 0.45 | 1.20 | 0.32 | 0.80 | 0.32 | 0.69 | 0.63 | 1.83 | 0.63 | 1.78 | 0.45 | 1.26 | 0.32 | 0.85 | 0.00 | 0.00 | 0.32 | 0.69 |
| **XSPL** | 0.45 | 1.06 | 1.34 | 3.21 | 0.71 | 1.76 | 1.14 | 3.01 | 0.89 | 2.71 | 0.55 | 1.64 | 1.00 | 2.37 | 1.38 | 3.29 | 0.71 | 1.76 | 1.00 | 2.65 | 0.71 | 2.14 | 0.45 | 1.34 |
| **XSLi** | 0.77 | 2.90 | 0.63 | 2.30 | 0.32 | 1.15 | 0.45 | 1.64 | 0.32 | 1.14 | 0.32. | 1.08 | 0.77 | 2.90 | 0.32 | 1.16 | 0.00 | 0.00 | 0.32 | 1.16 | 0.00 | 0.00 | 0.55 | 1.86 |
| **min** | 0.32 | 1.06 | 0.32 | 1.50 | 0.32 | 1.15 | 0.45 | 1.20 | 0.32 | 0.80 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.45 | 1.26 | 0.32 | 0.85 | 0.00 | 0.00 | 0.00 | 0.00 |
| **max** | 2.07 | 14.18 | 2.49 | 20.06 | 2.07 | 27.03 | 2.10 | 16.77 | 3.56 | 21.07 | 3.27 | 16.95 | 1.95 | 29.79 | 1.87 | 32.82 | 2.26 | 24.43 | 2.45 | 13.89 | 1.30 | 13.86 | 2.39 | 15.84 |
| **mean** | 1.00 | 5.11 | 1.11 | 5.70 | 1.12 | 5.96 | 1.08 | 5.14 | 1.15 | 5.59 | 1.01 | 4.78 | 0.99 | 6.08 | 0.86 | 5.67 | 1.05 | 5.98 | 0.91 | 4.57 | 0.61 | 3.46 | 0.82 | 4.12 |

**Table 3.5:** Absolute technical error of measurement (TEM) and relative technical error of measurement (%TEM) assessing the intra- and inter-observer error rates for the lumbar vertebrae (L1 – L4). Refer to Appendix I for measurement names and definitions. Bold indicates the highest %TEM.

| | Inter | | | | | | | | Intra | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L1 | | L2 | | L3 | | L4 | | L1 | | L2 | | L3 | | L4 | |
| | TEM | %TEM | TEM | %TEM | TEM | %TEM | TEM | %TEM | TEM | %TEM | TEM | %TEM | TEM | %TEM | TEM | % TEM |
| **XSLs** | 0.32 | 1.08 | 0.63 | 2.07 | 0.00 | 0.00 | 2.26 | 6.70 | 0.55 | 1.88 | 0.55 | 1.78 | 0.00 | 0.00 | 0.00 | 0.00 |
| **XCH** | 1.38 | 5.82 | 1.41 | 5.99 | 2.43 | **10.42** | 1.38 | 6.18 | 1.55 | 6.56 | 1.22 | 5.12 | 1.97 | **8.33** | 1.38 | 6.18 |
| **XAH** | 1.14 | 4.40 | 0.63 | 2.36 | 0.32 | 1.18 | 0.32 | 1.18 | 1.05 | 4.02 | 0.63 | 2.36 | 0.32 | 1.18 | 0.71 | 2.65 |
| **XPH** | 1.00 | 3.60 | 0.55 | 1.96 | 0.32 | 1.13 | 0.55 | 2.01 | 0.95 | 3.42 | 0.32 | 1.14 | 0.32 | 1.13 | 0.71 | 2.61 |
| **XALs** | 2.35 | **8.92** | 1.64 | 5.89 | 2.10 | **7.18** | 1.45 | 5.01 | 1.45 | 5.82 | 0.55 | 2.05 | 1.48 | 5.26 | 0.63 | 2.28 |
| **XALi** | 2.14 | **7.83** | 1.14 | 3.89 | 1.18 | 3.97 | 2.14 | 6.83 | 0.63 | 2.41 | 1.14 | 4.09 | 0.77 | 2.71 | 0.95 | 3.11 |
| **XAWs** | 2.00 | 5.08 | 2.19 | 5.14 | 1.79 | 4.01 | 1.55 | 3.30 | 1.34 | 3.48 | 0.71 | 1.70 | 1.22 | 2.79 | 1.00 | 2.16 |
| **XAWi** | 2.51 | 5.96 | 1.00 | 2.23 | 1.76 | 3.71 | 1.73 | 3.56 | 1.45 | 3.53 | 1.52 | 3.45 | 1.05 | 2.27 | 1.18 | 2.47 |
| **FSL** | 2.93 | **15.12** | 3.11 | **16.84** | 2.57 | **14.43** | 2.93 | **15.43** | 1.64 | **8.88** | 2.05 | **11.64** | 1.34 | 7.99 | 1.97 | **11.03** |
| **FCW** | 1.55 | 6.68 | 0.45 | 1.93 | 1.22 | 5.40 | 0.55 | 2.33 | 1.26 | 5.55 | 1.10 | 4.76 | 1.14 | 4.98 | 0.55 | 2.31 |
| **PH** | 0.32 | 1.94 | 0.71 | 4.29 | 0.45 | 2.76 | 0.32 | 2.12 | 0.45 | 2.73 | 0.63 | 3.86 | 0.45 | 2.76 | 0.77 | 5.10 |
| **PW** | 0.32 | 2.90 | 0.32 | 3.07 | 1.05 | **8.13** | 1.00 | 6.41 | 0.00 | 0.00 | 0.71 | 7.00 | 1.22 | **9.64** | 0.45 | 2.94 |
| **XPL** | 0.32 | 4.58 | 0.45 | 6.78 | 1.00 | **15.63** | 0.89 | 14.43 | 0.45 | 6.58 | 0.84 | 13.72 | 0.45 | **7.45** | 0.95 | **16.64** |
| **TPL** | 0.63 | 1.99 | 0.71 | 1.81 | 2.26 | 5.14 | 1.76 | 4.22 | 0.63 | 2.01 | 0.71 | 1.82 | 1.05 | 2.41 | 1.55 | 3.82 |
| **XTPW** | 0.45 | 0.71 | 0.45 | 0.56 | 0.45 | 0.51 | 0.45 | 0.55 | 0.45 | 0.71 | 0.32 | 0.40 | 0.71 | 0.81 | 0.32 | 0.39 |
| **XAPWs** | 2.93 | **8.52** | 2.76 | **7.41** | 3.33 | **8.48** | 3.07 | 6.91 | 2.21 | 6.34 | 2.81 | 7.66 | 3.54 | **9.00** | 2.86 | 6.42 |
| **XAPWi** | 0.00 | 0.00 | 0.32 | 0.94 | 0.45 | 1.17 | 0.77 | 1.73 | 0.77 | 2.50 | 0.32 | 0.94 | 0.63 | 1.66 | 0.32 | 0.71 |
| **APH** | 0.45 | 0.98 | 0.45 | 0.96 | 0.71 | 1.53 | 0.45 | 1.01 | 0.32 | 0.70 | 0.63 | 1.34 | 0.55 | 1.19 | 0.55 | 1.24 |
| **XSPL** | 0.00 | 0.00 | 0.71 | 1.93 | 1.22 | 3.37 | 1.10 | 3.28 | 0.00 | 0.00 | 0.95 | 2.57 | 0.45 | 1.22 | 1.18 | 3.56 |
| **XSLi** | 0.32 | 1.04 | 0.63 | 1.98 | 7.23 | 20.64 | 0.71 | 1.99 | 0.32 | 1.04 | 0.55 | 1.71 | 0.45 | 1.36 | 0.32 | 0.90 |
| **min** | 0.00 | 0.00 | 0.32 | 0.56 | 0.00 | 0.00 | 0.32 | 0.55 | 0.00 | 0.00 | 0.32 | 0.40 | 0.00 | 0.00 | 0.00 | 0.00 |
| **max** | 2.93 | 15.12 | 3.11 | 16.84 | 3.33 | 15.63 | 3.07 | 15.43 | 2.21 | 8.88 | 2.81 | 13.72 | 3.54 | 9.64 | 2.86 | 16.64 |
| **mean** | 1.20 | 4.53 | 1.03 | 4.00 | 1.29 | 5.17 | 1.30 | 4.90 | 0.90 | 3.53 | 0.93 | 4.07 | 0.98 | 3.83 | 0.95 | 3.98 |

## 3.5 Results: Exploration of Vertebral Variation

To determine whether universal, non-specific standards were possible for assessing vertebrae or if specific vertebrae had to be identified before further analysis, the dimensions of the vertebrae in the various types were compared.

### 3.5.1 Cervical Vertebrae

The correlation coefficients for cervical vertebrae demonstrated both positive and negative relationships among the variables (Figure 3.1). Moderate ($r$ = 0.33 – 0.68) to strong ($r$ = 0.71 – 0.81) positive correlations were noted between maximum inferior sagittal length and maximum inferior articular length ($r$ = 0.81), maximum transverse process width and transverse process length ($r$ = 0.81), maximum spinous process length and maximum transverse process width ($r$ = 0.80), maximum superior sagittal length and maximum superior articular length ($r$ = 0.75) and maximum inferior articular width and maximum superior articular width ($r$ = 0.76) measurements. Foramen sagittal length was the only variable to show negative correlations ($r$ = -0.06 – -0.23).

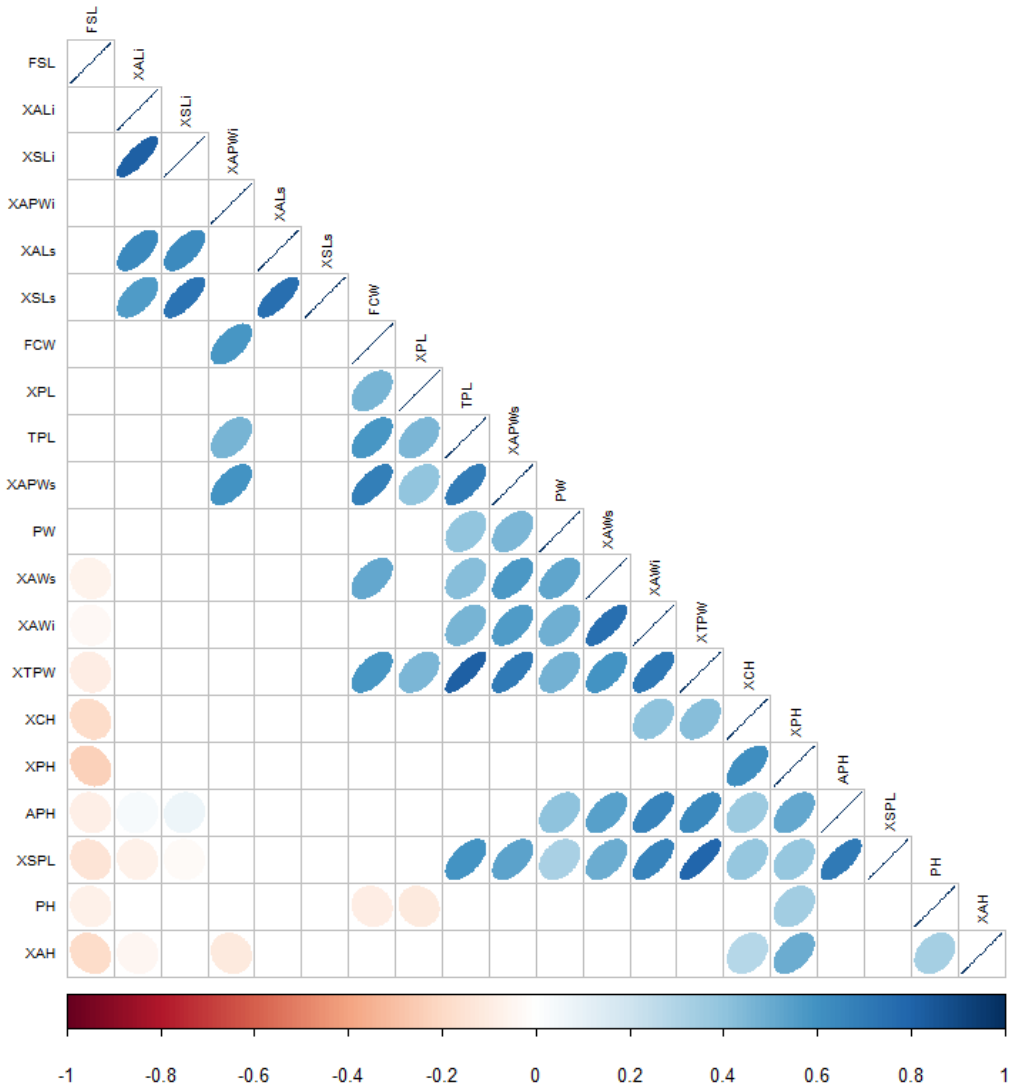


**Figure 3.1:** Correlation plot depicting the relationship among cervical vertebrae (C3-C7) variables. Red indicates negative correlations, blue indicates positive correlations, the ellipse width indicates the magnitude of the correlation, and the blank boxes indicate non-significant correlations. Refer to Appendix I for measurement names and definitions.

The ANOVA tests detected statistically significant differences among the different vertebral measurements in the cervical vertebrae for all variables, except for maximum superior sagittal, maximum superior articular length, maximum inferior articular length, foramen sagittal length, and maximum inferior sagittal length (Table 3.6). When the cervical vertebrae were further explored with Tukey's HSD, results revealed significant differences for various measurements in the atypical cervical vertebrae, more often among the third, fifth, sixth, and seventh cervical vertebrae (Appendix III, Figures 1-20). Furthermore, results revealed significant differences in

the height of the pedicle, transverse processes, and articular width measurements of different cervical vertebrae.

**Table 3.6:** ANOVA results evaluating the cervical vertebrae for each measurement. Bold indicates significance. Refer to Appendix I for measurement names and definitions.

| | Cervical Vertebrae | |
|---|---|---|
| | **F Value** | **Pr(>F)** |
| **XSLs** | 1.005 | 0.38 |
| **XCH** | 5.498 | < **0.05** |
| **XAH** | 10.84 | < **0.05** |
| **XPH** | 6.651 | < **0.05** |
| **XALs** | 0.808 | 0.52 |
| **XALi** | 0.535 | 0.71 |
| **XAWs** | 18.52 | < **0.05** |
| **XAWi** | 48.32 | < **0.05** |
| **FSL** | 1.066 | 0.38 |
| **FCW** | 4.848 | < **0.05** |
| **PH** | 6.929 | < **0.05** |
| **PW** | 12.82 | < **0.05** |
| **XPL** | 4.075 | < **0.05** |
| **TPL** | 12.93 | < **0.05** |
| **XTPW** | 41.44 | < **0.05** |
| **XAPWs** | 13.68 | < **0.05** |
| **XAPWi** | 8.83 | < **0.05** |
| **APH** | 46.73 | < **0.05** |
| **XSPL** | 137.2 | < **0.05** |
| **XSLi** | 0.535 | 0.71 |

### 3.5.2 Upper Thoracic Vertebrae

The correlation coefficients in the upper thoracic vertebrae (T1-T6) demonstrated both positive and negative relationships among the variables (Figure 3.2). Substantial weak negative ($r$ = -0.14 - -0.62) correlations were shown throughout the measurements. Positive correlations ($r$ = 0.65 – 0.93) were also noted throughout the upper thoracic vertebral measurements. The strongest positive correlations were noted between maximum transverse process width and transverse process length ($r$ = 0.93) maximum inferior and superior articular process width ($r$ = 0.86), maximum inferior and superior articular length ($r$ = 0.92) and maximum superior and inferior sagittal length ($r$ = 0.93).

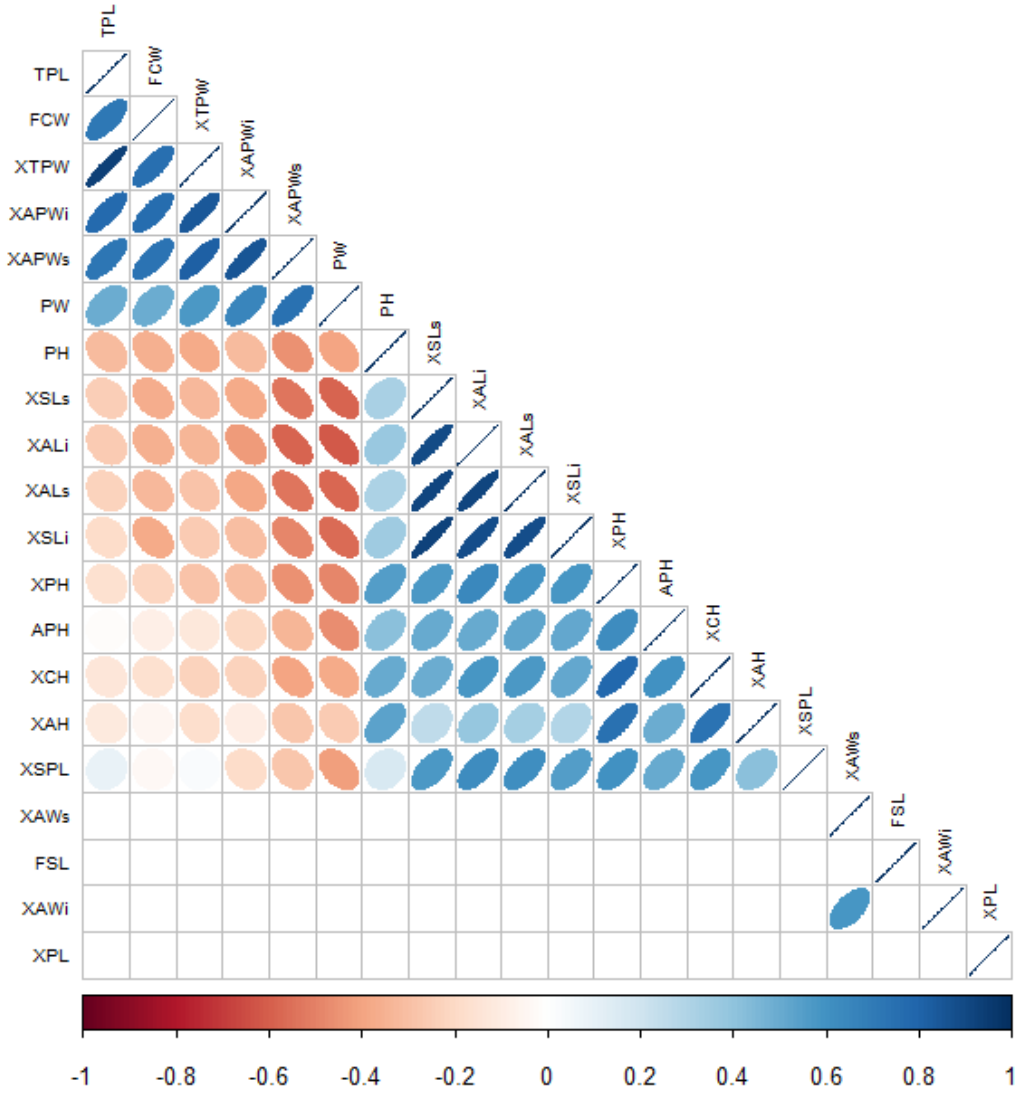


**Figure 3.2:** Correlation plot depicting the relationship among upper thoracic vertebrae (T1-T6) variables. Red indicates negative correlations, blue indicates positive correlations, the ellipse's size indicates the magnitude of the correlation, and the blank boxes indicate non-significant correlations. Refer to Appendix I for measurement names and definitions.

In the upper thoracic vertebrae (T1-T6), ANOVA detected significant differences for all variables except maximum superior articular width, maximum inferior articular width, and foramen sagittal length measurements (Table 3.7). As Tukey's HSD was further explored, significant differences were discovered among the measurements of different upper thoracic vertebrae (i.e., T1-T6), specifically the first, second, fourth and sixth thoracic vertebrae (Appendix III, Figures 21-40). Results further showed that the maximum superior and inferior

articular widths, foramen sagittal lengths, and pedicle lengths of the different upper thoracic vertebrae did not differ significantly.

**Table 3.7:** ANOVA results evaluating the upper thoracic vertebrae for each measurement. Bold indicates significance. Refer to Appendix I for measurement names and definitions.

| Upper Thoracic Vertebrae | | |
|---|---|---|
| | **F Value** | **Pr(>F)** |
| **XSLs** | 52.62 | < **0.05** |
| **XCH** | 19.31 | < **0.05** |
| **XAH** | 9.697 | < **0.05** |
| **XPH** | 23.94 | < **0.05** |
| **XALs** | 49.89 | < **0.05** |
| **XALi** | 48.55 | < **0.05** |
| **XAWs** | 0.955 | 0.45 |
| **XAWi** | 1.454 | 0.21 |
| **FSL** | 0.54 | 0.746 |
| **FCW** | 23.57 | < **0.05** |
| **PH** | 23.5 | < **0.05** |
| **PW** | 56.83 | < **0.05** |
| **XPL** | 1.853 | 0.11 |
| **TPL** | 24.8 | < **0.05** |
| **XTPW** | 40.54 | < **0.05** |
| **XAPWs** | 86.74 | < **0.05** |
| **XAPWi** | 36.39 | < **0.05** |
| **APH** | 13.81 | < **0.05** |
| **XSPL** | 15.26 | < **0.05** |
| **XSLi** | 36.13 | < **0.05** |

### 3.5.3 Lower Thoracic Vertebrae

Correlation coefficients for lower thoracic vertebrae (T7-T12) demonstrated positive and negative weak relationships among the variables (Figure 3.3). Maximum spinous process length, transverse process length and maximum transverse process width showed weak negative correlations ($r$ = -0.09 - -0.66) throughout the measurements. Additionally, weak positive correlations were noted between the lower thoracic vertebral measurements. The strongest positive correlations were noted between maximum transverse process width and transverse process length ($r$ = 0.85), maximum inferior and superior articular process length ($r$ = 0.82), maximum inferior and superior articular widths ($r$ = 0.94), maximum superior and inferior sagittal length ($r$ = 0.92).

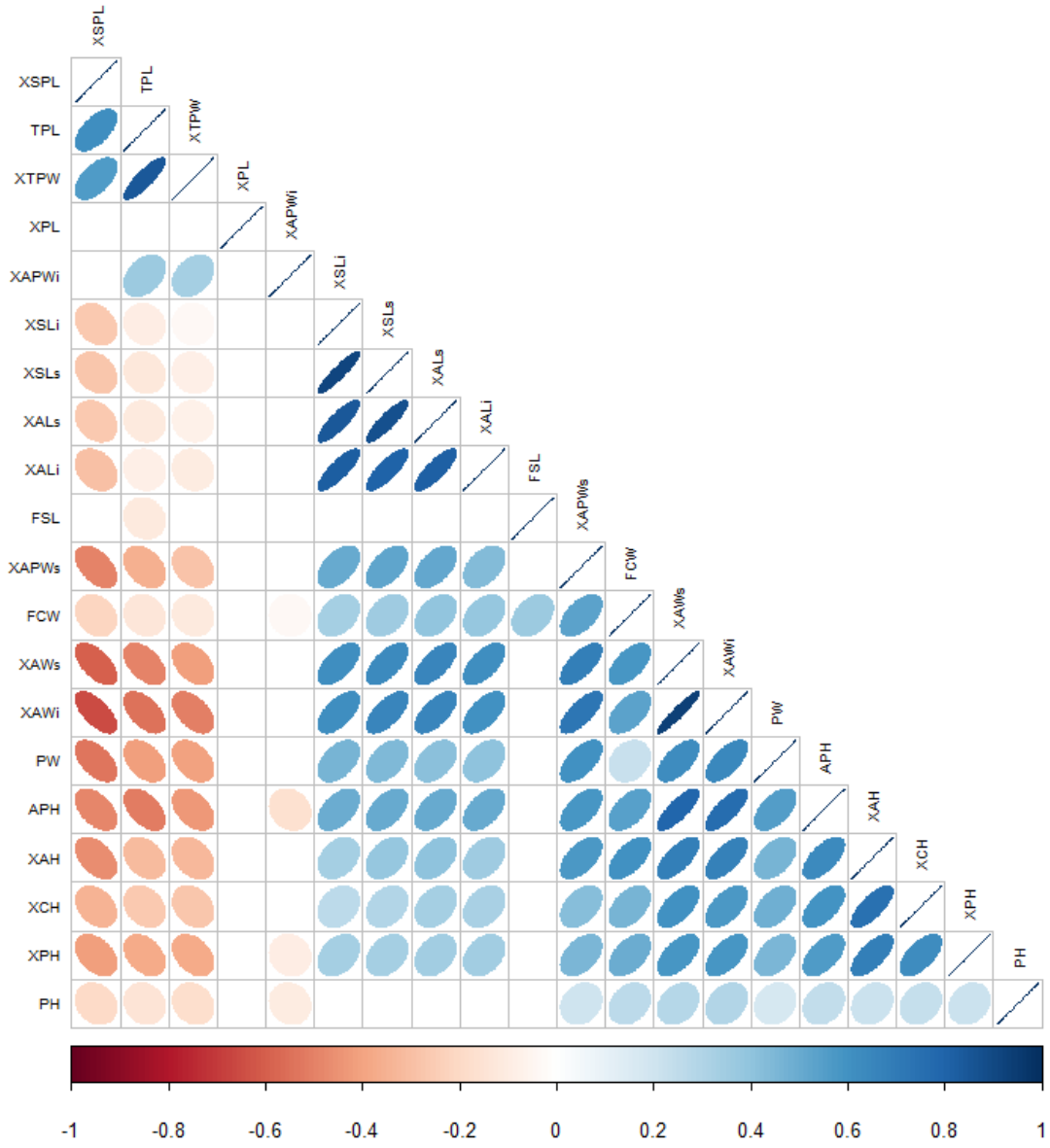


**Figure 3.3:** Correlation plot depicting the relationship among lower thoracic vertebrae (T7-T12) variables. Red indicates negative correlations, blue indicates positive correlations, the ellipse's size indicates the magnitude of the correlation, and the blank boxes indicate non-significant correlations. Refer to Appendix I for measurement names and definitions.

In the lower thoracic vertebrae (T7-T12), ANOVA detected significant differences for all variables, except the foramen sagittal length (Table 3.8). When further explored with Tukey's HSD, significant differences were found among the different lower thoracic vertebra types (i.e., T7-T12). When compared to the typical vertebrae, such as the seventh, ninth, and tenth thoracic

vertebrae, the atypical lower thoracic vertebrae (T12) showed no significant differences using Tukey's HSD (Appendix III, Figures 31-50).

**Table 3.8:** ANOVA results evaluating the lower thoracic vertebrae for each measurement. Bold indicates significance. Refer to Appendix I for measurement names and definitions.

| Lower Thoracic Vertebrae | | |
|---|---|---|
| | **F Value** | **Pr(>F)** |
| **XSLs** | 9.163 | **< 0.05** |
| **XCH** | 17.39 | **< 0.05** |
| **XAH** | 37.15 | **< 0.05** |
| **XPH** | 23.06 | **< 0.05** |
| **XALs** | 9.94 | **< 0.05** |
| **XALi** | 6.497 | **< 0.05** |
| **XAWs** | 59.83 | **< 0.05** |
| **XAWi** | 76.97 | **< 0.05** |
| **FSL** | 2.65 | **< 0.05** |
| **FCW** | 16.72 | **< 0.05** |
| **PH** | 3.136 | **< 0.05** |
| **PW** | 18.42 | **< 0.05** |
| **XPL** | 0.845 | 0.52 |
| **TPL** | 32.19 | **< 0.05** |
| **XTPW** | 28.46 | **< 0.05** |
| **XAPWs** | 26.57 | **< 0.05** |
| **XAPWi** | 19.23 | **< 0.05** |
| **APH** | 59.06 | **< 0.05** |
| **XSPL** | 33.84 | **< 0.05** |
| **XSLi** | 7.716 | **< 0.05** |

### 3.5.4 Lumbar Vertebrae

The lumbar vertebral correlation coefficients demonstrated both positive and negative correlations between measurements (Figure 3.4). The moderate ($r$ = 0.29 – 0.64) to strongest ($r$ = 0.71 – 0.81) positive correlations were noted between maximum transverse process width and transverse process length ($r$ = 0.94), maximum inferior and superior articular process width ($r$ = 0.88), maximum inferior and superior articular length ($r$ = 0.83), maximum superior sagittal length and maximum superior articular length ($r$ = 0.90) and maximum inferior sagittal length and maximum inferior articular width ($r$ = 0.90).

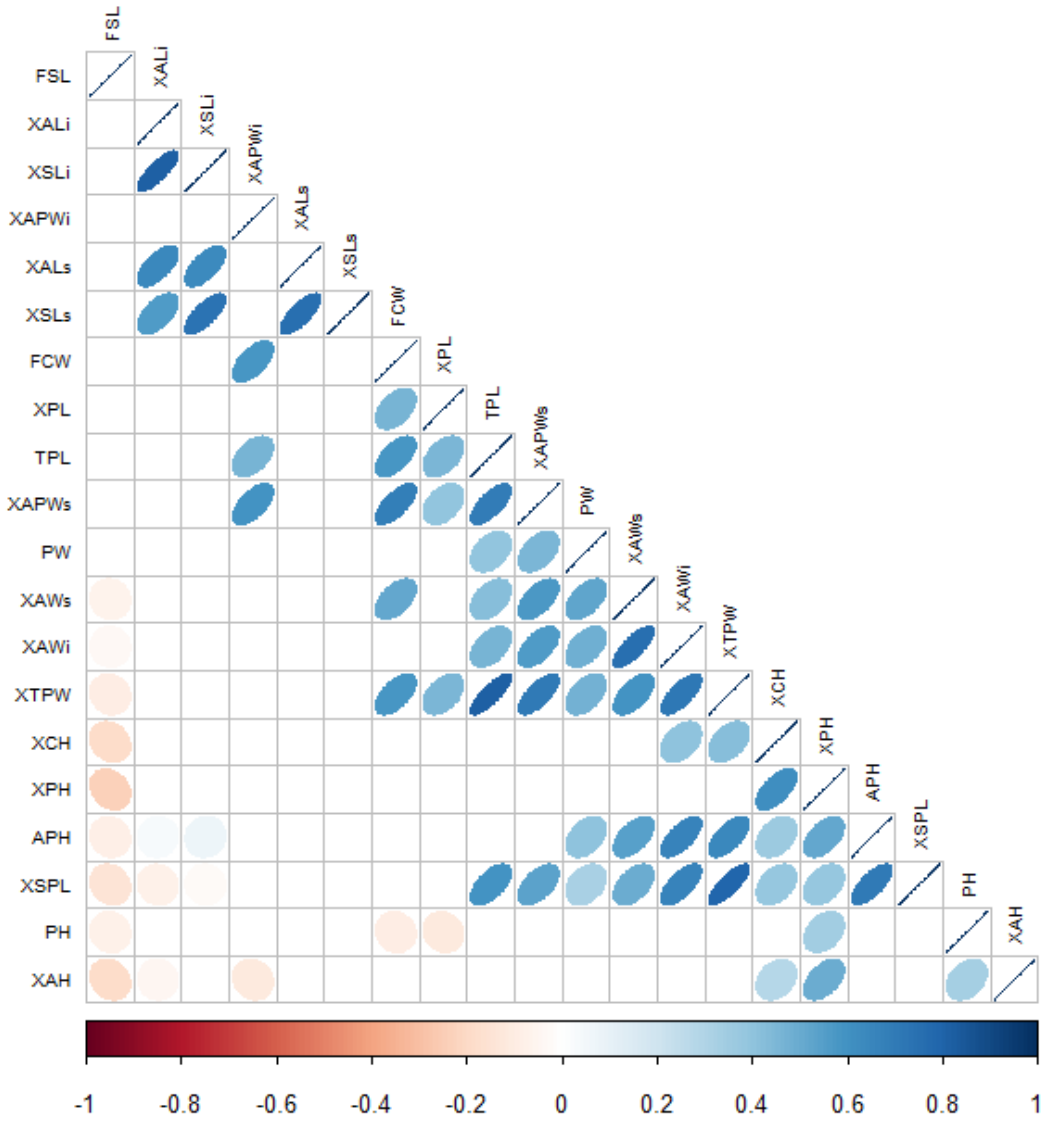


**Figure 3.4:** Correlation plot depicting the relationship among lumbar vertebrae (L1-L4) variables. Red indicates negative correlations, blue indicates positive correlations, the ellipse's size indicates the correlation, and the blank boxes indicate non-significant correlations. Refer to Appendix I for measurement names and definitions.

According to ANOVA, all variables except for foramen sagittal length, foramen coronal width, maximum pedicle length, and articular process height of the lumbar vertebrae (L1-L4) showed significant differences (Table 3.9). Tukey's HSD analysis revealed significant differences in measurements among the different types of lumbar vertebrae (i.e., L1-L4). The atypical vertebrae for the lumbar vertebrae, specifically the first lumbar vertebrae (L1), showed no significant differences in Tukey's HSD test (Appendix III, Figures 51-70). In addition, the vertebrae closest to the atypical vertebrae (i.e., L2 and L4) did not show significant differences.

**Table 3.9:** ANOVA results evaluating the lumbar vertebrae for each measurement. Bold indicates significance. Refer to Appendix I for measurement names and definitions.

| | Lumbar Vertebrae | |
|---|---|---|
| | **F Value** | **Pr(>F)** |
| **XSLs** | 20.79 | < **0.05** |
| **XCH** | 7.496 | < **0.05** |
| **XAH** | 3.178 | < **0.05** |
| **XPH** | 5.724 | < **0.05** |
| **XALs** | 10.12 | < **0.05** |
| **XALi** | 13.55 | < **0.05** |
| **XAWs** | 11.84 | < **0.05** |
| **XAWi** | 10.65 | < **0.05** |
| **FSL** | 2.099 | 0.11 |
| **FCW** | 1.677 | 0.18 |
| **PH** | 8.563 | < **0.05** |
| **PW** | 22.09 | < **0.05** |
| **XPL** | 1.976 | 0.12 |
| **TPL** | 25.02 | < **0.05** |
| **XTPW** | 32.45 | < **0.05** |
| **XAPWs** | 14 | < **0.05** |
| **XAPWi** | 40.84 | < **0.05** |
| **APH** | 1.059 | 0.37 |
| **XSPL** | 5.189 | < **0.05** |
| **XSLi** | 19.03 | < **0.05** |

## 3.6 Summary

- Maximum centroid height, foramen sagittal length, foramen coronal width, pedicle height, pedicle width, and maximum pedicle length measurements were significantly different between the vertebrae and thus will not be useful for the creation of universal formulae.
- Several measurements were shown to have repeatability issues; thus, maximum centroid height, foramen sagittal length, foramen coronal width, and pedicle height, width, and maximum pedicle length measurements were removed from further analyses.
- The atypical vertebrae (C7, T1 and T12) showed vast differences, along with the vertebrae closest to the atypical vertebrae (C6, T2, T11, L1 and L4).
- The sixth cervical, second thoracic, eleventh thoracic and fourth lumbar vertebrae have been excluded from the study because they differ too much from the rest of the vertebrae and will not be useful for the creation of universal formulae.

# CHAPTER 4: POPULATION AFFINITY AND SEX ESTIMATION FROM THE VERTEBRAE

In chapter 3, the variation exploration component explored the size variation among sequential vertebrae within and among the different subtypes (i.e., cervical, thoracic, and lumbar vertebrae) to determine possible single vertebral or combined vertebral standards for population affinity and sex estimation. Using the information from the variation exploration component, classification models were created to gauge the predictive accuracy of vertebral measurements when estimating population affinity and sex. The classification component focused on the quantifiable differences in the vertebrae in order to develop standards that can be used to estimate population affinity and sex in South Africa. Furthermore, this component assessed whether universal, non-specific standards can be established or if a specific vertebra needs to be identified first before classification can occur.

## 4.1 Skeletal Sample

For the classification component, the study sample consisted of the selection of vertebrae suggested to be useful for a universal formula in the variation exploration component; this includes cervical (C3 to C6), thoracic (T2 to T11), and lumbar (L1 to L4) vertebrae of 120 adult South African individuals (60 black and 60 white) with equal sex distribution (30 males and 30 females per population group). The morphology of the thoracic vertebrae is variable, as the upper and lower thoracic play different roles in the vertebral column, for example, the upper thoracic (T1-T6) has less load-bearing capacity compared to the lower thoracic (T7-T12) vertebrae. Therefore, the thoracic vertebrae were separated into upper thoracic (T1-T6) and lower thoracic (T7-T12) vertebrae. The skeletal remains were obtained from the Pretoria Bone Collection (PBC), housed in the Department of Anatomy at the University of Pretoria.

All personal information was anonymised for each individual, with only the sex, age, and population affinity recorded for the study. The sample included individuals between 27 and 93 years of age. However, it should be acknowledged that the dimensions of the vertebral body may be affected in older individuals due to vertebral compression and osteophyte growth. Table 4.1 provides the mean age distribution for the classification component of the skeletal sample for each population group and sex.

For bilateral measurements (i.e., pedicle and transverse process measurements), only the left side was measured. Any measurements that were affected by the extensive presence of pathology (e.g., osteophytosis or vertebral compression), vertebral deformity (e.g., scoliosis, spondylolysis, or sacralisation), an indication of spinal surgical procedures, or post-mortem damage were excluded from the study, however, individuals with minimal presence of pathology were included in the sample. Additionally, the exclusion of one vertebra or measurement did not exclude the individual from the sample.

**Table 4.1:** Mean age distribution of the skeletal sample.

| | Black | | | White | | |
|---|---|---|---|---|---|---|
| | **Males (n=30)** | **Females (n=30)** | **Pooled (n=60)** | **Males (n=30)** | **Females (n=30)** | **Pooled (n=60)** |
| **Age (years)** | 35 | 38 | 37 | 55 | 59 | 57 |

## 4.2 Methods

After exploring the variation of the various vertebrae and their measurements in chapter 3, measurements from a range of typical and non-transitional vertebrae were selected for the creation of single vertebral univariate and multivariate models and combined universal univariate and multivariate models for population affinity and sex estimation. In the current chapter, the vertebral measurements were explored for their potential to estimate population affinity and sex.

Univariate models were created to assess the accuracy of each individual measurement for each vertebra in identifying population affinity and sex, which could be useful when only fragmentary vertebrae are available. Universal univariate models were created for each individual measurement per population affinity and sex for each vertebral sub-type (i.e., combined models for cervical (C3-C6), upper thoracic (T2-T6), lower thoracic (T7-T11) and lumbar vertebrae (L1-L4)).

Multivariate models were also created to estimate population affinity and sex. The multivariate models were created for each individual vertebra and included the various measurements retained after stepwise analyses for those vertebrae. Additionally, combined universal multivariate vertebral models were created that included all the measurements from the various vertebrae sub-types (i.e., models for cervical (C3-C6), upper thoracic (T2-T6), lower thoracic (T7-T11) and lumbar vertebrae (L1-L4)). The individual multivariate models could be useful

for population affinity and sex estimation if intact vertebrae of known vertebra sub-type and number were available for analysis. However, in cases where the specific vertebra number is not identifiable, the universal multivariate models could be useful, as only the sub-type needs to be identified to estimate population and sex.

### 4.2.1 Osteometric analysis

A series of 14 measurements were retained from the variation exploration component to assess the cervical, thoracic, and lumbar vertebrae in the classification component. The principal investigator collected osteometric data on a selection of cervical, thoracic, and lumbar vertebrae, including the third to sixth cervical vertebrae (C3 - C6), the second to eleventh thoracic (T2 - T11) and first to fourth lumbar (L1 - L4) vertebrae. The first, second and seventh cervical vertebrae, first and twelfth thoracic and fifth lumbar vertebrae were excluded due to morphological variability, as established in the variation exploration component. Refer to Table 4.2 for the retained measurements and their associated measurement abbreviations.

**Table 4.2:** Measurement abbreviations for the variables retained for the classification component of the study. Refer to Appendix I and II for more measurement information.

| | | | |
|---|---|---|---|
| **Maximum Superior Sagittal Length** | XSLs | **Transverse Process Length** | TPL |
| **Maximum Anterior Height** | XAH | **Maximum Transverse Process Width** | XTPW |
| **Maximum Posterior Height** | XPH | **Maximum Inferior Articular Width** | XAPWi |
| **Maximum Superior Articular Length** | XALs | **Articular Process Height** | APH |
| **Maximum Inferior Articular Length** | XALi | **Maximum Spinous Process Length** | XSPL |
| **Maximum Superior Articular Width** | XAWs | **Maximum Inferior Sagittal Length** | XSLi |
| **Maximum Inferior Articular Width** | XAWi | **Maximum Pedicle Length** | XPL |

### 4.2.2 Statistical Analysis

All statistical analyses were performed using R (version 4.0.5) and the RStudio environment (R Core Team, 2020). Outliers were detected and removed before statistical analysis using univariate boxplots. Descriptive statistics, including the mean and standard deviations, were assessed to analyse patterns in the vertebral measurements of the various population and sex groups. ANOVA was used to test for significant differences in the vertebral measurements between the population and sexes groups. A multitude of univariate and multivariate models was employed to identify the most accurate combination of predictor variables. After taking the mean of each vertebra separately, the mean of each measurement was combined per subtype of vertebra. In this manner, the method not only developed a univariate or specific formula but also determined if universal formulas could be useful. Finally, linear discriminant analysis

(LDA) was run with univariate and multivariate classification models in order to assess the potential of the measurements in estimating population affinity and sex. In biological anthropology, LDA is a classification method that incorporates measurements to evaluate biological parameters (sex, population affinity) using mathematical formulae (Ousley *et al.*, 2012; Tabachnick *et al.*, 2019). LDA calculates factors or weights for each variable (i.e., measurements), which maximises the mean differences among groups. The factors can then be used to classify unknown individuals. An unknown individual classification is based on the similarities and discriminant function scores produced with LDA, allowing comparison to each reference group centroid, thereby classifying the unknown individual into the group with the smallest distance from the centroid (Ousley *et al.*, 2012).

There are several requirements for the LDA to produce functions with the highest possible classification accuracy, including adequate sample size, multivariate normality, no outliers and equal group variation. Firstly, the sample size is extremely important, as accurate calculations are related to the number of measurements analysed. The basic criterion needed is that the smallest sample must be at least one individual larger than the number of variables used in the model (Ousley *et al.*, 2012; Tabachnick *et al.*, 2019). Another requirement is multivariate normality of data, both univariate and multivariate normality, to accurately estimate the parameters and probabilities of LDA (Ousley *et al.*, 2012; Tabachnick *et al.*, 2019). Outliers are typically measurements or individuals that are outside the normal variance of the sample. Outliers can be due to measurement error, recording error, an encoding error, human variation, pathology, or a combination of these reasons. Therefore, removing outliers, especially in multivariate analyses, is required and recommended, especially if the sample size is large enough (Ousley *et al.*, 2012). Lastly, equal group variation (i.e., homogeneity of variance), which is dependent on the standard deviations, is a measure of variation within a group that quantifies differences among the classified groups. Therefore, as in univariate analyses, the within-group variation must be relatively similar to the centroid to make a comparison using a common measure of variability (Ousley *et al.*, 2012; Tabachnick *et al.*, 2019).

Multivariate models were created using all the measurements taken per vertebra to test the classification accuracies of each vertebral sub-type (i.e., L1, L2, L3, L4, respectively) and universal models were created using all the measurements combining each vertebral sub-type (i.e., combining all lumbar vertebrae simultaneously (L1-L4)). Table 4.3 provides the variables included in each univariate and multivariate classification model and associated measurements.

**Table 4.3:** Variables included in each univariate and multivariate classification models.

| Vertebrae sub-type | Vertebrae | *n* |
|---|---|---|
| **Individual cervical models** | **C3** | 74 |
| | **C4** | 80 |
| | **C5** | 69 |
| | **C6** | 63 |
| **Universal cervical model** | **Combining all cervical vertebrae (C3-C7)** | 286 |
| **Individual upper thoracic models** | **T2** | 96 |
| | **T3** | 107 |
| | **T4** | 97 |
| | **T5** | 88 |
| | **T6** | 89 |
| **Universal upper thoracic model** | **Combining all upper thoracic vertebrae (T2-T6)** | 478 |
| **Lower thoracic models** | **T7** | 89 |
| | **T8** | 96 |
| | **T9** | 91 |
| | **T10** | 96 |
| | **T11** | 99 |
| **Universal lower thoracic model** | **Combining all lower thoracic vertebrae (T7-T11)** | 475 |
| **Lumbar models** | **L1** | 73 |
| | **L2** | 59 |
| | **L3** | 51 |
| | **L4** | 43 |
| **Universal lumbar model** | **Combining all lumbar vertebrae (L1-L4)** | 226 |

## 4.3 Results

### 4.3.1 Cervical Vertebrae

The descriptive statistics demonstrated variability among the cervical vertebrae of black and white South African males and females. Tables A1 to A4 (see Appendix IV) present the descriptive statistics of the cervical vertebrae, including the sample size, mean and standard deviation for each measurement. Overall, white South Africans ($\mu$ = 5.31 – 55.51) had larger measurement means than black South Africans ($\mu$ = 4.8 – 52.96), except for the maximum superior sagittal length and the maximum transverse process width which were smaller. Compared to females ($\mu$ = 4.97 – 51.89), males ($\mu$ = 5.13 – 56.11) had greater measurement means. From the third cervical to the sixth cervical vertebra, the transverse and spinous processes increased in size, while the articular widths became larger to accommodate the articulation of larger sequential vertebra.

ANOVA demonstrated significant differences between black and white South Africans for most of the measurements across all cervical vertebrae, with a few exceptions. Specifically, maximum superior sagittal length was only significantly different between the population groups for the sixth cervical vertebra, while transverse process length, maximum transverse

process width and maximum spinous process length were significantly different for all cervical vertebrae, except for the sixth cervical vertebra. When comparing the sexes, maximum pedicle length was noted as not significantly different between the sexes for any of the cervical vertebrae. Additionally, articular process height was not significantly different when assessing the third and fourth cervical vertebrae for sex differences (Table 4.4).

**Table 4.4:** ANOVA results evaluating population groups and sexes for each measurement for the cervical vertebra (C3-C6). Bold indicates significant variables. Refer to Appendix I for measurement names and definitions.

| | **Population** | | | | **Sex** | | | |
|---|---|---|---|---|---|---|---|---|
| | **C3** | **C4** | **C5** | **C6** | **C3** | **C4** | **C5** | **C6** |
| **XSLs** | 0.466 | 0.022 | 0.047 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | 0.014 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.024 | **<0.01** | **<0.01** |
| **XAWi** | 0.186 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.120 | 0.369 | 0.708 | 0.328 |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | 0.144 | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | 0.584 | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.038 | 0.020 | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | 0.473 | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | 0.877 | 0.160 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

With the universal cervical model (combined means of C3 – C6), ANOVA detected statistically significant differences among the vertebral body lengths and articular process, spinous process and articular widths of white South Africans. Among black South Africans, the only measurements that did not differ significantly included the maximum superior sagittal length, maximum posterior height, maximum superior articular length, maximum inferior articular length, and maximum inferior sagittal length. Similar results were seen when comparing the sexes. Among males, the only measurements that were not significantly different included the maximum superior sagittal length, maximum posterior height, maximum superior articular length, maximum inferior articular length, and maximum inferior sagittal length. In females, the vertebral body lengths, articular process, spinous process, and articular width did not differ significantly (Table 4.5).

**Table 4.5:** ANOVA results evaluating population groups and sexes for each measurement using the universal cervical model (C3-C6). Bold indicates significant variables. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Blacks** | **Whites** | **Males** | **Females** |
| **XSLs** | 0.427 | **<0.01** | 0.026 | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | 0.023 |
| **XPH** | 0.155 | 0.427 | 0.199 | 0.565 |
| **XALs** | 0.236 | **<0.01** | 0.163 | **<0.01** |
| **XALi** | 0.073 | **<0.01** | 0.010 | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **TPL** | **<0.01** | 0.158 | **<0.01** | 0.074 |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | 0.672 | **<0.01** | 0.208 | **<0.01** |

When attempting population affinity estimation using univariate models, the classification accuracies ranged between 0% and 89% for the third cervical vertebra, between 44% and 81% for the fourth cervical vertebra, between 35% and 86% for the fifth cervical vertebra, and between 42% and 84% for the sixth cervical vertebra (Table 4.6). For sex estimation, the univariate models yielded accuracies between 56% and 89% for the third cervical vertebra, between 38% and 86% for the fourth cervical vertebra, between 35% and 81% for the fifth cervical vertebra, and between 22% and 98% for the sixth cervical vertebrae (Table 4.7).

**Tables 4.6:** Univariate LDA correct classification accuracy (%) for population affinity using the cervical vertebrae (C3-C6). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | C3 | | | | | | C4 | | | | | | C5 | | | | | | C6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | |
| variable | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % |
| **XSLs** | 19 | 41 | 18 | 64 | 37 | 50 | 29 | 60 | 16 | 69 | 45 | **80** | 32 | 65 | 11 | 55 | 43 | 62 | 31 | 82 | 14 | 56 | 45 | 71 |
| **XAH** | 33 | 72 | 18 | 64 | 51 | 69 | 36 | 75 | 20 | 56 | 56 | 64 | 35 | 74 | 13 | 65 | 48 | 70 | 23 | 61 | 13 | 52 | 36 | 57 |
| **XPH** | 31 | 67 | 19 | 68 | 50 | 68 | 40 | 83 | 22 | 64 | 62 | 68 | 42 | 86 | 12 | 60 | 54 | **78** | 28 | 74 | 13 | 52 | 41 | 65 |
| **XALs** | 23 | 50 | 15 | 54 | 38 | 51 | 35 | 73 | 14 | 78 | 49 | 76 | 35 | 71 | 7 | 35 | 42 | 61 | 24 | 63 | 16 | 64 | 40 | 63 |
| **XALi** | 25 | 54 | 19 | 68 | 44 | 59 | 26 | 54 | 23 | 83 | 49 | 78 | 35 | 71 | 10 | 50 | 45 | 65 | 27 | 71 | 18 | 72 | 45 | 71 |
| **XAWs** | 25 | 54 | 19 | 68 | 44 | 59 | 29 | 60 | 24 | 75 | 53 | 70 | 28 | 57 | 15 | 75 | 43 | 62 | 31 | 82 | 17 | 68 | 48 | **76** |
| **XAWi** | 23 | 50 | 13 | 46 | 36 | 49 | 31 | 65 | 25 | 75 | 56 | 70 | 29 | 59 | 13 | 65 | 42 | 61 | 25 | 66 | 12 | 48 | 37 | 59 |
| **XPL** | 38 | 59 | 18 | 43 | 56 | 53 | 24 | 50 | 22 | 47 | 46 | 56 | 38 | 78 | 8 | 40 | 46 | 67 | 25 | 66 | 15 | 60 | 40 | 63 |
| **TPL** | 27 | 83 | 12 | 64 | 39 | 76 | 36 | 75 | 24 | 67 | 60 | 64 | 36 | 73 | 14 | 70 | 50 | 72 | 17 | 45 | 9 | 36 | 26 | 41 |
| **XTPW** | 38 | 72 | 24 | 86 | 62 | 78 | 33 | 69 | 24 | 75 | 57 | 74 | 30 | 61 | 10 | 50 | 40 | 58 | 16 | 42 | 15 | 60 | 31 | 49 |
| **XAPWi** | 35 | 76 | 17 | 89 | 52 | **82** | 42 | 88 | 25 | 67 | 67 | 68 | 35 | 71 | 14 | 70 | 49 | 71 | 21 | 55 | 18 | 72 | 39 | 62 |
| **APH** | 36 | 78 | 17 | 61 | 53 | 72 | 34 | 71 | 26 | 61 | 60 | 59 | 31 | 63 | 11 | 55 | 42 | 61 | 32 | 84 | 13 | 52 | 45 | 71 |
| **XSPL** | 32 | 70 | 19 | 68 | 51 | 69 | 37 | 77 | 22 | 58 | 59 | 64 | 30 | 61 | 13 | 65 | 43 | 62 | 24 | 63 | 15 | 60 | 39 | 62 |
| **XSLi** | 0 | 0 | 5 | 18 | 5 | 1 | 30 | 63 | 18 | 64 | 48 | 73 | 25 | 51 | 12 | 60 | 37 | 54 | 28 | 74 | 13 | 52 | 41 | 65 |

**Tables 4.7:** Univariate LDA correct classification accuracy (%) for sex using the cervical vertebrae (C3-C6). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | C3 | | | | | | C4 | | | | | | C5 | | | | | | C6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Females | | Males | | Total | | Females | | Males | | Total | | Females | | Males | | Total | | Females | | Males | | Total | |
| variable | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % |
| **XSLs** | 34 | 89 | 25 | 69 | 59 | **80** | 34 | 81 | 27 | 71 | 61 | **76** | 28 | 78 | 20 | 61 | 48 | 70 | 23 | 74 | 13 | 41 | 36 | 57 |
| **XAH** | 27 | 71 | 20 | 56 | 47 | 64 | 33 | 79 | 23 | 61 | 56 | 70 | 23 | 64 | 14 | 42 | 37 | 54 | 21 | 68 | 18 | 56 | 39 | 62 |
| **XPH** | 27 | 71 | 23 | 64 | 50 | 68 | 33 | 79 | 21 | 55 | 54 | 68 | 16 | 44 | 20 | 61 | 36 | 52 | 26 | 84 | 18 | 56 | 44 | 70 |
| **XALs** | 28 | 74 | 28 | 78 | 56 | 76 | 36 | 86 | 21 | 55 | 47 | 71 | 20 | 56 | 23 | 70 | 43 | 62 | 19 | 61 | 18 | 56 | 37 | 59 |
| **XALi** | 28 | 74 | 30 | 83 | 58 | 78 | 26 | 62 | 29 | 76 | 55 | 69 | 31 | 86 | 19 | 58 | 50 | 72 | 19 | 61 | 18 | 56 | 37 | 59 |
| **XAWs** | 25 | 66 | 27 | 75 | 52 | 70 | 23 | 55 | 23 | 61 | 46 | 56 | 21 | 58 | 21 | 64 | 42 | 61 | 15 | 48 | 22 | 69 | 37 | 59 |
| **XAWi** | 25 | 66 | 27 | 75 | 52 | 70 | 23 | 55 | 23 | 61 | 46 | 58 | 24 | 67 | 21 | 64 | 45 | 65 | 25 | 74 | 18 | 53 | 43 | 63 |
| **XPL** | 24 | 63 | 17 | 47 | 41 | 56 | 16 | 38 | 15 | 39 | 31 | 39 | 11 | 31 | 25 | 76 | 36 | 52 | 14 | 45 | 7 | 22 | 21 | 33 |
| **TPL** | 23 | 61 | 24 | 67 | 47 | 64 | 28 | 67 | 30 | 79 | 58 | 73 | 28 | 78 | 19 | 58 | 47 | 68 | 22 | 71 | 23 | 72 | 45 | 71 |
| **XTPW** | 28 | 74 | 27 | 75 | 55 | 74 | 30 | 71 | 27 | 71 | 57 | 71 | 29 | 81 | 22 | 67 | 51 | **74** | 26 | 84 | 22 | 89 | 48 | **76** |
| **XAPWi** | 26 | 68 | 24 | 67 | 53 | 68 | 29 | 69 | 18 | 47 | 47 | 59 | 27 | 75 | 21 | 64 | 48 | 70 | 22 | 71 | 26 | 81 | 48 | **76** |
| **APH** | 22 | 58 | 22 | 61 | 44 | 59 | 23 | 55 | 21 | 55 | 44 | 55 | 27 | 75 | 20 | 61 | 47 | 68 | 19 | 61 | 19 | 59 | 38 | 60 |
| **XSPL** | 26 | 68 | 21 | 58 | 47 | 64 | 28 | 67 | 22 | 58 | 50 | 63 | 23 | 64 | 19 | 58 | 42 | 61 | 21 | 98 | 19 | 59 | 40 | 63 |
| **XSLi** | 31 | 82 | 23 | 64 | 54 | 73 | 31 | 74 | 25 | 66 | 56 | 70 | 22 | 61 | 22 | 67 | 44 | 64 | 19 | 61 | 20 | 63 | 39 | 62 |

The accuracies of the univariate universal cervical (measurement means of C3 to C6) models were slightly lower than those of the individual univariate models, ranging between 40% and 78% for population affinity and between 37% and 84% for sex estimation (Table 4.8).

**Table 4.8:** Univariate LDA correct classification accuracies (%) for population affinity and sex estimation using the universal cervical model (C3-C6). Bold indicates the highest total accuracy. Refer to Appendix I for measurement names and definitions.

| | Population | | | | | | Sex | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Females | | Males | | Total | |
| variable | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % |
| **XSLs** | 109 | 60 | 58 | 55 | 167 | 58 | 112 | 76 | 95 | 68 | 207 | **72** |
| **XAH** | 102 | 56 | 73 | 70 | 175 | 61 | 84 | 57 | 89 | 64 | 173 | 60 |
| **XPH** | 141 | 78 | 66 | 63 | 207 | 72 | 115 | 78 | 74 | 53 | 189 | 66 |
| **XALs** | 131 | 72 | 46 | 44 | 177 | 62 | 124 | 84 | 73 | 53 | 197 | 69 |
| **XALi** | 138 | 76 | 52 | 50 | 190 | 66 | 87 | 59 | 110 | 79 | 197 | 69 |
| **XAWs** | 121 | 67 | 63 | 60 | 184 | 64 | 95 | 65 | 71 | 51 | 166 | 58 |
| **XAWi** | 124 | 69 | 63 | 60 | 187 | 65 | 101 | 69 | 74 | 53 | 175 | 61 |
| **XPL** | 72 | 40 | 71 | 68 | 143 | 50 | 54 | 37 | 77 | 55 | 131 | 46 |
| **TPL** | 125 | 69 | 73 | 70 | 198 | 69 | 103 | 70 | 85 | 61 | 188 | 66 |
| **XTPW** | 117 | 65 | 56 | 53 | 173 | 60 | 97 | 66 | 99 | 71 | 196 | 68 |
| **XAPWi** | 136 | 75 | 76 | 72 | 212 | **74** | 96 | 65 | 97 | 70 | 193 | 67 |
| **APH** | 114 | 63 | 74 | 70 | 188 | 66 | 91 | 62 | 85 | 61 | 176 | 62 |
| **XSPL** | 128 | 71 | 57 | 54 | 185 | 65 | 93 | 63 | 77 | 55 | 170 | 59 |
| **XSLi** | 107 | 59 | 60 | 57 | 167 | 58 | 103 | 70 | 90 | 64 | 193 | 67 |

Multivariate models were created by incorporating all of the measurements collected per vertebra. The accuracies ranged between 77.5% and 83.8% for population affinity and between 73% and 82.4% for sex. The multivariate classification accuracies of the universal cervical model were 80.1% and 76.2% for population affinity and sex, respectively. Stepwise variable selection in multivariate models resulted in variable model performances, where different combinations of variables were included in the models for each vertebra. However, maximum pedicle length, maximum inferior articular length, maximum superior articular width, maximum spinous process length, maximum pedicle length, and maximum articular height were frequently removed from the analyses for both population affinity and sex estimation (Table 4.9).

**Table 4.9:** Classification accuracies (%) for the multivariate cervical models and multivariate universal cervical model (C3 – C6) when using all variables and with stepwise variable selection. Refer to Appendix I for measurement names and definitions.

| | Population | | | | Sex | | | |
|---|---|---|---|---|---|---|---|---|
| **Model** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** |
| **C3** | 74 | 82.4 | 87.9 | XPL, XALs, XAWs | 74 | 83.8 | 86.2 | XAWi, XTPW |
| **C4** | 80 | 76.3 | 86.3 | XALi, XAWs, XALs, XSPL, XAH | 80 | 77.5 | 81.3 | XPL, XAWi |
| **C5** | 69 | 78.2 | 87.1 | APH, XSLi, XPH, XAWs, XALi | 69 | 79.7 | 85.7 | XALs, XAH |
| **C6** | 63 | 73 | 82.9 | XALi, XALs, XAH, XPH, XSLi, XSPL | 63 | 77.8 | 81.2 | XAPWi, XALi, XALs, XSLi |
| **Universal cervical model** | 286 | 80.1 | 81.8 | XPL, XSLi | 286 | 76.2 | 81.9 | XAH, XPH, XAPi, APH |

### 4.3.2 Upper Thoracic Vertebrae

Tables A6 to A9 (see Appendix IV) present the descriptive statistics of the cervical vertebrae, including the sample size, mean and standard deviation for each measurement. White South Africans ($\mu$ = 5.26 – 64.93) had overall larger measurement means than black South Africans, ($\mu$ = 4.48 – 67.86) and males ($\mu$ = 5.03 – 64.46) had larger measurement means than females ($\mu$ = 4.69 – 57.88). From the second to sixth thoracic vertebrae, the vertebral body dimensions, specifically the maximum superior sagittal length ($\mu$ = 16.56 – 26.40), the maximum inferior sagittal length ($\mu$ = 17.83 – 27.35), and the spinous process length ($\mu$ = 36.32 – 49.58), increased in size.

ANOVA demonstrated significant differences between black and white South Africans for most of the measurements across all upper thoracic vertebrae, with a few exceptions. Specifically, when assessing the fourth thoracic vertebrae, maximum pedicle length was noted as not significantly different between black and white South Africans. When comparing the sexes, ANOVA demonstrated significant differences for most measurements, except pedicle length, which did not differ significantly when assessing the second and third thoracic vertebrae (Table 4.10).

**Table 4.10:** ANOVA results evaluating population groups and sexes for each measurement for the upper thoracic vertebrae (T2-T6). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | Population | | | | | Sex | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **T2** | **T3** | **T4** | **T5** | **T6** | **T2** | **T3** | **T4** | **T5** | **T6** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | **<0.01** | **<0.01** | 0.276 | **<0.01** | **<0.01** | 0.439 | 0.138 | **<0.01** | **<0.01** | **<0.01** |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

The universal upper thoracic model combined the means of T2 – T6. ANOVA detected significant differences among the measurements of the upper thoracic vertebrae, which demonstrated significant differences between black and white South Africans for most measurements, except for the maximum anterior height, maximum superior articular width, maximum pedicle length and articular process height when assessing black South Africans, and maximum anterior height for white South Africans. When comparing the sexes, maximum anterior height was noted as not significantly different (Table 4.11).

**Table 4.11:** ANOVA results evaluating population groups and sexes for each measurement for all the upper thoracic vertebrae (T2-T6). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Blacks** | **Whites** | **Males** | **Females** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | 0.224 | 0.015 | 0.142 | 0.169 |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | 0.082 | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | 0.014 | **<0.01** | **<0.01** | **<0.01** |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | 0.026 | **<0.01** | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

When attempting univariate population affinity estimation using LDA in the upper thoracic vertebrae, the classification accuracies ranged between 42% and 84% for the second thoracic vertebra, between 52% and 89% for the third thoracic vertebra, between 51% and 92% for the fourth thoracic vertebra, between 48% and 89% for the fifth thoracic vertebra, and between 48% and 88% for the sixth thoracic vertebra (Table 4.12). The classification accuracies for the univariate models for sex estimation from 22% to 98% for the second thoracic vertebra, from 48% to 89% for the third thoracic vertebra, from 47% to 79% for the fourth thoracic vertebra, from 52% to 82% for the fifth thoracic vertebra, and from 50% to 82% for the sixth thoracic vertebra (Table 4.13).

**Table 4.12:** Univariate LDA correct classification accuracy (%) for population affinity using the upper thoracic vertebrae (T2-T6). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | T2 | | | | | | T3 | | | | | | T4 | | | | | | T5 | | | | | | T6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | |
| variable | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % |
| **XSLs** | 39 | 75 | 22 | 50 | 61 | 64 | 42 | 74 | 31 | 62 | 73 | 68 | 44 | 88 | 37 | 79 | 81 | 84 | 40 | 87 | 30 | 71 | 70 | 80 | 42 | 88 | 32 | 78 | 74 | **83** |
| **XAH** | 29 | 56 | 28 | 64 | 57 | 59 | 33 | 58 | 36 | 72 | 69 | 64 | 27 | 54 | 41 | 87 | 68 | 70 | 40 | 87 | 23 | 55 | 63 | 72 | 38 | 79 | 23 | 56 | 61 | 69 |
| **XPH** | 45 | 87 | 23 | 52 | 68 | 71 | 42 | 74 | 28 | 56 | 70 | 65 | 32 | 64 | 41 | 87 | 73 | 75 | 36 | 78 | 32 | 76 | 68 | 77 | 33 | 69 | 36 | 88 | 69 | 78 |
| **XALs** | 39 | 75 | 27 | 61 | 66 | 69 | 34 | 60 | 27 | 54 | 61 | 57 | 41 | 82 | 39 | 83 | 80 | 82 | 41 | 89 | 33 | 79 | 74 | 84 | 37 | 77 | 33 | 80 | 70 | 79 |
| **XALi** | 40 | 77 | 22 | 50 | 62 | 65 | 51 | 89 | 37 | 74 | 88 | **82** | 45 | 90 | 33 | 70 | 78 | 80 | 38 | 83 | 34 | 81 | 72 | 82 | 39 | 81 | 30 | 73 | 69 | 78 |
| **XAWs** | 36 | 69 | 34 | 77 | 70 | 73 | 34 | 60 | 36 | 70 | 70 | 65 | 36 | 72 | 35 | 74 | 71 | 73 | 35 | 76 | 27 | 64 | 62 | 70 | 39 | 81 | 28 | 68 | 67 | 75 |
| **XAWi** | 40 | 77 | 27 | 61 | 67 | 70 | 44 | 77 | 27 | 54 | 71 | 66 | 36 | 72 | 30 | 64 | 66 | 68 | 37 | 80 | 28 | 67 | 65 | 74 | 40 | 83 | 87 | 66 | 127 | 75 |
| **XPL** | 39 | 75 | 36 | 82 | 75 | **78** | 38 | 67 | 35 | 70 | 73 | 68 | 27 | 54 | 24 | 51 | 51 | 53 | 25 | 54 | 20 | 48 | 45 | 51 | 23 | 48 | 24 | 59 | 47 | 53 |
| **TPL** | 38 | 73 | 27 | 61 | 65 | 68 | 34 | 60 | 37 | 74 | 71 | 66 | 34 | 68 | 36 | 77 | 70 | 72 | 37 | 80 | 34 | 81 | 71 | 81 | 36 | 75 | 30 | 73 | 66 | 74 |
| **XTPW** | 35 | 67 | 28 | 64 | 63 | 66 | 39 | 68 | 35 | 70 | 74 | 69 | 41 | 82 | 37 | 79 | 78 | 80 | 30 | 65 | 33 | 79 | 63 | 72 | 36 | 75 | 33 | 80 | 69 | 78 |
| **XAPWi** | 39 | 75 | 33 | 75 | 72 | 75 | 41 | 72 | 35 | 70 | 76 | 71 | 38 | 76 | 36 | 77 | 74 | 76 | 31 | 67 | 37 | 88 | 68 | 77 | 37 | 77 | 33 | 80 | 70 | 79 |
| **APH** | 28 | 54 | 28 | 64 | 56 | 58 | 43 | 75 | 26 | 52 | 69 | 64 | 39 | 78 | 35 | 74 | 74 | 76 | 30 | 65 | 28 | 67 | 58 | 66 | 36 | 75 | 27 | 66 | 63 | 71 |
| **XSPL** | 31 | 60 | 66 | 66 | 97 | 63 | 36 | 63 | 30 | 60 | 66 | 62 | 36 | 72 | 34 | 72 | 70 | 72 | 37 | 80 | 30 | 71 | 67 | 76 | 37 | 77 | 32 | 78 | 69 | 78 |
| **XSLi** | 36 | 69 | 28 | 64 | 64 | 66 | 44 | 77 | 37 | 74 | 81 | 76 | 46 | 92 | 38 | 81 | 84 | **87** | 39 | 85 | 37 | 88 | 76 | **86** | 42 | 88 | 30 | 73 | 72 | 81 |

**Table 4.13:** Univariate LDA correct classification accuracy (%) for sex using the upper thoracic vertebrae (T2-T6). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | T2 | | | | | | T3 | | | | | | T4 | | | | | | T5 | | | | | | T6 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | |
| variable | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % | *n* | % |
| **XSLs** | 38 | 83 | 27 | 54 | 65 | 68 | 41 | 76 | 33 | 62 | 74 | 69 | 32 | 68 | 28 | 56 | 60 | 62 | 26 | 57 | 30 | 61 | 56 | 64 | 26 | 67 | 25 | 50 | 51 | 57 |
| **XAH** | 33 | 72 | 38 | 76 | 71 | 74 | 32 | 59 | 38 | 72 | 70 | 65 | 22 | 47 | 39 | 78 | 61 | 63 | 20 | 51 | 36 | 73 | 56 | 64 | 32 | 82 | 26 | 52 | 58 | 65 |
| **XPH** | 29 | 63 | 43 | 86 | 72 | **75** | 41 | 76 | 30 | 57 | 71 | 66 | 27 | 57 | 39 | 78 | 66 | 68 | 28 | 72 | 31 | 63 | 59 | 67 | 23 | 59 | 35 | 70 | 58 | 65 |
| **XALs** | 38 | 83 | 32 | 64 | 70 | 73 | 39 | 72 | 40 | 75 | 79 | 74 | 32 | 68 | 33 | 66 | 65 | 67 | 29 | 74 | 28 | 57 | 57 | 64 | 25 | 64 | 30 | 60 | 55 | 62 |
| **XALi** | 39 | 85 | 27 | 54 | 66 | 69 | 40 | 74 | 29 | 55 | 69 | 64 | 37 | 79 | 28 | 56 | 65 | 67 | 29 | 74 | 32 | 65 | 61 | 69 | 29 | 74 | 29 | 58 | 58 | 65 |
| **XAWs** | 30 | 65 | 34 | 68 | 64 | 67 | 36 | 67 | 41 | 77 | 77 | 72 | 35 | 74 | 37 | 74 | 72 | **74** | 32 | 82 | 31 | 63 | 63 | 72 | 30 | 77 | 28 | 56 | 58 | 65 |
| **XAWi** | 37 | 80 | 30 | 60 | 67 | 70 | 48 | 89 | 34 | 64 | 82 | **77** | 36 | 77 | 33 | 66 | 69 | 71 | 28 | 72 | 34 | 69 | 62 | 70 | 29 | 74 | 25 | 50 | 54 | 61 |
| **XPL** | 30 | 65 | 31 | 62 | 61 | 64 | 26 | 48 | 26 | 49 | 52 | 49 | 31 | 66 | 31 | 62 | 62 | 64 | 26 | 67 | 29 | 59 | 55 | 63 | 24 | 62 | 36 | 72 | 60 | **67** |
| **TPL** | 28 | 61 | 39 | 78 | 67 | 70 | 37 | 69 | 43 | 81 | 80 | 75 | 31 | 70 | 36 | 72 | 67 | 69 | 26 | 67 | 38 | 78 | 64 | 73 | 28 | 72 | 31 | 62 | 59 | 62 |
| **XTPW** | 29 | 63 | 36 | 72 | 65 | 68 | 40 | 74 | 39 | 74 | 79 | 74 | 35 | 74 | 34 | 68 | 69 | 71 | 26 | 67 | 39 | 80 | 65 | 74 | 24 | 62 | 34 | 68 | 58 | 65 |
| **XAPWi** | 34 | 74 | 34 | 68 | 68 | 71 | 38 | 70 | 35 | 66 | 73 | 68 | 34 | 72 | 35 | 70 | 69 | 71 | 23 | 59 | 36 | 73 | 59 | 67 | 22 | 56 | 35 | 70 | 57 | 64 |
| **APH** | 31 | 67 | 37 | 74 | 68 | 71 | 43 | 80 | 29 | 55 | 72 | 67 | 34 | 72 | 33 | 66 | 67 | 69 | 29 | 74 | 38 | 78 | 67 | **76** | 22 | 56 | 34 | 68 | 56 | 62 |
| **XSPL** | 31 | 67 | 35 | 70 | 66 | 69 | 37 | 69 | 34 | 54 | 71 | 66 | 32 | 68 | 33 | 66 | 65 | 67 | 25 | 64 | 33 | 67 | 58 | 70 | 25 | 64 | 29 | 58 | 54 | 61 |
| **XSLi** | 34 | 74 | 32 | 64 | 66 | 69 | 38 | 70 | 34 | 67 | 72 | 67 | 32 | 68 | 27 | 54 | 59 | 61 | 26 | 67 | 31 | 63 | 57 | 65 | 21 | 54 | 27 | 54 | 48 | 54 |

Compared to the individual univariate upper thoracic models, the accuracy of the universal upper thoracic model was slightly lower, with correct classification ranging between 54% and 79% for population affinity and between 57% and 79% for sex estimation (Table 4.14).

**Table 4.14:** Univariate LDA correct classification accuracy (%) for population affinity and sex using the upper thoracic vertebrae (T2-T6). Bold indicates the highest total accuracy. Refer to Appendix I for measurement names and definitions.

| | Population | | | | | | Sex | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Black** | | **White** | | **Total** | | **Females** | | **Males** | | **Total** | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 192 | 76 | 135 | 60 | 327 | 68 | 135 | 60 | 159 | 63 | 294 | 62 |
| **XAH** | 141 | 56 | 178 | 79 | 319 | 67 | 128 | 57 | 193 | 77 | 321 | 67 |
| **XPH** | 163 | 64 | 169 | 75 | 332 | 69 | 143 | 63 | 177 | 70 | 320 | 67 |
| **XALs** | 183 | 72 | 144 | 64 | 327 | 68 | 157 | 69 | 146 | 58 | 303 | 63 |
| **XALi** | 206 | 81 | 135 | 60 | 341 | 71 | 146 | 65 | 156 | 62 | 302 | 63 |
| **XAWs** | 191 | 75 | 142 | 63 | 333 | 70 | 179 | 79 | 158 | 63 | 337 | **71** |
| **XAWi** | 167 | 66 | 162 | 72 | 329 | 69 | 159 | 69 | 179 | 71 | 338 | 70 |
| **XPL** | 136 | 54 | 150 | 67 | 286 | 60 | 111 | 49 | 153 | 61 | 264 | 55 |
| **TPL** | 172 | 68 | 152 | 68 | 324 | 68 | 152 | 67 | 179 | 71 | 331 | 69 |
| **XTPW** | 183 | 72 | 172 | 77 | 355 | **74** | 155 | 69 | 172 | 68 | 327 | 68 |
| **XAPWi** | 188 | 74 | 158 | 70 | 346 | 72 | 139 | 62 | 185 | 73 | 324 | 68 |
| **APH** | 167 | 66 | 152 | 68 | 319 | 67 | 158 | 70 | 171 | 68 | 329 | 69 |
| **XSPL** | 176 | 69 | 134 | 60 | 310 | 65 | 163 | 72 | 149 | 59 | 312 | 65 |
| **XSLi** | 203 | 80 | 141 | 62 | 344 | 72 | 145 | 64 | 152 | 60 | 297 | 62 |

Multivariate models were created incorporating all the measurements collected per vertebra for the upper thoracic vertebrae. Classification accuracies for the multivariate models ranged between 67% and 81.3% for population affinity and between 78.5% and 91.1% for sex estimation. The multivariate classification accuracies of the universal upper thoracic model were 80.5% and 67.6% for population affinity and sex, respectively. When employing stepwise variable selection for the individual multivariate models and universal models, different combinations of variables were included in the models for each vertebra; however, maximum superior sagittal length, maximum inferior articular length, maximum superior articular width, maximum inferior articular width, maximum transverse process width, maximum spinous process length, were frequently removed from the analyses for both population affinity and sex estimation (Table 4.15).

**Table 4.15:** Classification accuracies (%) for each multivariate upper thoracic models and multivariate universal upper thoracic model (T2-T6) for population affinity and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | | | Sex | | | |
|---|---|---|---|---|---|---|---|---|
| **Model** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** |
| **T2** | 96 | 86.4 | 86.7 | XSLs, XALi | 96 | 74 | 81.4 | APH, XSPL, XAWs, XAPWi |
| **T3** | 107 | 78.5 | 83.5 | XSLs, XALi | 107 | 81.3 | 85.3 | XAH, APH, XALi, XAPi |
| **T4** | 97 | 81.4 | 88.7 | XAWs, XSLi, XSLs, XALi | 97 | 70.1 | 81.4 | XAWi, XAH, APH, XAPWi, XALi, XTPW |
| **T5** | 88 | 81.8 | 88.8 | TPL, XAWi, XTPW | 88 | 67 | 75.1 | XAWs, XSLs |
| **T6** | 89 | 85.3 | 91.1 | XALi | 89 | 76.4 | 83.2 | XSLs, XAPi, XSPL |
| **Universal upper thoracic model** | 478 | 80.5 | 82.6 | XSPL, XAH, TPL | 478 | 67.6 | 75.5 | XAWi, APH |

### 4.3.3 Lower Thoracic Vertebrae

In the lower thoracic vertebrae, the mean and standard deviations differed between white and black South Africans and between males and females. Table A11 to A14 (see Appendix IV) presents the descriptive statistics of the lower thoracic vertebrae, including the sample size, mean and standard deviation for each measurement. The results demonstrated that white South Africans ($\mu$ = 5.41 – 64.69) had larger measurements in comparison to black South Africans ($\mu$ = 4.88 – 57.66). In addition, when comparing sexes, males ($\mu$ = 5.17 – 64.23) had larger measurements than females ($\mu$ = 5.10 – 57.70). From the seventh thoracic vertebrae to the eleventh thoracic vertebrae, the dimensions of the vertebral bodies, specifically the maximum superior sagittal length ($\mu$ = 23.30 – 31.27), maximum anterior height ($\mu$ = 18.07 – 22.44), maximum posterior height ($\mu$ = 19.23 – 25.12), maximum inferior articular width ($\mu$ = 25.73 – 38.33), articular process height ($\mu$ = 32.76 – 40.98), and maximum inferior sagittal length ($\mu$ = 23.98 – 31.96), increased from the seventh thoracic vertebrae to the eleventh thoracic vertebrae. Transverse process length ($\mu$ = 31.93 – 24.17), maximum transverse process width ($\mu$ = 62.83 – 48.65) and spinous process length ($\mu$ = 49.47 – 32.93) decreased from the seventh thoracic vertebrae to the eleventh thoracic vertebrae.

ANOVA demonstrated significant differences between black and white South Africans for the majority of the measurements across all of the lower thoracic vertebrae, with a few exceptions.

Specifically, maximum pedicle length was noted as not significantly different between the population groups when assessing the seventh and eighth thoracic vertebrae. Additionally, maximum inferior articular process width was noted as not significantly different between black and white South Africans for the eleventh thoracic vertebra. When comparing the sexes, ANOVA demonstrated significant differences between males and females for most of the measurements across the upper thoracic vertebrae (T7-T11). Maximum pedicle length was noted as not significantly different when assessing the tenth thoracic vertebrae. Furthermore, the maximum anterior height and articular process height of the eleventh thoracic vertebrae did not differ significantly between the sexes (Table 4.16).

**Table 4.16:** ANOVA results evaluating population groups and sexes for each measurement for lower thoracic vertebrae (T7-T11). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | **Population** | | | | | **Sex** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **T7** | **T8** | **T9** | **T10** | **T11** | **T7** | **T8** | **T9** | **T10** | **T11** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | **0.011** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.109 |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | 0.554 | 0.448 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.648 | **<0.01** |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.054 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.026 |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

With the universal lower thoracic model, ANOVA demonstrated significant differences between black and white South Africans for the majority of the measurements, except for maximum anterior height, maximum superior articular width, maximum pedicle length and articular process height for black South Africans. When comparing the sexes, maximum anterior height and maximum pedicle length were noted as not significantly different between the sexes (Table 4.17).

**Table 4.17:** ANOVA results evaluating population affinity and sex for each measurement for all the lower thoracic vertebrae (T7-T11). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Blacks** | **Whites** | **Males** | **Females** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | 0.281 | **<0.01** | 0.113 | 0.152 |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | 0.082 | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | 0.016 | **<0.01** | 0.081 | 0.075 |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | 0.026 | **<0.01** | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

When attempting to classify the individuals using univariate models for the lower thoracic vertebrae, the population affinity estimation accuracy ranged from 25% to 94% for the seventh thoracic vertebrae, from 44% to 89% for the eighth thoracic vertebrae, from 54% to 92% for the ninth thoracic vertebrae, from 48% to 93% for the tenth thoracic vertebrae, and from 50% to 92% for the eleventh thoracic vertebrae (Table 4.18). For sex estimation, the univariate models yielded accuracies between 51% and 87% for the seventh thoracic vertebrae, between 44% and 85% for the eighth thoracic vertebrae, between 45% and 80% for the ninth thoracic vertebrae, between 34% and 81% for the tenth thoracic vertebrae, and between 38% and 85% for the eleventh thoracic vertebrae, respectively (Table 4.19).

**Tables 4.18:** Univariate LDA correct classification accuracy (%) for population affinity using the lower thoracic vertebrae (T7-T11). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | T7 | | | | | | T8 | | | | | | T9 | | | | | | T10 | | | | | | T11 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 47 | 92 | 24 | 63 | 71 | **80** | 41 | 77 | 33 | 77 | 74 | 77 | 42 | 86 | 32 | 76 | 74 | 81 | 50 | 93 | 30 | 71 | 80 | 83 | 44 | 85 | 39 | 83 | 83 | **84** |
| **XAH** | 36 | 71 | 24 | 63 | 60 | 67 | 35 | 66 | 20 | 47 | 55 | 57 | 36 | 73 | 20 | 78 | 56 | 52 | 36 | 67 | 24 | 57 | 60 | 63 | 28 | 84 | 33 | 70 | 61 | 62 |
| **XPH** | 41 | 80 | 25 | 66 | 66 | 74 | 45 | 85 | 27 | 63 | 72 | 75 | 35 | 71 | 33 | 79 | 68 | 75 | 39 | 72 | 30 | 71 | 69 | 72 | 43 | 83 | 29 | 62 | 72 | 73 |
| **XALs** | 40 | 78 | 30 | 79 | 70 | 79 | 46 | 87 | 32 | 74 | 78 | **81** | 44 | 90 | 28 | 67 | 72 | 79 | 49 | 91 | 32 | 76 | 81 | 84 | 45 | 87 | 35 | 74 | 80 | 81 |
| **XALi** | 42 | 82 | 27 | 71 | 69 | 78 | 47 | 89 | 25 | 58 | 72 | 75 | 44 | 90 | 30 | 71 | 74 | 81 | 48 | 89 | 33 | 79 | 81 | 84 | 47 | 90 | 34 | 72 | 81 | 82 |
| **XAWs** | 40 | 78 | 28 | 74 | 68 | 76 | 44 | 83 | 29 | 67 | 73 | 76 | 35 | 71 | 32 | 76 | 67 | 74 | 42 | 78 | 30 | 71 | 72 | 75 | 38 | 73 | 29 | 62 | 67 | 68 |
| **XAWi** | 42 | 82 | 24 | 63 | 66 | 74 | 45 | 85 | 28 | 65 | 73 | 76 | 39 | 80 | 26 | 62 | 65 | 71 | 42 | 78 | 28 | 67 | 70 | 73 | 36 | 69 | 34 | 72 | 70 | 71 |
| **XPL** | 18 | 35 | 25 | 66 | 43 | 48 | 37 | 70 | 16 | 37 | 53 | 55 | 36 | 73 | 23 | 55 | 59 | 65 | 44 | 81 | 20 | 48 | 64 | 67 | 32 | 62 | 29 | 62 | 61 | 62 |
| **TPL** | 39 | 76 | 26 | 68 | 65 | 73 | 34 | 64 | 25 | 58 | 59 | 61 | 33 | 67 | 31 | 74 | 64 | 70 | 36 | 67 | 25 | 60 | 61 | 64 | 33 | 63 | 29 | 62 | 62 | 63 |
| **XTPW** | 38 | 75 | 27 | 71 | 65 | 73 | 36 | 68 | 30 | 70 | 66 | 69 | 34 | 69 | 30 | 71 | 64 | 70 | 35 | 65 | 28 | 67 | 63 | 66 | 30 | 58 | 30 | 64 | 60 | 61 |
| **XAPWi** | 40 | 78 | 31 | 82 | 71 | **80** | 40 | 75 | 34 | 79 | 74 | 77 | 35 | 71 | 33 | 79 | 68 | 75 | 35 | 65 | 26 | 62 | 61 | 64 | 26 | 50 | 29 | 62 | 55 | 56 |
| **APH** | 30 | 59 | 30 | 79 | 60 | 67 | 32 | 60 | 30 | 70 | 62 | 65 | 35 | 71 | 29 | 69 | 64 | 70 | 39 | 72 | 21 | 50 | 60 | 63 | 36 | 69 | 30 | 64 | 66 | 67 |
| **XSPL** | 41 | 80 | 27 | 71 | 68 | 76 | 44 | 83 | 28 | 65 | 72 | 75 | 32 | 65 | 26 | 62 | 58 | 64 | 36 | 67 | 25 | 60 | 61 | 64 | 34 | 65 | 26 | 55 | 60 | 61 |
| **XSLi** | 45 | 88 | 26 | 68 | 71 | **80** | 45 | 85 | 32 | 85 | 77 | 80 | 45 | 92 | 30 | 71 | 75 | **82** | 49 | 91 | 33 | 79 | 82 | **85** | 48 | 92 | 33 | 70 | 81 | 82 |

**Tables 4.19:** Univariate LDA correct classification accuracy (%) for sex using the lower thoracic vertebrae (T7-T11). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | T7 | | | | | | T8 | | | | | | T9 | | | | | | T10 | | | | | | T11 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | | Female | | Male | | Total | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 26 | 59 | 29 | 64 | 55 | 62 | 29 | 69 | 32 | 59 | 61 | 64 | 32 | 73 | 37 | 57 | 69 | 65 | 33 | 70 | 31 | 63 | 64 | 67 | 30 | 64 | 30 | 58 | 60 | 61 |
| **XAH** | 31 | 70 | 26 | 58 | 57 | 64 | 33 | 79 | 29 | 54 | 62 | 65 | 24 | 55 | 21 | 45 | 45 | 49 | 34 | 72 | 29 | 59 | 63 | 66 | 22 | 47 | 32 | 62 | 54 | 55 |
| **XPH** | 34 | 77 | 25 | 56 | 59 | 66 | 23 | 55 | 41 | 76 | 64 | 67 | 25 | 57 | 28 | 60 | 53 | 58 | 28 | 60 | 26 | 53 | 54 | 56 | 29 | 62 | 20 | 38 | 49 | 49 |
| **XALs** | 30 | 68 | 27 | 60 | 57 | 64 | 32 | 76 | 29 | 54 | 61 | 64 | 34 | 77 | 30 | 64 | 64 | 70 | 35 | 74 | 25 | 51 | 60 | 63 | 34 | 72 | 29 | 56 | 63 | 64 |
| **XALi** | 33 | 75 | 25 | 56 | 58 | 65 | 30 | 71 | 33 | 61 | 63 | 66 | 35 | 80 | 26 | 55 | 61 | 67 | 35 | 74 | 27 | 55 | 62 | 65 | 35 | 74 | 27 | 52 | 62 | 63 |
| **XAWs** | 32 | 73 | 27 | 60 | 59 | 66 | 33 | 79 | 29 | 54 | 62 | 65 | 31 | 70 | 33 | 70 | 64 | 70 | 33 | 70 | 28 | 57 | 61 | 64 | 36 | 77 | 32 | 62 | 68 | 69 |
| **XAWi** | 26 | 59 | 32 | 71 | 58 | 65 | 32 | 76 | 35 | 65 | 67 | 70 | 30 | 68 | 30 | 64 | 60 | 66 | 38 | 81 | 31 | 63 | 69 | 72 | 32 | 68 | 35 | 67 | 67 | 68 |
| **XPL** | 25 | 57 | 39 | 87 | 64 | 72 | 34 | 81 | 24 | 44 | 58 | 60 | 32 | 73 | 24 | 51 | 56 | 62 | 16 | 34 | 0 | 0 | 16 | 16 | 32 | 68 | 35 | 67 | 67 | 68 |
| **TPL** | 35 | 80 | 29 | 64 | 64 | 72 | 32 | 76 | 46 | 85 | 78 | 81 | 33 | 75 | 36 | 77 | 69 | 76 | 38 | 81 | 34 | 69 | 72 | 75 | 33 | 70 | 44 | 85 | 77 | 78 |
| **XTPW** | 34 | 77 | 30 | 67 | 64 | 72 | 31 | 74 | 41 | 76 | 72 | 75 | 34 | 77 | 35 | 75 | 69 | 76 | 36 | 77 | 36 | 73 | 72 | 75 | 33 | 70 | 38 | 73 | 71 | 72 |
| **XAPWi** | 29 | 66 | 27 | 60 | 56 | 63 | 26 | 62 | 37 | 69 | 63 | 66 | 30 | 68 | 33 | 70 | 63 | 69 | 29 | 62 | 34 | 69 | 63 | 66 | 29 | 62 | 37 | 71 | 66 | 67 |
| **APH** | 27 | 61 | 34 | 76 | 61 | 69 | 27 | 64 | 36 | 67 | 63 | 66 | 29 | 66 | 28 | 60 | 57 | 63 | 28 | 60 | 29 | 59 | 57 | 59 | 26 | 55 | 25 | 48 | 51 | 52 |
| **XSPL** | 32 | 73 | 29 | 64 | 61 | 69 | 29 | 69 | 36 | 67 | 65 | 68 | 29 | 66 | 29 | 62 | 58 | 64 | 35 | 74 | 31 | 63 | 66 | 69 | 33 | 70 | 30 | 58 | 63 | 64 |
| **XSLi** | 26 | 59 | 23 | 51 | 49 | 55 | 29 | 69 | 27 | 50 | 56 | 58 | 32 | 73 | 24 | 51 | 56 | 62 | 35 | 74 | 26 | 53 | 61 | 64 | 35 | 74 | 25 | 48 | 60 | 61 |

The classification accuracy of the universal lower thoracic model was slightly lower than the univariate lower thoracic models, with population affinity estimation ranging from 53% to 81% and sex estimation ranging from 49% to 77% (Table 4.20).

**Table 4.20:** Univariate LDA correct classification accuracy (%) for population affinity and sex using the universal lower thoracic model (T7-T11). Bold indicates the highest total accuracy. Refer to Appendix I for measurement names and definitions.

| | Population | | | | | | Sex | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Black** | | **White** | | **Total** | | **Females** | | **Males** | | **Total** | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 190 | 76 | 135 | 60 | 325 | 68 | 133 | 59 | 158 | 63 | 291 | 61 |
| **XAH** | 139 | 55 | 178 | 79 | 283 | 67 | 127 | 57 | 193 | 77 | 320 | 67 |
| **XPH** | 162 | 65 | 168 | 75 | 330 | 69 | 142 | 63 | 175 | 70 | 317 | 67 |
| **XALs** | 181 | 72 | 144 | 64 | 325 | 68 | 155 | 69 | 145 | 58 | 300 | 63 |
| **XALi** | 204 | 81 | 134 | 60 | 338 | 71 | 144 | 64 | 155 | 62 | 299 | 63 |
| **XAWs** | 188 | 75 | 142 | 63 | 330 | 69 | 177 | 79 | 158 | 63 | 335 | **71** |
| **XAWi** | 164 | 65 | 161 | 72 | 325 | 68 | 154 | 69 | 178 | 71 | 332 | 70 |
| **XPL** | 134 | 53 | 150 | 67 | 284 | 60 | 109 | 49 | 152 | 61 | 261 | 55 |
| **TPL** | 170 | 68 | 170 | 76 | 340 | 72 | 151 | 67 | 178 | 71 | 329 | 69 |
| **XTPW** | 180 | 72 | 171 | 76 | 351 | **74** | 153 | 68 | 171 | 68 | 324 | 68 |
| **XAPWi** | 186 | 74 | 158 | 71 | 344 | 72 | 157 | 70 | 156 | 62 | 313 | 66 |
| **APH** | 166 | 66 | 152 | 58 | 318 | 67 | 158 | 71 | 171 | 68 | 329 | 69 |
| **XSPL** | 173 | 69 | 133 | 59 | 306 | 64 | 161 | 72 | 148 | 59 | 309 | 65 |
| **XSLi** | 200 | 80 | 141 | 63 | 341 | 72 | 143 | 64 | 151 | 60 | 294 | 62 |

The measurements per vertebra for the lower thoracic vertebrae were combined into multivariate models, where the classification accuracies ranged between 69.2% and 80% for population affinity estimation and between 78.8% and 89.6% for sex estimation. A variety of combinations of variables were used in stepwise variable selection for each vertebra; however, maximum superior sagittal length, maximum anterior height, maximum anterior height, maximum inferior articular width, maximum transverse process width, maximum spinous process length, and articular process height were frequently removed from the analyses for both population affinity and sex estimation in the multivariate models (Table 4.21).

With the universal multivariate lower thoracic model, the classification accuracies were slightly lower compared to the multivariate models. The universal multivariate classification accuracies were 79.2% and 70.9% for population affinity and sex, respectively. In the universal lower thoracic model, stepwise variables were selected for each vertebra. However, maximum posterior height, maximum superior articular length, and maximum spinous process length were frequently removed from the analyses for sex, while maximum posterior height, maximum inferior articular length, maximum inferior articular process width and articular process height were frequently removed from the analyses for population affinity (Table 4.21).

**Table 4.21:** Classification accuracies (%) for each multivariate lower thoracic models and multivariate universal lower thoracic model (T7-T11) for population affinity and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | | | Sex | | | |
|---|---|---|---|---|---|---|---|---|
| **Model** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** |
| **T7** | 89 | 82 | 87.4 | XSPL, XAH, XPL, XAWi, XAWs, XSLs | 89 | 71.9 | 81.1 | XPH, XSPL, APH, XALs |
| **T8** | 96 | 89.6 | 90.8 | XSPL | 96 | 80 | 81.6 | XAH, XALs, XAWi, XALi |
| **T9** | 91 | 80.2 | 83.7 | XALi, XAWi | 91 | 69.2 | 79.2 | XAPWi, XPH, XSLs |
| **T10** | 96 | 83.3 | 87.6 | XTPW, XAWi | 96 | 71.9 | 79.1 | XAWs, XTPW, XSPL |
| **T11** | 99 | 78.8 | 85 | APH, XSPL, XAH | 99 | 72.7 | 81.8 | XTPW, XSLs, TPL, XAH |
| **All lower thoracic** | 475 | 79.2 | 81.7 | XPH, XALs, XSPL | 475 | 70.9 | 74.3 | XPH, XALi, XAPWi, APH |

### 4.3.4 Lumbar Vertebrae

A comparison of the means and standard deviations of the lumbar vertebrae in white and black South African males and females revealed considerable variation. Table A11 to A14 (see Appendix IV) presents the descriptive statistics of the cervical vertebra, including the sample size, mean and standard deviation for each measurement. Overall, white South Africans ($\mu$ = 8.97 – 77.01) have the larger measurement means compared to black South Africans ($\mu$ = 7.72 – 76.68). Overall, males ($\mu$ = 7.87 – 80.42) have greater variability and greater measurement means compared to females ($\mu$ = 8.83 – 72.84). Several dimensions of the vertebral body, namely the maximum superior sagittal length ($\mu$ = 27.26 – 35.23), maximum superior articular length ($\mu$ = 23.05 – 31.19), maximum inferior articular length ($\mu$ = 24.66 – 31.65), maximum superior articular width ($\mu$ = 37.23 – 46.92), maximum inferior articular width ($\mu$ = 39.41 – 49.45), and maximum inferior sagittal length ($\mu$ = 28.33 – 35.42) increased the lower the vertebrae were positioned in the spine, from the first lumbar vertebrae to the fourth lumbar vertebrae. Additionally, maximum transverse process width ($\mu$ = 31.38 -m44.87), maximum pedicle length ($\mu$ = 6.96 – 11.38), and maximum inferior articular process width ($\mu$ = 26.81 – 44.05) increased from the first lumbar vertebrae to the fourth lumbar vertebrae.

In most of the measurements across the lumbar vertebrae, ANOVA showed significant differences between black and white South Africans. However, the maximum pedicle length of the third and fourth lumbar vertebrae did not differ significantly for population affinity.

Additionally, maximum inferior articular process width was noted as not significantly different between black and white South Africans, when assessing the third lumbar vertebrae and maximum transverse process width when assessing all the lumbar vertebrae. When comparing the sexes, ANOVA demonstrated significant differences between males and females for most of the measurements across all of the lumbar vertebrae, except for maximum anterior height, which was noted as not significantly different when assessing all the lumbar vertebrae. In addition, multiple measurements did not differ significantly when assessing the lumbar vertebrae, specifically the maximum pedicle length and maximum transverse process width when assessing the first lumbar vertebrae, maximum pedicle length when assessing the second lumbar vertebrae, maximum inferior articular process width when assessing the third lumbar vertebrae and maximum transverse process width and articular process height when assessing the fourth lumbar vertebrae (Table 4.22).

**Table 4.22:** ANOVA results evaluating population affinity and sex for each measurement for lumbar vertebrae (L1-L4). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | **Population** | | | | **Sex** | | | |
|---|---|---|---|---|---|---|---|---|
| | **L1** | **L2** | **L3** | **L4** | **L1** | **L2** | **L3** | **L4** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.469 | 0.948 | 0.462 | 0.202 |
| **XPH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.312 | 0.946 | **<0.01** | **<0.01** |
| **TPL** | **<0.01** | 0.085 | 0.783 | 0.710 | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | 0.074 | 0.351 | 0.273 | 0.754 | 0.031 | **<0.01** | **<0.01** | 0.042 |
| **XAPWi** | **<0.01** | **<0.01** | 0.256 | **<0.01** | **<0.01** | **<0.01** | 0.219 | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | 0.041 |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

For the universal lumbar model, ANOVA showed significant differences between black and white South Africans for most of the measurements, except for maximum anterior height, maximum superior articular width, maximum pedicle length, and articular process height when assessing black South Africans. When comparing the sexes, maximum anterior height and maximum pedicle length were noted as not significantly different for either of the sexes (Table 4.23).

**Table 4.23:** ANOVA results evaluating population affinity and sex for each measurement for the universal lumbar model (L1-L4). Bold indicates the significant variables. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Blacks** | **Whites** | **Males** | **Females** |
| **XSLs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPH** | **<0.01** | 0.091 | 0.070 | **<0.01** |
| **XALs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XALi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWs** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XPL** | 0.036 | **<0.01** | **<0.01** | **<0.01** |
| **TPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XTPW** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XAPWi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **APH** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSPL** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |
| **XSLi** | **<0.01** | **<0.01** | **<0.01** | **<0.01** |

When assessing the lumbar vertebrae, univariate population affinity estimation revealed classification accuracies between 48% and 93% for the first lumbar vertebrae, between 52% and 81% for the second lumbar vertebrae, between 47% and 82% for the third lumbar vertebrae, and between 14% and 87% for the fourth lumbar vertebrae (Table 4.24). When comparing the sexes, the univariate lumbar models demonstrated sex classification accuracies between 0% and 85% for the first lumbar vertebrae, between 13% and 77% for the second lumbar vertebrae, between 35% and 79% for the third lumbar vertebrae, and between 48% and 81% for the fourth lumbar vertebrae (Table 4.25).

**Tables 4.24:** Univariate LDA correct classification accuracy (%) for population affinity using the lumbar vertebrae (L1-L4). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | L1 | | | | | | L2 | | | | | | L3 | | | | | | L4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | | Black | | White | | Total | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 41 | 93 | 19 | 66 | 60 | 82 | 28 | 78 | 15 | 65 | 43 | 73 | 27 | 79 | 12 | 71 | 39 | 76 | 20 | 71 | 11 | 73 | 31 | 72 |
| **XAH** | 33 | 75 | 19 | 66 | 52 | 71 | 29 | 81 | 17 | 74 | 46 | 78 | 26 | 76 | 11 | 65 | 37 | 73 | 22 | 79 | 9 | 60 | 31 | 72 |
| **XPH** | 31 | 71 | 16 | 55 | 47 | 64 | 23 | 64 | 18 | 78 | 41 | 65 | 21 | 62 | 12 | 71 | 33 | 65 | 17 | 61 | 9 | 60 | 26 | 61 |
| **XALs** | 38 | 86 | 21 | 72 | 59 | 81 | 28 | 78 | 17 | 74 | 45 | 76 | 28 | 82 | 12 | 71 | 40 | 78 | 23 | 82 | 13 | 87 | 36 | 84 |
| **XALi** | 34 | 77 | 20 | 69 | 54 | 74 | 25 | 69 | 16 | 70 | 41 | 69 | 22 | 65 | 12 | 71 | 34 | 67 | 20 | 71 | 9 | 60 | 29 | 67 |
| **XAWs** | 29 | 66 | 18 | 62 | 47 | 64 | 22 | 61 | 13 | 57 | 35 | 59 | 18 | 53 | 8 | 47 | 26 | 51 | 20 | 71 | 9 | 60 | 29 | 67 |
| **XAWi** | 30 | 68 | 16 | 55 | 46 | 63 | 24 | 67 | 14 | 61 | 38 | 64 | 24 | 71 | 9 | 53 | 33 | 65 | 23 | 82 | 11 | 73 | 34 | 79 |
| **XPL** | 32 | 73 | 16 | 55 | 48 | 66 | 26 | 72 | 14 | 61 | 40 | 68 | 27 | 79 | 9 | 53 | 36 | 71 | 19 | 68 | 13 | 87 | 32 | 74 |
| **TPL** | 24 | 55 | 19 | 66 | 43 | 59 | 20 | 56 | 13 | 57 | 33 | 56 | 19 | 56 | 10 | 59 | 29 | 57 | 14 | 50 | 11 | 73 | 25 | 58 |
| **XTPW** | 22 | 50 | 20 | 69 | 42 | 58 | 19 | 53 | 12 | 52 | 31 | 53 | 23 | 68 | 10 | 59 | 33 | 65 | 4 | 14 | 4 | 27 | 8 | 19 |
| **XAPWi** | 27 | 61 | 14 | 48 | 41 | 56 | 20 | 56 | 13 | 57 | 33 | 56 | 17 | 50 | 8 | 47 | 25 | 49 | 18 | 64 | 9 | 60 | 27 | 63 |
| **APH** | 28 | 64 | 17 | 59 | 45 | 62 | 21 | 58 | 12 | 52 | 33 | 56 | 19 | 56 | 11 | 65 | 30 | 59 | 18 | 64 | 10 | 67 | 28 | 65 |
| **XSPL** | 29 | 66 | 14 | 48 | 43 | 59 | 24 | 57 | 13 | 57 | 37 | 63 | 24 | 71 | 13 | 77 | 37 | 73 | 21 | 75 | 11 | 73 | 32 | 74 |
| **XSLi** | 38 | 86 | 19 | 66 | 57 | 78 | 28 | 78 | 14 | 61 | 42 | 71 | 23 | 67 | 11 | 65 | 34 | 67 | 17 | 61 | 10 | 67 | 27 | 63 |

**Tables 4.25:** Univariate LDA correct classification accuracy (%) for sex using the lumbar vertebrae (L1-L4). Bold indicates the highest total accuracy per vertebra. Refer to Appendix I for measurement names and definitions.

| | L1 | | | | | | L2 | | | | | | L3 | | | | | | L4 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Females | | Males | | Total | | Females | | Males | | Total | | Females | | Males | | Total | | Females | | Males | | Total | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 25 | 64 | 22 | 65 | 47 | 64 | 22 | 71 | 14 | 50 | 36 | 61 | 14 | 61 | 17 | 61 | 31 | 61 | 10 | 63 | 13 | 48 | 23 | 54 |
| **XAH** | 22 | 56 | 13 | 38 | 35 | 48 | 16 | 52 | 20 | 71 | 36 | 61 | 11 | 48 | 20 | 71 | 31 | 61 | 8 | 50 | 18 | 67 | 26 | 61 |
| **XPH** | 27 | 69 | 17 | 50 | 44 | 60 | 4 | 13 | 0 | 0 | 4 | 7 | 12 | 52 | 14 | 50 | 26 | 51 | 12 | 75 | 16 | 59 | 28 | 65 |
| **XALs** | 30 | 77 | 18 | 53 | 48 | 66 | 22 | 71 | 16 | 57 | 38 | 64 | 16 | 70 | 13 | 46 | 29 | 57 | 10 | 63 | 16 | 59 | 26 | 61 |
| **XALi** | 30 | 77 | 21 | 62 | 51 | 70 | 21 | 68 | 17 | 61 | 38 | 64 | 17 | 74 | 18 | 64 | 35 | 69 | 10 | 63 | 16 | 59 | 26 | 61 |
| **XAWs** | 30 | 77 | 24 | 71 | 54 | 74 | 23 | 74 | 19 | 68 | 42 | 71 | 15 | 65 | 21 | 75 | 36 | 71 | 12 | 75 | 19 | 70 | 31 | 72 |
| **XAWi** | 33 | 85 | 24 | 71 | 57 | 78 | 24 | 77 | 19 | 68 | 43 | 73 | 16 | 70 | 18 | 64 | 34 | 67 | 13 | 81 | 16 | 59 | 29 | 67 |
| **XPL** | 0 | 0 | 13 | 38 | 13 | 18 | 15 | 48 | 19 | 68 | 34 | 58 | 17 | 74 | 20 | 71 | 37 | 73 | 13 | 81 | 18 | 67 | 31 | 72 |
| **TPL** | 21 | 54 | 21 | 62 | 42 | 58 | 20 | 65 | 18 | 64 | 38 | 64 | 17 | 74 | 20 | 71 | 37 | 73 | 9 | 56 | 18 | 67 | 27 | 63 |
| **XTPW** | 18 | 46 | 22 | 65 | 40 | 55 | 20 | 65 | 18 | 64 | 38 | 64 | 15 | 65 | 22 | 79 | 37 | 73 | 9 | 56 | 18 | 67 | 27 | 63 |
| **XAPWi** | 28 | 72 | 20 | 59 | 48 | 66 | 19 | 61 | 17 | 61 | 36 | 61 | 13 | 57 | 15 | 54 | 28 | 55 | 11 | 69 | 20 | 74 | 31 | 72 |
| **APH** | 27 | 69 | 21 | 62 | 48 | 66 | 17 | 55 | 13 | 46 | 30 | 51 | 14 | 61 | 17 | 61 | 31 | 61 | 9 | 56 | 13 | 48 | 22 | 51 |
| **XSPL** | 29 | 74 | 19 | 56 | 48 | 66 | 16 | 52 | 15 | 54 | 31 | 53 | 8 | 35 | 17 | 61 | 25 | 49 | 9 | 56 | 16 | 59 | 25 | 58 |
| **XSLi** | 26 | 67 | 25 | 74 | 51 | 70 | 21 | 68 | 12 | 43 | 33 | 56 | 16 | 70 | 15 | 54 | 31 | 61 | 11 | 69 | 16 | 59 | 27 | 63 |

In the universal univariate lumbar model, classification accuracies were slightly lower than those from the individual univariate models, with estimates ranging from 40% to 82% for the population affinity and 45% to 75% for the sexes (Table 4.26).

**Table 4.26:** Univariate LDA correct classification accuracy (%) for population affinity and sex using the universal lumbar model (L1-L4). Bold indicates the highest total accuracy. Refer to Appendix I for measurement names and definitions.

| | Population | | | | | | Sex | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Black | | White | | Total | | Females | | Males | | Total | |
| **variable** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** | ***n*** | **%** |
| **XSLs** | 108 | 76 | 53 | 63 | 161 | 71 | 70 | 64 | 73 | 62 | 143 | 63 |
| **XAH** | 101 | 71 | 61 | 72 | 162 | 72 | 49 | 45 | 64 | 55 | 113 | 50 |
| **XPH** | 98 | 69 | 55 | 65 | 153 | 68 | 65 | 60 | 55 | 47 | 120 | 53 |
| **XALs** | 117 | 82 | 58 | 69 | 175 | **77** | 72 | 66 | 72 | 62 | 144 | 64 |
| **XALi** | 106 | 75 | 50 | 60 | 156 | 69 | 69 | 63 | 77 | 66 | 146 | 65 |
| **XAWs** | 87 | 61 | 48 | 57 | 135 | 60 | 78 | 72 | 88 | 75 | 166 | **73** |
| **XAWi** | 83 | 58 | 57 | 68 | 140 | 62 | 76 | 70 | 83 | 71 | 159 | 70 |
| **XPL** | 98 | 69 | 59 | 70 | 157 | 69 | 64 | 59 | 78 | 57 | 142 | 63 |
| **TPL** | 70 | 49 | 40 | 48 | 110 | 49 | 71 | 65 | 76 | 65 | 147 | 65 |
| **XTPW** | 73 | 51 | 36 | 43 | 109 | 48 | 62 | 57 | 73 | 62 | 135 | 60 |
| **XAPWi** | 86 | 61 | 34 | 40 | 120 | 53 | 77 | 71 | 58 | 50 | 135 | 60 |
| **APH** | 77 | 54 | 56 | 67 | 133 | 59 | 62 | 57 | 74 | 63 | 136 | 60 |
| **XSPL** | 96 | 68 | 60 | 71 | 156 | 69 | 89 | 63 | 66 | 56 | 155 | 60 |
| **XSLi** | 95 | 67 | 55 | 65 | 150 | 66 | 76 | 70 | 69 | 60 | 145 | 64 |

Based on all the measurements collected for each lumbar vertebra, multivariate lumbar models were created. For population affinity estimation the classification accuracies ranged between 69.2% and 80%, and between 78.8% and 89.6% for sex estimation. Stepwise variable selection in the multivariate lumbar models was employed and removed different combinations of variables included for each vertebra, except for the third lumbar vertebra which removed no variables. However, maximum inferior articular length, maximum transverse process width, maximum superior sagittal length, transverse process length and maximum pedicle length were frequently removed from the analyses for both population affinity and sex estimation.

The classification accuracy was slightly lower when comparing the multivariate universal lumbar model with the multivariate lumbar models. The universal multivariate classification accuracies were 79.2% and 70.9% for population affinity and sex, respectively. When employing stepwise variable selection, different combinations of variables were included in the multivariate universal lumbar model; however, maximum spinous process length, maximum inferior sagittal length and maximum inferior articular process width were frequently removed from the analyses for population affinity, while articular process height,

transverse process length and maximum inferior articular length were frequently removed for sex estimation (Table 4.27).

**Table 4.27:** Classification accuracies (%) for each multivariate lumbar models and multivariate universal lumbar model (L1-L4) for population affinity and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | | | Sex | | | |
|---|---|---|---|---|---|---|---|---|
| **Model** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** | ***n*** | **LDA (%)** | **Stepwise (%)** | **Variables removed** |
| **L1** | 73 | 79.5 | 88 | XALi, XTPW | 73 | 64.4 | 77.1 | XAPWi, XAWi, APH, XPL, XALs, XTPW |
| **L2** | 59 | 84.7 | 89.7 | XSLs, TPL, XPL | 59 | 76.3 | 84.3 | TPL, APH, XSPL, XAPi |
| **L3** | 51 | 88.2 | 90.7 | None | 51 | 76.5 | 86.3 | APH, XPH, XSLi |
| **L4** | 43 | 88.4 | 93.5 | XAH, XAWi | 43 | 74.4 | 88.5 | XTPW |
| **Universal lumbar model** | 226 | 84.1 | 87.2 | XSPL, XSLi, XAPWi | 226 | 80 | 82.4 | APH, TPL, XALi |

## 4.4 Summary

- The vertebral body and spinous process dimensions were noted to increase in size, except for the lower thoracic region, where spinous process length and transverse process dimensions decreased in size.
- Population affinity and sex classification accuracies were high, with populations classifying better when using the thoracic and lumbar vertebrae and sex classifying better when using the cervical vertebrae.
- Univariate models demonstrated the highest classification accuracies compared to multivariate models, with cervical (98% for C6) and thoracic (92% for T4 and T9) vertebrae performing the best.
- Individual multivariate vertebrae models (i.e., L1, L2, L3, L4), particularly for the lumbar vertebrae, classified the best, specifically the third (90.7% and 86.3%) and fourth (93.5% and 88.5%) lumbar vertebrae for both population affinity and sex estimation.
- Multivariate universal models (for each vertebral sub-type) indicated that the upper thoracic (82.6% and 75.5%), lower thoracic (81.7% and 74.3%) and lumbar (87.2% and 82.4%) vertebrae performed the best when classifying according to population affinity and sex estimation.

# CHAPTER 5: DISCUSSION

Several researchers have studied the vertebrae with regard to sexual dimorphism and population variation (Cheng *et al.*, 1998; Wescott, 2000; Pastor, 2005; Soegiharto *et al.*, 2008; Yu *et al.*, 2008; Marlow *et al.*, 2011; Gama *et al.*, 2015; Ostrofsky *et al.*, 2015; Torimitsu *et al.*, 2016; Montasser *et al.*, 2017; Ramadan *et al.*, 2017; Oura *et al.*, 2018; Rozendaal *et al.*, 2020). However, to date, a very limited number of vertebrae have been investigated (i.e., first and second cervical vertebrae, first and twelfth thoracic vertebrae and the fifth lumbar vertebrae) with the focus mainly placed on sexual dimorphism (Cheng *et al.*, 1998; Wescott, 2000; Pastor, 2005; Soegiharto *et al.*, 2008; Yu *et al.*, 2008; Marlow *et al.*, 2011; Gama *et al.*, 2015; Montasser *et al.*, 2017; Oura *et al.*, 2018). The current study aimed to expand on previous research, as previous studies lack universal standards for estimating population affinity and sex using vertebral measurements. Two components were included in the study to effectively investigate sexual dimorphism and population variation among modern South Africans: (1) an exploration component, and (2) a classification component. To determine whether universal vertebral standards for population affinity and sex estimation can be created, the variation exploration component evaluated the size variation among vertebrae both within and among vertebral types (cervical, thoracic, and lumbar vertebrae). Classification models were created based on the information provided by the variation exploration component to estimate population affinity and sex.

In exploring the vertebral variation, the results demonstrated that both the atypical vertebrae (C7, T1 and T12) as well as the vertebrae closest to the atypical vertebrae (i.e., C6, T2, T11, L1 and L4) showed vast differences among the vertebrae and measurements. Because these vertebrae are so different to the rest of the vertebrae, the specific vertebrae will have to be correctly identified prior to further analyses and they will not be useful to establish universal standards. Atypical vertebrae (i.e., C6, T2, T11, L1 and L4) retain characteristics of the preceding vertebrae in the vertebral column, for example, the first thoracic vertebra retains characteristics of the cervical vertebrae such as the spinous process that projects more horizontally and vertebral body that presents more saddle-shaped and interlocking than thoracic vertebrae (White *et al.*, 2005). However, the first lumbar vertebra was included in the sample to explore the lumbar variation attributable to sexual dimorphism and population affinity. Previous research indicated that the first lumbar vertebra produced high accuracies for sex; therefore, the first lumbar vertebra was included to establish whether the first lumbar vertebra

would produce similar accuracies for estimating population affinity as well as to compare accuracies to the remaining lumbar vertebrae.

Multiple measurements showed repeatability issues, with errors greater than 7%. Most of the measurements that presented with large errors were small measurements, where even a small margin of error results in very high %TEM levels. Additionally, the high error rates can be ascribed to difficulty in locating the correct landmark to place the caliper, as the area on the bone (such as the pedicle) tends to be highly variable among and within individuals. To minimize measurement error, it is necessary to use the appropriate instrumentation, understand the measurement definition, and use highly reliable and repeatable measurements. It was noted that minimal experience was required in these measurements. However, knowledge of vertebral landmarks is required as landmarks were difficult to locate on some measurements due to the measurements, additionally, the measurements are not typically used by forensic anthropologists. After the variation of the vertebrae was assessed, a total of 14 measurements were retained for the creation of multivariate and univariate models to estimate population affinity and sex. Multiple multivariate and univariate models were created using all variables for a single vertebra as well as a universal model using all variables for combined sub-type vertebrae (i.e., cervical (C3-C6), upper thoracic (T2-T6), lower thoracic (T7-T11) and lumbar vertebrae (L1-L4)). The universal models were created for vertebrae to be able to estimate population affinity and sex without defining the specific vertebral number.

A series of different models were created to thoroughly capture the variation and explore the potential of the vertebrae when estimating population affinity and sex. While the literature has shown that multivariate models typically produce the best results (Liebenberg *et al.*, 2015), the availability of univariate standards can also be beneficial to biological anthropologists in instances where bones are taphonomically altered or fragmentary. Two iterations of all models were analysed. First, classification models (both univariate and multivariate) were created for each vertebra on its own to determine whether the classification accuracies would be higher if the specific number of the vertebra within the sequence of the vertebral column is known. Second, classification models (both univariate and multivariate) were created for each category of the vertebra to determine if universal discriminant functions can be used to estimate population affinity and sex without identifying the specific number of a vertebra.

When comparing the univariate models among the vertebrae, there were no clear trends regarding which variables performed the best. In other words, the classification accuracy for a

specific variable differed substantially among vertebrae and was not consistently the best indicator of either population affinity or sex. For example, when estimating population affinity, maximum superior sagittal length was one of the poorest classifiers for the third cervical vertebrae; however, it was observed to be the greatest classifier of all the variables when estimating population affinity for the fourth cervical vertebrae. The combination of all of the measurement means per vertebral subtype for the universal models demonstrated overall more intermediate classification accuracies. Thus, there are small variations in the size and shape of connecting vertebrae that variably influence the discriminatory power of measurements from one vertebra to the next. However, by combining the means, the individual vertebra would not need to be identified in order to make use of the method for estimating the parameters of the biological profile.

Results for the univariate models demonstrate higher classification accuracies than the multivariate models, especially for population affinity estimation. The high classification accuracies for most of the univariate models demonstrate that if fragmentary vertebrae are present, single variable analyses can be used to estimate both population affinity and sex. While the current study demonstrated that population affinity and sex estimation is possible using univariate methods, single variable classification has limitations as the use of a single dimension may also result in higher misclassification rates of both population affinity and sex. The high rates of misclassification are due to univariate models only being able to capture the limited amount of human variation expressed in that single variable. More variables allow for more information to be assembled, which might increase classification accuracy (Ousley et al., 2012). While more variables from multiple bones can assess more human variation, even just using multiple measurements from a single vertebra already provides a greater number of measurements than a single variable examined by univariate analysis, thus providing more information about the individual.

While univariate models can be employed with fairly high accuracy, the approach is not necessarily the most effective for properly distinguishing between the population and sex groups. As such, multivariate models are better able to capture the variation and give overall, more robust results. The greater performance of multivariate models compared to univariate models is evident in the classification accuracies, where the multivariate models consistently achieved accuracies above 80%. This result is not unexpected, as many recent publications have confirmed the advantages of employing a combination of variables (Ostrofsky *et al.*,

2015; Krüger *et al.*, 2017; Ramadan *et al.*, 2017; Hora and Sladek, 2018; Oura *et al.*, 2018; Liebenberg *et al.*, 2019; Rozendaal *et al.*, 2020). In other words, multivariate models should be used where possible when estimating population affinity and sex from the vertebrae.

The study also aimed to determine if the specific number of the vertebra needs to be identified prior to further analysis. While some vertebrae can easily be identified due to unique morphological features, others may be much more difficult to identify correctly, particularly some of the mid-cervical and mid-thoracic vertebrae (White *et al.*, 2005). A comparison of the single multivariate vertebra models to the corresponding universal multivariate models revealed that the more specific, single vertebra models achieved slightly higher classification accuracies (about 1% to 9% higher, depending on the vertebra and vertebral sub-type). However, the classification accuracy should not be the only factor taken into consideration when selecting models for analyses. Other important factors include the sample size, as well as the overall generalisability of the model. The sample size of the single vertebra models is fairly small, largely due to missing variables resulting from postmortem damage, osteophytosis or vertebral compression. In turn, the sample size affects how well a model can generalise information to a test sample that was not used to train the model, and of course the overall population. Models made with smaller samples have been shown to overfit data, thereby producing overly optimistic results (Reunanen, 2003; Babyak, 2004; Roberts *et al.*, 2017). But when tested on independent samples, these models often demonstrate a substantial decrease in classification accuracy as the models are too specific and generalise information poorly when applied to the general population (Ousley *et al.*, 2012). Another problem that may arise with the single vertebra models, is if the practitioner identifies a specific vertebra incorrectly and attempts to use the incorrect model (for example using the C3 model on a C4 vertebra). As was noted with the univariate models, each vertebra has a unique combination of dimensions with small albeit significant differences in the size and shape that can affect the accuracy of measurements. Further validation studies are required to establish how the incorrect identification of vertebrae will affect the discriminatory power of the single vertebra models. Based on the results, universal models made by combining all of the vertebrae per sub-type can be used to classify population affinity and sex with fair accuracy. Moreover, the combination of data allows for larger samples and greater generalisability and will not be adversely affected in instances where specific vertebrae are identified incorrectly. Overall, the vertebral sub-types achieved similar accuracies for population affinity estimation, indicating that cervical, thoracic and lumbar models can all be useful for assessing population groups.

A variety of different skeletal elements have been studied in the South African population regarding population affinity and sex estimation (Pastor, 2005; Krüger, 2015; Torimitsu *et al*., 2016; Liebenberg *et al*., 2019). The vertebrae are usually preserved relatively well, with minor damage and weathering except for transverse processes and spinous processes. Research exploring population affinity and sex have used various methods and skeletal elements to achieve high classification accuracies. Based on craniometric and postcranial studies on population affinity and sex estimation, the accuracy of this study is comparable to published methods frequently used and recognized as best practices; however, most studies have examined more than two groups (Stull *et al.*, 2014; Krüger *et al.*, 2015; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019). The use of two populations means that group affinity probabilities and classification accuracies are high, especially when comparing white and black South Africans due to their substantial population differences. When a third population, such as Coloured South Africans, is entered into the comparison, typically a decrease in accuracies is seen, especially in the South African population as black and coloured South Africans may present with large amounts of overlap (Stull *et al.*, 2014; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019).

Other than variations among population groups, ageing and bone pathology should also be considered in population and sex estimation using vertebrae. Alterations in vertebrae, especially those of the lumbar spine, have been observed with ageing. The differences between the two populations could result from pathological conditions associated with advanced age (i.e., osteophytes, wedging, compression). In the current sample, the mean age of white South Africans was substantially higher than that of the black South Africans, which is a result of the overall higher mean age of white South Africans in the skeletal collection (L'Abbé *et al.*, 2005). The presence of age-related pathological conditions could affect measurements, particularly vertebral body measurements, used to estimate population and sex. For example, osteophytes can affect the vertebral body height and length, as spurs form on the borders of the vertebral body. With age, the anterior and posterior heights of the vertebrae can also decrease, giving the appearance of a wedge-shaped vertebra, which is more frequent in men than in women (Snodgrass, 2004a; Garoufi *et al.*, 2020). The difference between males and females is partially due to load-bearing capacity differences, brought on by differences in physical activity, which may impact bone mass, microarchitecture, and size throughout life. Additionally, anatomical differences in the transfer of weight between the vertebral column and pelvis between sexes and populations could affect variation in estimations.

The universal multivariate models (for all vertebral subtypes: cervical, thoracic and lumbar vertebrae) were found to have fairly similar, although slightly higher, accuracies to the individual multivariate models, which is most likely the result of the larger sample size obtained by combining the relevant vertebrae measurements per subtype. The increased sample size provided more information for the discriminant functions to create group boundaries, making the models more proficient in quantifying the variation and thereby maximising group differences to classify either population affinity or sex. Both universal univariate and multivariate models performed similarly and yielded similar classification accuracies. Depending on the condition of the remains, practitioners are free to utilise any combination of variables, individual variables or vertebrae on their own while still yielding reliable results.

Interestingly, the thoracic vertebrae demonstrated lower accuracies (around 74% to 75% compared to the 82% obtained with both cervical and lumbar stepwise-selected models) when attempting to estimate sex. Previous studies on sex estimation have shown that cervical and lumbar vertebrae variables are higher than thoracic vertebrae variables (Allbright, 2007). As such the thoracic vertebrae are less useful for sex estimation than the lumbar and cervical models but can still be used in instances where only thoracic vertebrae are recovered. Additionally, similar and higher classification accuracies were obtained in the current study when compared to previous South African studies that used other bone models exploring population affinity and sex estimation (Kibii *et al.*, 2010; Ostrofsky *et al.*, 2015; Ünlütürk, 2016). Several studies have evaluated the variation of the first and second cervical vertebrae using multiple measurements, achieving accuracy ranging between 70.9% and 92.9% for sex estimation, similar to the current research (Marino, 1995; Wescott, 2000; Marlow *et al.*, 2011; Gama *et al.*, 2015; Torimitsu *et al.*, 2016; Rozendaal *et al.*, 2020). In addition, previous studies involving lumbar vertebrae have shown greater classification accuracy than studies of thoracic and cervical vertebrae, as seen in the current study. (Taylor *et al.*, 1984; Ünlütürk, 2016; Hora and Sladek, 2018; Oura *et al.*, 2018).

Based on the results of the current study, white South Africans had higher classification accuracy in most vertebrae than black South Africans, while males had higher accuracy than females. The measurements that demonstrated the most sexual dimorphism and population variation were the vertebral body, spinous process and transverse process length and height measurements. As mentioned, certain measurements proved to be better at estimating population affinity and sex than others. The transverse process length and maximum posterior

height measurements were the most discriminating variables for both population affinity and sex estimation. A possible reason for the increased transverse process and vertebral body dimension measurements observed may be due to the differences in growth patterns between the sexes. In the coronal plane, female vertebrae are relatively taller and thinner than those of males. In comparison with males, the height of the female vertebral body is higher, while the transverse diameter of the male vertebral body is larger. Approximately between the ages of eight and 21 years old, the thoracic and lumbar vertebrae (specifically from the sixth thoracic vertebra to the fifth lumbar vertebra) increase in size and dimensions significantly in males compared to females (Bellemare *et al.*, 2003). Additionally, sexual dimorphism in spinal development results in females having a thinner thoracolumbar spine than males because of differences in growth rates during puberty (Taylor and Twomey, 1984). Male vertebrae have been found to be 25% larger than females because of delayed apoptosis in males associated with increased testosterone levels during puberty (Bellemare *et al*., 2003). Furthermore, the spinous process is an attachment site for the back muscles, and as males tend to be more muscular than females, the spinous process of males tends to be larger than females, thereby adding to the sexual dimorphism (Atkinson, 1967; Taylor *et al.*, 1984; Bellemare *et al.*, 2003; Allbright, 2007; Masharawi and Salame, 2011; Aylott *et al.*, 2012; Waxenbaum *et al.*, 2018). The larger muscle mass noted in males may also explain why the vertebral body measurements are good sex estimators, especially in the lower thoracic and lumbar vertebrae, as they act as the major load-bearing aspects for the vertebrae and support the upper body weight. The weight-bearing function of the vertebral bodies may also result in larger vertebral bodies in males, which would explain why the measurements associated with the body are more sexually dimorphic.

### 5.1 Practical Application in Forensic Anthropology and Future Recommendations

Although estimation of population affinity and sex from the vertebrae is not necessary for situations involving complete skeletal remains, the universal formula could be useful in instances where remains are incomplete or fragmentary. The current study demonstrated that even without prior knowledge of vertebral number, population affinity and sex could be estimated successfully from single vertebrae with comparable accuracies to some other common bone models (Stull *et al.*, 2014; Krüger *et al.*, 2015; Krüger *et al.*, 2017; Liebenberg *et al.*, 2019). The vertebrae demonstrated high classifications of 78% to 93% for population affinity and 73% to 92% for sex estimation. Therefore, the vertebrae bone models can be used

as an additional technique when crania and postcranial elements are not available to estimate population affinity and sex. With specialised software, such as FORDISC, a custom database can be imported, as the software creates discriminant functions applying numerous combinations of variables for individual analysis (L'Abbé *et al.*, 2013; Ousley and Jantz, 2013).

In order to meet the inclusion criteria, a large number of older individuals were included in the sample, with the mean age for the white South Africans being higher than the black South African sample. As a result of the composition of the Pretoria Bone Collection, demographics include primarily black and white South Africans, with black South Africans, regardless of age, making up the majority of the collection. On the other hand, white South Africans make up the minority of the collection, with more older individuals represented in the collection (L'Abbé *et al*., 2005). Because the white South Africans in the skeletal collection have older mean ages, particularly the females, data analyses on sexual dimorphism and population variation may be affected. However, despite the white South African sample having an older mean age, efforts were made to exclude any individuals, vertebrae, or measurements that were clearly influenced by age. Even though age influences the vertebrae and may potentially affect classification accuracy, these influences can typically be seen in the development of osteophytes, in the compression and wedging of vertebral bodies, or in pathology. Until these influences are tested, the age-related effects on classification remain unknown and, in turn, should be further investigated. If there are obvious changes in the vertebral body because of ageing or spinal disease, these measurements of the vertebral body should be excluded from analyses. The age difference between sexes may also affect the analyses, as ageing may alter vertebrae morphology and lead to incorrect classification. Research needs to be conducted on influences on vertebral classification accuracy, considering age cohorts and the interaction between age, sexes, and population groups. Additionally, future research on a larger sample size that includes individuals housed throughout south African collections as well as creating models that account age related changes.

Future research assessing further South African populations, including coloured and Indian South Africans, will improve understanding of the vertebral sexual dimorphism and population variation of modern South Africans. Further explorations, such as assessing the effects of using thermally altered fragmentary vertebrae, using vertebrae with major pathology present and using heavily fragmentary vertebrae could improve the universal formulae and models, allowing further univariate and multivariate analyses to be used in fragmentary or partial

remains. Lastly, to improve the validity and reliability of the universal formula, a validation study should be conducted on an unrelated, independent test sample.

# CHAPTER 6: CONCLUSION

The current study assessed osteometric variation of a selection of vertebrae to examine population variation and sexual dimorphism, and to determine whether a universal discriminant function can effectively predict population affinity and sex without prior identification of vertebral number in a South African sample. Through the use of univariate and multivariate analyses, the results demonstrated that differences exist among the vertebrae of black and white South African males and females. The majority of sexual dimorphism and population variation is attributed to differences in the size of the vertebral body and spinous processes, with males and white South Africans presenting with greater means than females and black South Africans, respectively.

Multivariate models yielded the best results, as the inclusion of multiple variables maximised group differences. With the use of single vertebrae and combined vertebrae sub-type multivariate models, population affinity and sex can be estimated with comparable or even higher accuracies than commonly used methods making use of other postcranial bone models for estimating population affinity and sex. However, only two populations were examined in the current study, while commonly used methods that assess bone models typically include at least three populations (black, white and Coloured South Africans). Furthermore, multivariate universal models are recommended even though a variety of different standards are available for use, such as single vertebrae univariate models and universal univariate models. While not the best tool for exploring human variation, univariate models still allow for accurate estimation of population affinity and sex from single vertebrae, which are particularly useful in the analysis of taphonomically altered remains. It is also recommended that the standards be used with FORDISC, after they have been validated, which allows for case-specific analyses where the practitioner has more flexibility in choosing which models to use. The current study has shown the potential of using vertebral models, both univariate and multivariate, to estimate population affinity and sex in a forensic setting.

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# APPENDICES

## APPENDIX I – MEASUREMENT DEFINITIONS

*The various measurements included in the study were modified from Cheng (1998); Gama (2015); Marlow and Pastor (2011); Oura *et al*. (2018); and Torimitsu *et al*. (2016).

**Refer to Appendix II for diagrams illustrating the measurements.

**Maximum Superior Sagittal Length (XSLs):** Maximum superior length from the most anterior to the posterior aspect of the vertebral body along the sagittal plane.

**Maximum Inferior Sagittal Length (XSLi):** Maximum inferior length from the most anterior to the posterior aspect of the vertebral body along the sagittal plane.

**Maximum Centroid Height (XCH):** Maximum height at the mid-point of the vertebral body.

**Maximum Anterior Height (XAH):** Maximum height taken at the most anterior aspect of the vertebral body, from the most superior to the most inferior point.

**Maximum Posterior Height (XPH):** Maximum height taken at the midpoint of the posterior aspect of the vertebral body, from the most superior to the most inferior point.

**Maximum Superior Articular Length (XALs):** Maximum length of the superior articular aspect of the vertebral body. The measurement is taken on the inner edge of the ring apophysis from the anterior to posterior aspect.

**Maximum Inferior Articular Length (XALi):** Maximum length of the inferior articular aspect of the vertebral body. The measurement is taken on the inner edge of the ring apophysis from the anterior to posterior aspect.

**Maximum Superior Articular Width (XAWs):** Maximum length of the superior articular aspect of the vertebral body. The measurement is taken on the inner edge of the ring apophysis from the most lateral aspects.

**Maximum Inferior Articular Width (XAWi):** Maximum width of the inferior articular aspect of the vertebral body. The measurement is taken on the inner edge of the ring apophysis from the most lateral aspects.

**Foramen Sagittal Length (FSL):** Length of the vertebral foramen taken at the sagittal plane.

**Foramen Coronal Width (FCW):** Maximum width of the vertebral foramen taken at the coronal plane.

**Pedicle Height (PH):** Height of the pedicle (midpoint) from the most inferior to superior aspect at the coronal plane. The measurement is the most minimum measurement of the pedicle height.

**Pedicle Width (PW):** Width of the pedicle at the midpoint of the coronal plane. For the cervical and lumbar vertebrae, the caliper is placed diagonally at the midpoint of the pedicle. Additionally, the measurement is taken at an angle on the foramen transversarium for the cervical vertebrae and the vertebral foramen. For the thoracic and lumbar vertebrae, place the caliper in the middle of the pedicle.

**Maximum Pedicle Length (XPL):** Maximum pedicle length from the posterior aspect of the vertebral body to the most anterior aspect of the articular process.

**Transverse Process Length (TPL):** Length of the transverse process from where the lamina meets the spinous process to the most lateral aspect of the process. For the cervical vertebrae, the caliper is placed on the posterior tubercle of the transverse process to the midpoint, where the lamina and spinous process meet. The caliper is placed on the most lateral aspect of one transverse process to the midpoint, where the lamina and spinous process meet for the thoracic and lumbar vertebrae.

**Maximum Transverse Process Width (XTPW):** Maximum width of the transverse processes, taken from the most lateral (left end) to the most lateral (right end). For the cervical vertebrae, the caliper is placed on the posterior tubercle of both transverse processes. The caliper is placed on the most lateral aspect of both the transverse processes for the thoracic and lumbar vertebrae.

**Maximum Superior Articular Process Width (XAPWs):** Maximum distance between the left and right superior articular processes and the lateral articular borders.

**Maximum Inferior Articular Process Width (XAPWi):** Maximum distance between the left and right inferior articular processes and the lateral articular borders.

**Articular Process Height (APH):** Maximum height of both articular processes from the most superior aspect to the most inferior of the articular processes.

**Maximum Spinous Process Length (XSPL):** Maximum length of the spinous process from the articular process to the most posterior aspect of the process. For the cervical vertebrae, the measurement is taken from the point where the laminas meet the spinous process to the most posterior aspect of the spinous process, including the bifid vertebrae. The thoracic and lumbar vertebrae measurement is taken from the point where the laminas meet the spinous process to the most inferior-posterior aspect of the spinous process.

# APPENDIX II – MEASUREMENT ILLUSTRATIONS

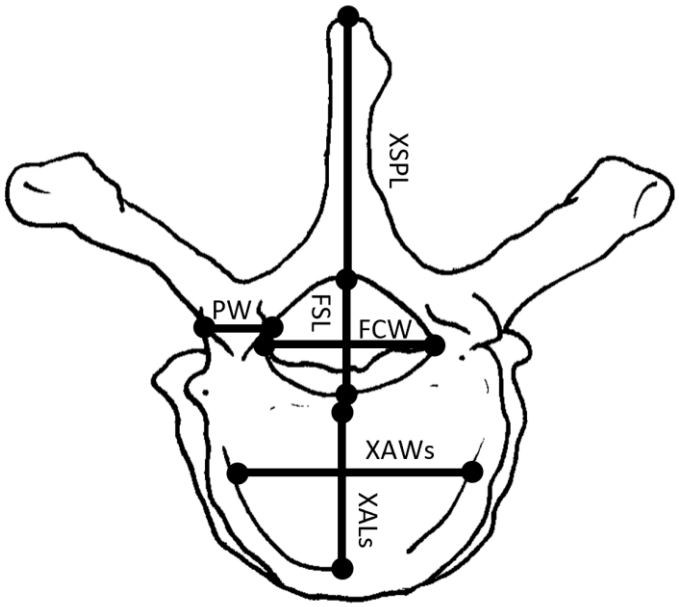


**Figure A**: Superior view of a typical vertebra showing measurements of the vertebral body, foramen, pedicle, and spinous process. Refer to Appendix I for measurement names and definitions.

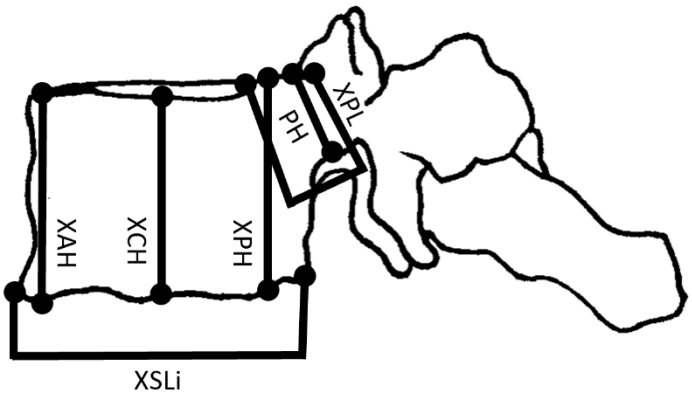


**Figure B:** Lateral view of a typical vertebra showing measurements of the vertebral body and pedicle. Refer to Appendix I for measurement names and definitions.

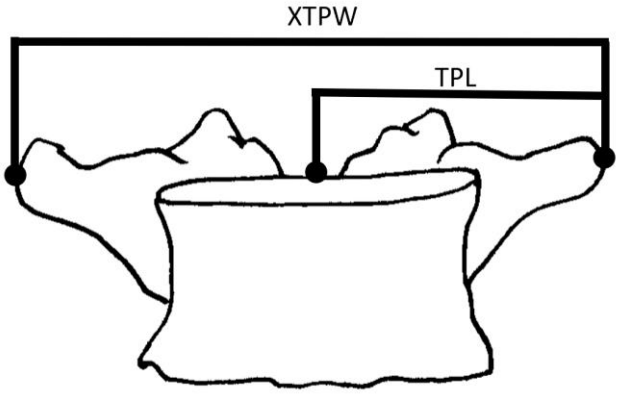


**Figure C:** Anterior view of a typical vertebra showing measurements of the articular process. Refer to Appendix I for measurement names and definitions.

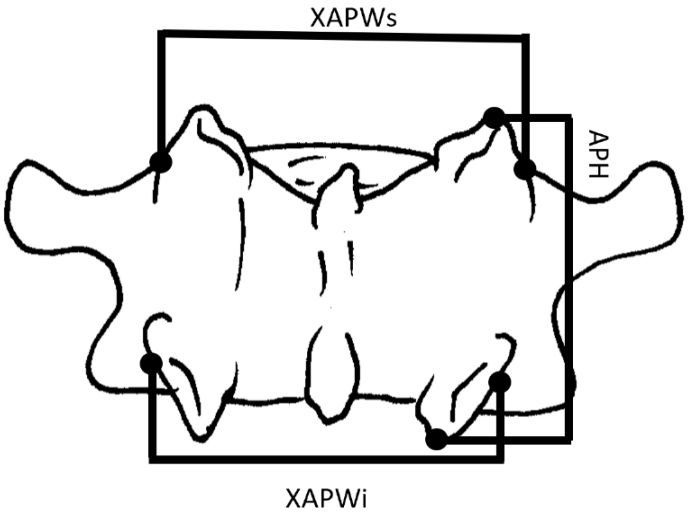


**Figure D:** Posterior view of a typical vertebra showing measurements of the superior and inferior articular processes. Refer to Appendix I for measurement names and definitions.

# APPENDIX III – TUKEY'S HSD RESULTS

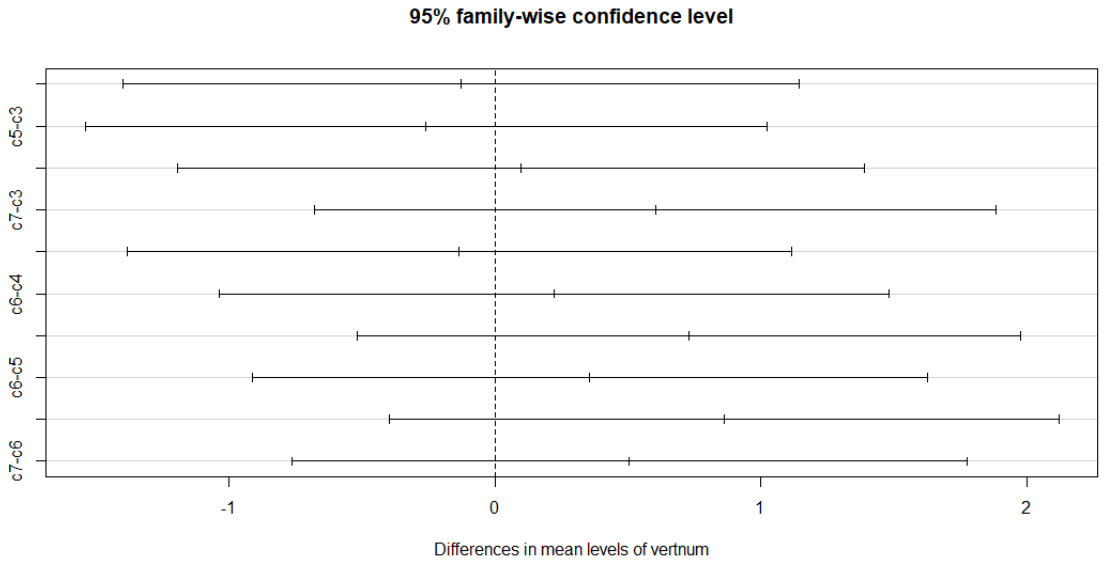


**Figure 1:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Superior Sagittal Length measurement.

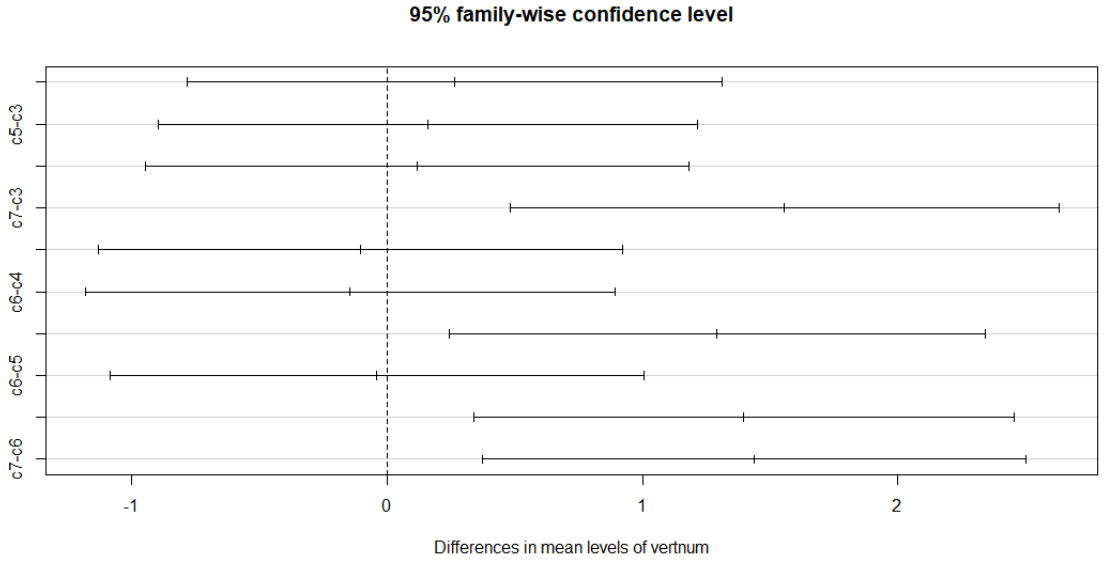


**Figure 2:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Centroid Height measurement.

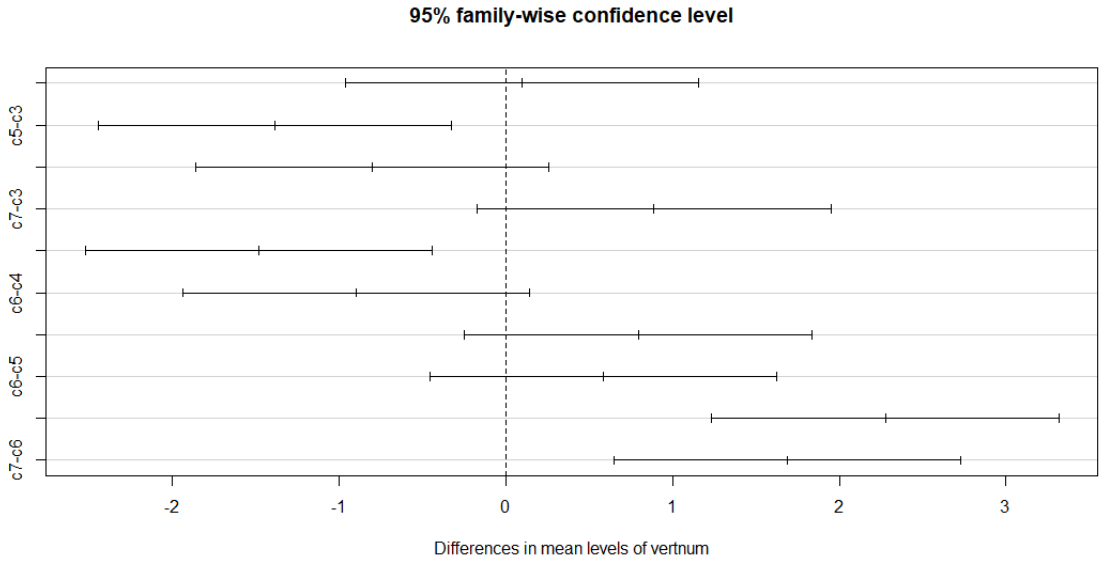


**Figure 3:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Anterior Height measurement.

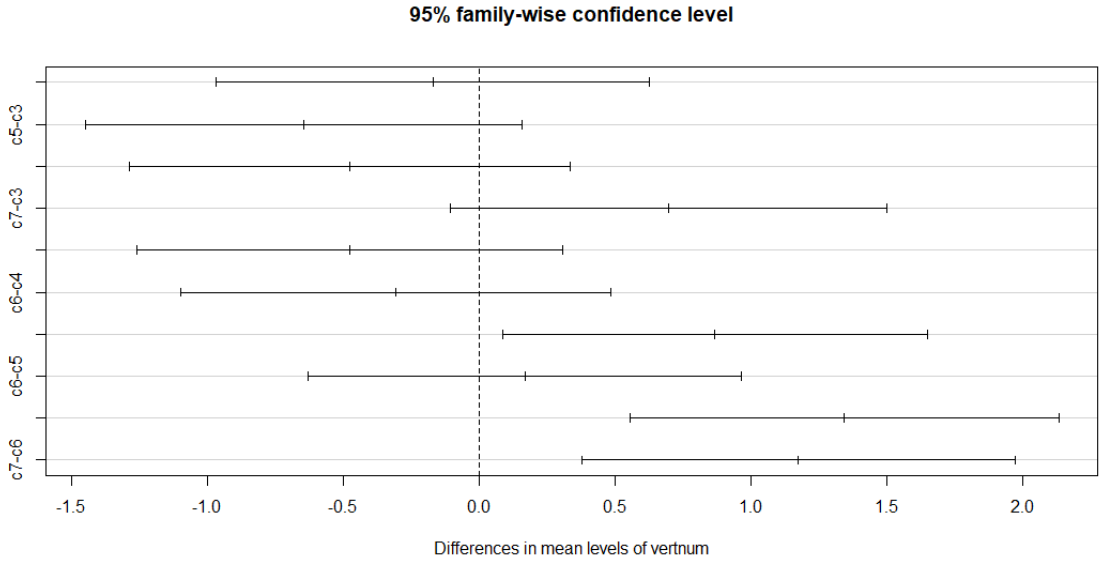


**Figure 4:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Posterior Height measurement.

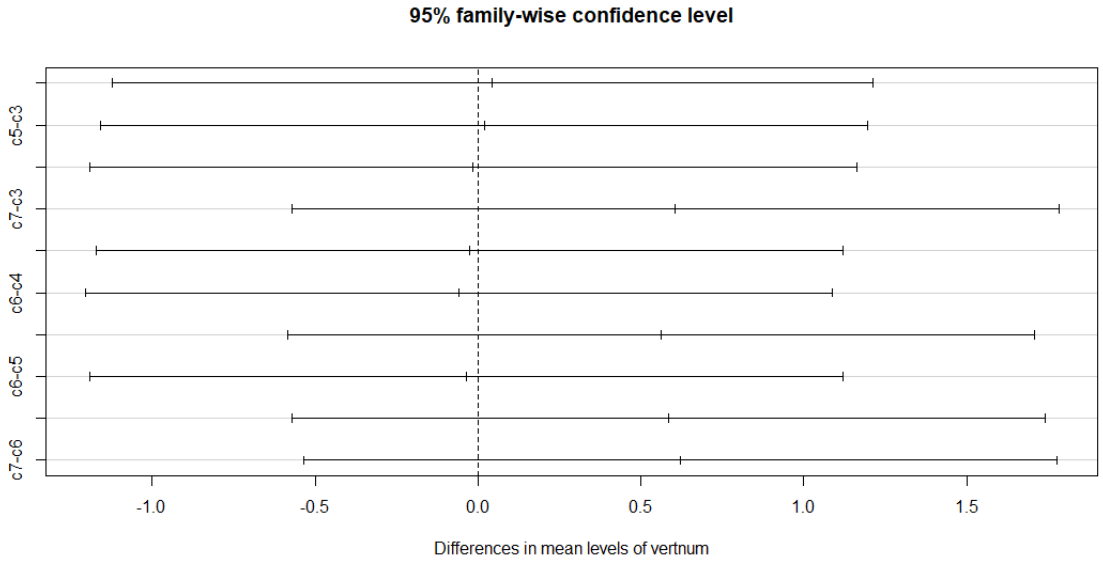


**Figure 5:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Superior Articular Length measurement.

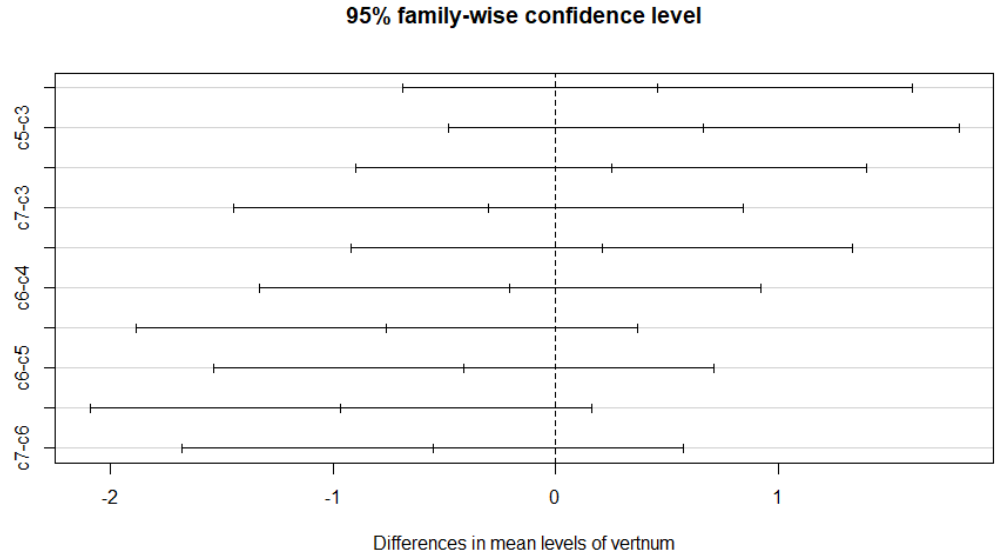


**Figure 6:** Results for the Tukey's HSD differences among the cervical vertebrae (C3-C7) Maximum Superior Articular Length measurement.

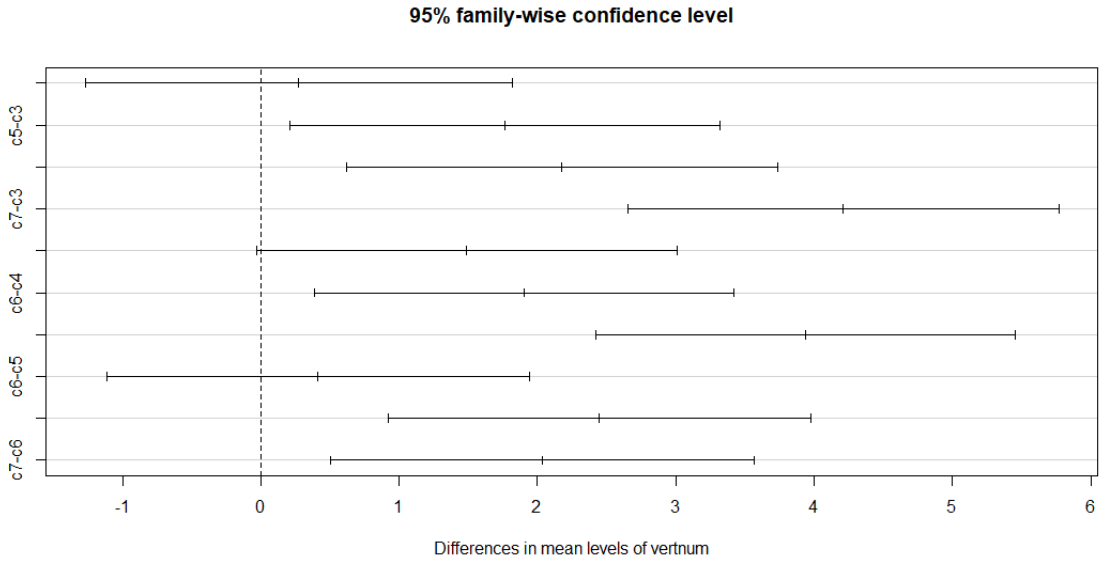


**Figure 7:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Superior Articular Width measurement.

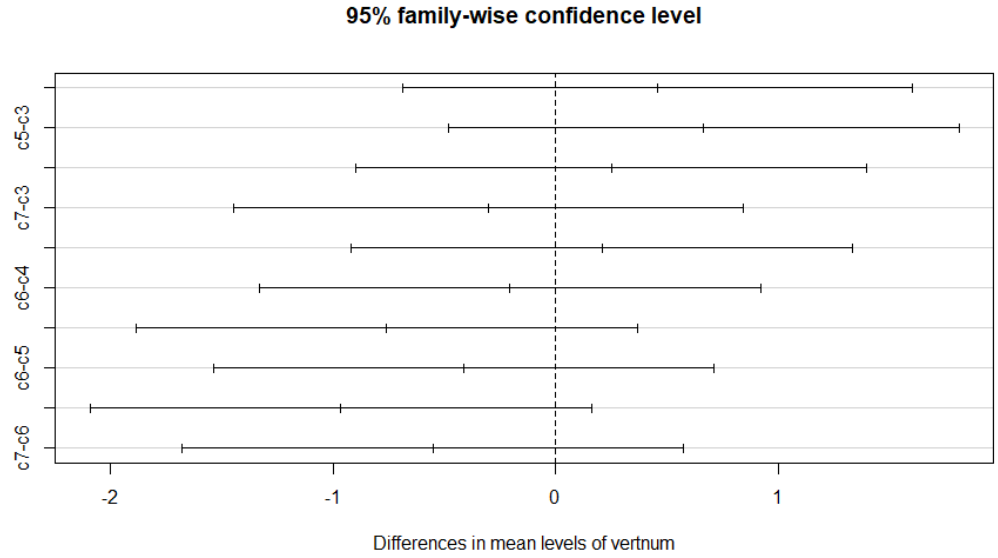


**Figure 8:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Inferior Articular Width measurement.

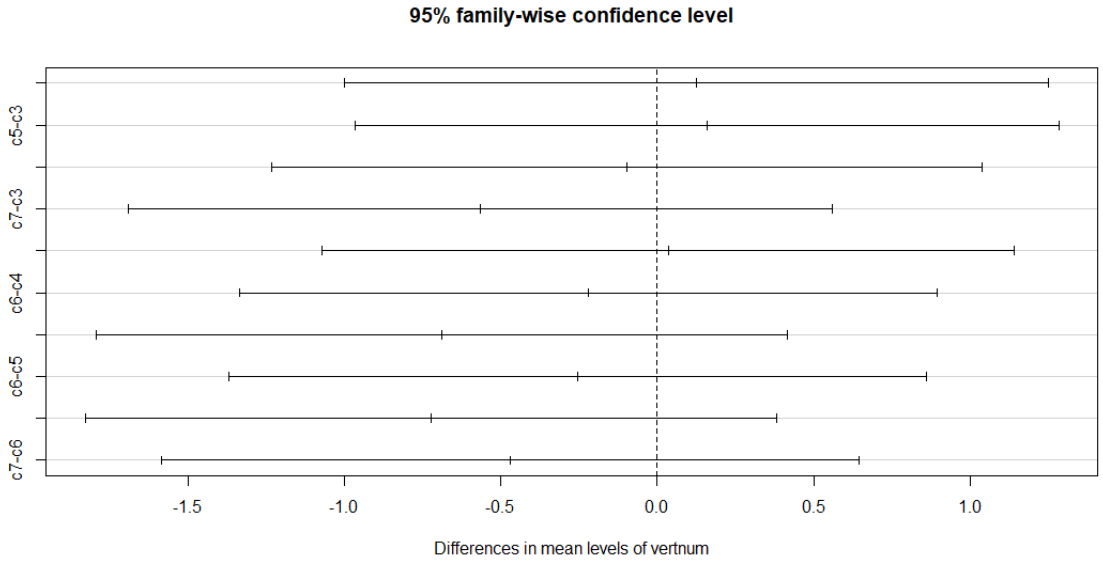


**Figure 9:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Foramen Sagittal Length measurement.

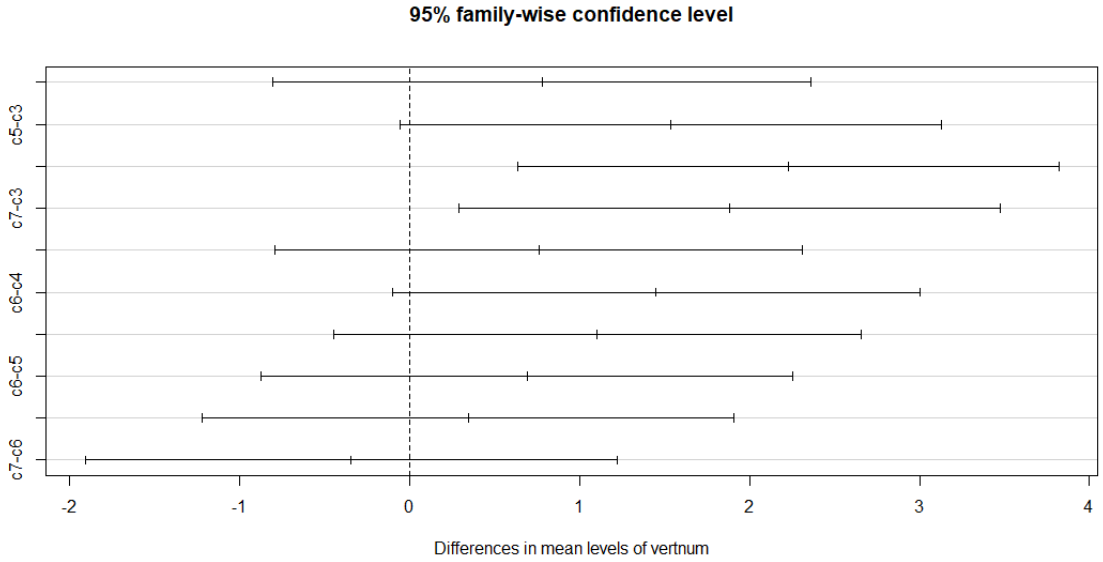


**Figure 10:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Foramen Coronal Width measurement.

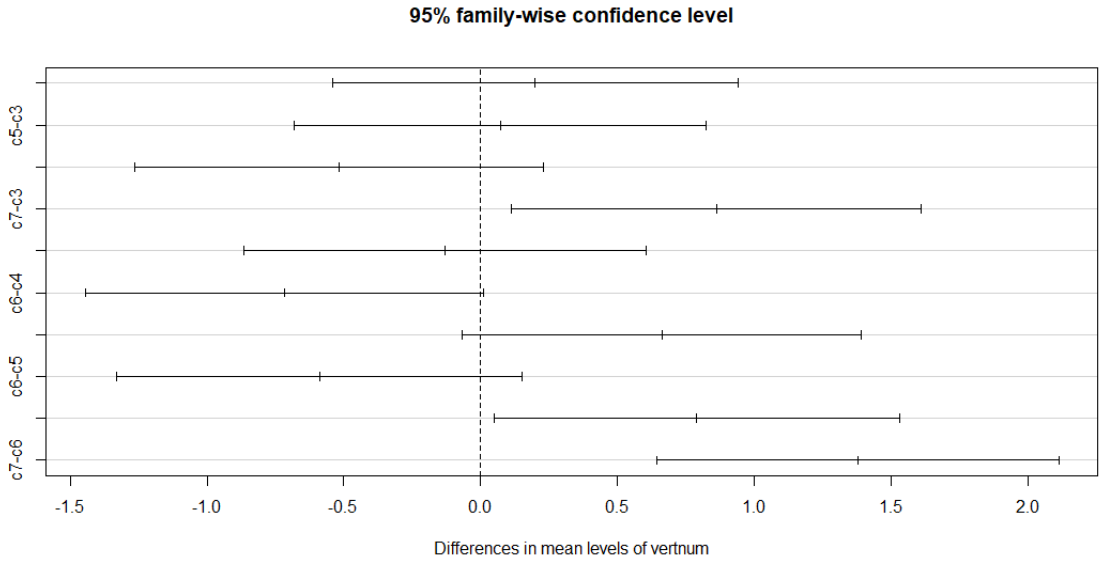


**Figure 11:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Pedicle Height measurement.

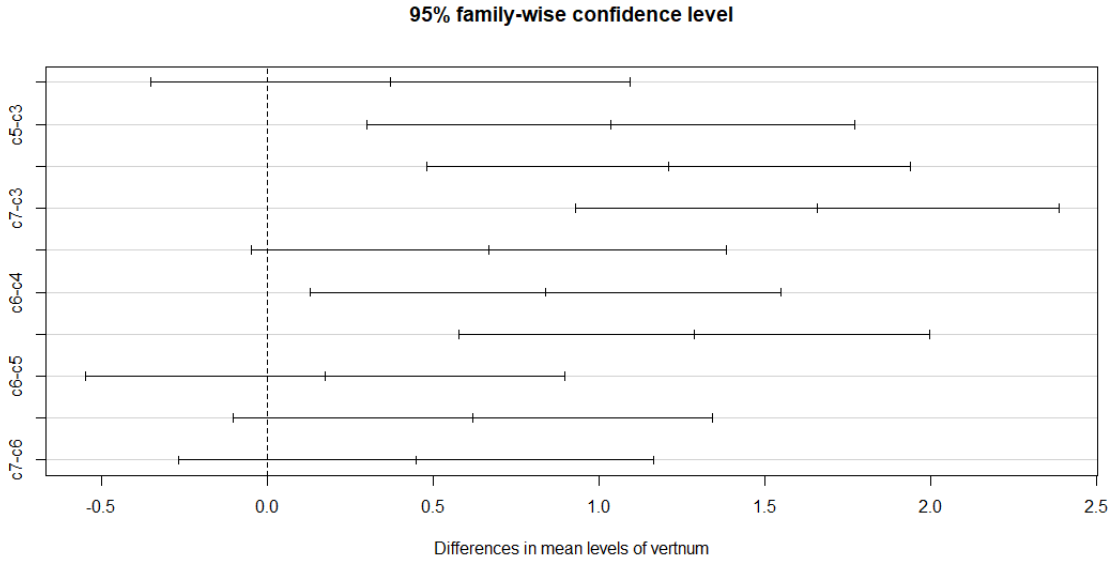


**Figure 12:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Pedicle Width measurement.

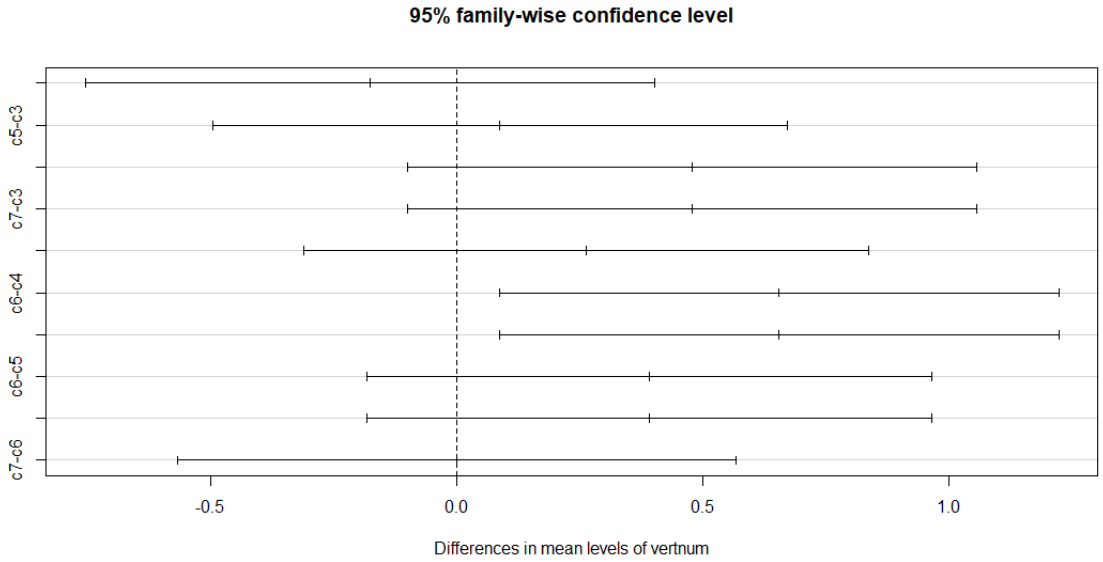


**Figure 13:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Pedicle Length measurement.

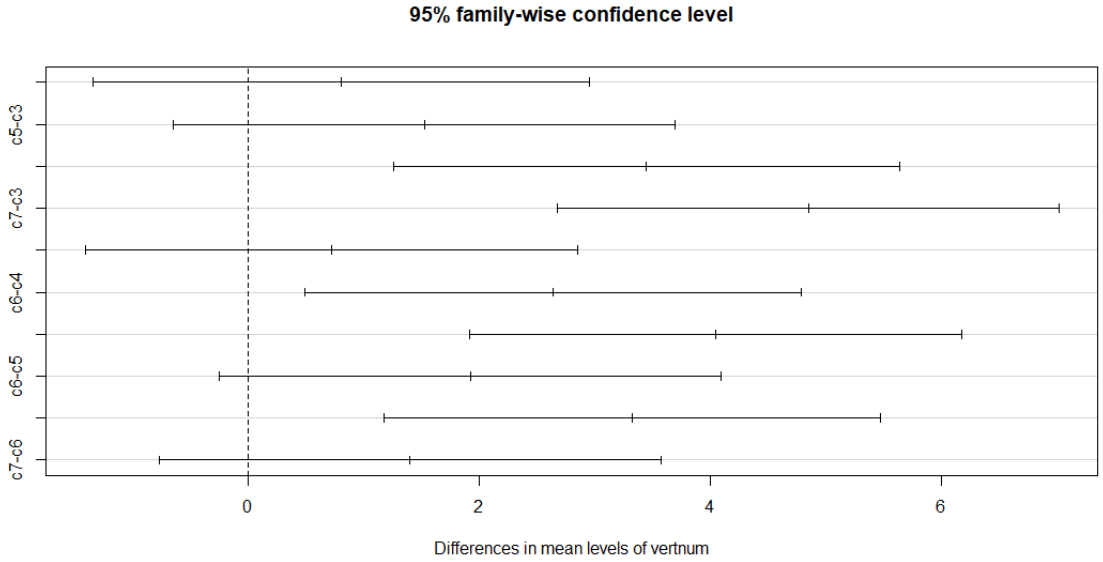


**Figure 14:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Transverse Process Length measurement.

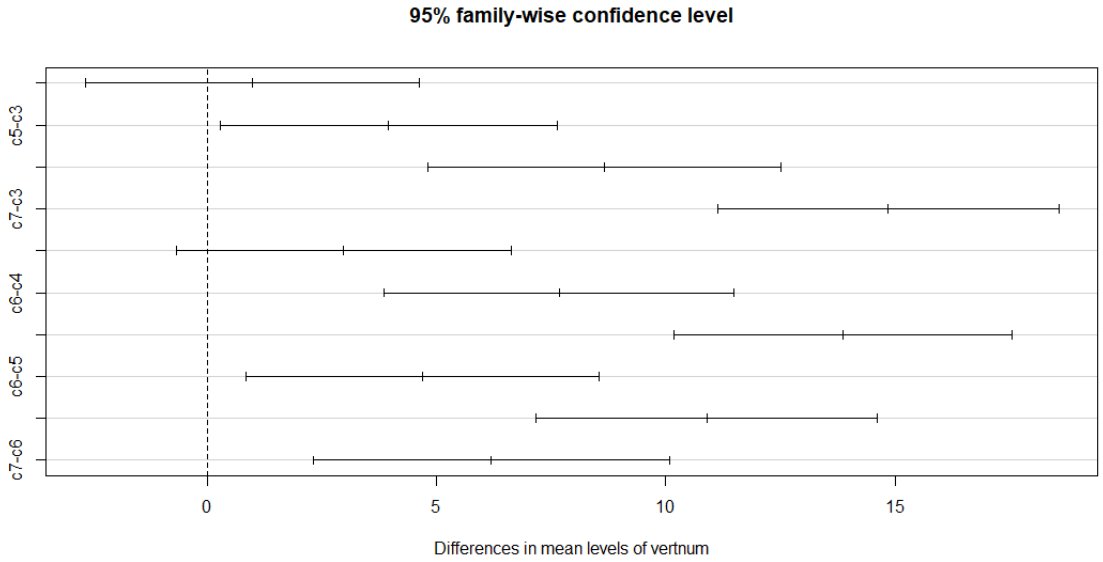


**Figure 15:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Transverse Process Width measurement.

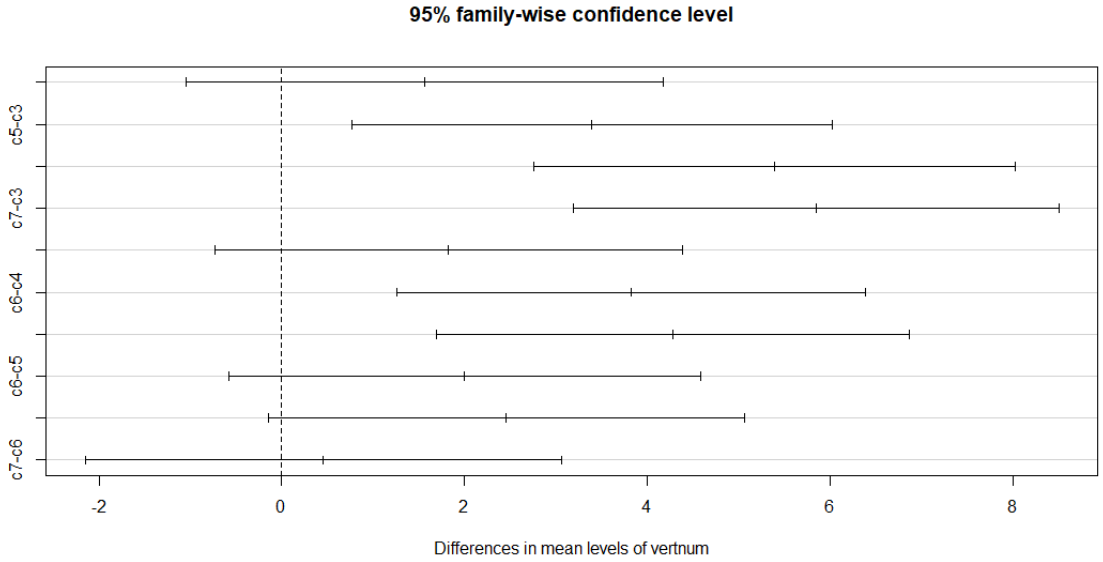


**Figure 16:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Superior Articular Process Width measurement.

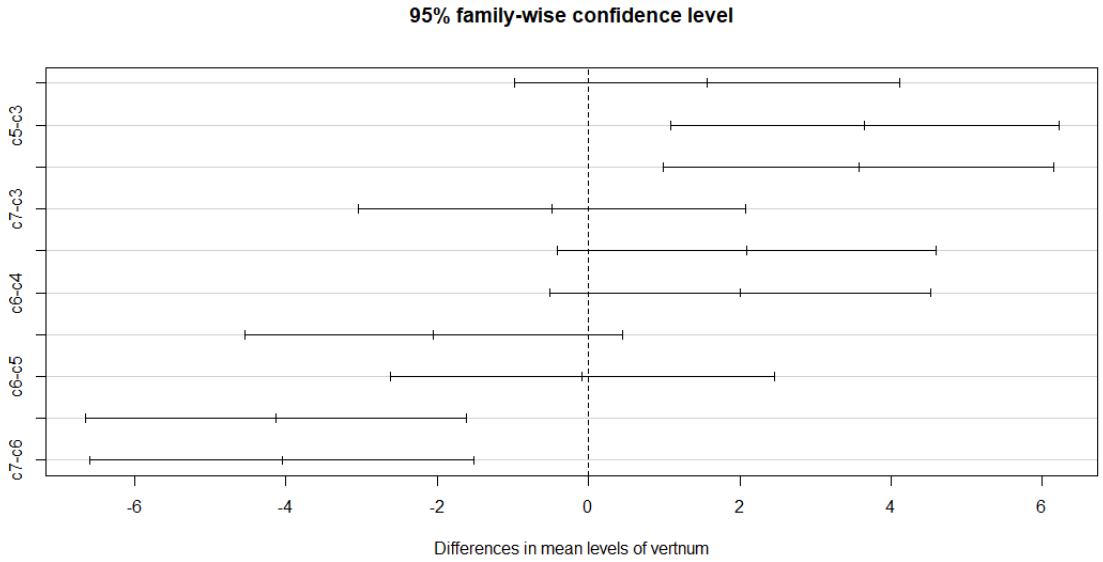


**Figure 17:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Inferior Articular Process Width measurement.

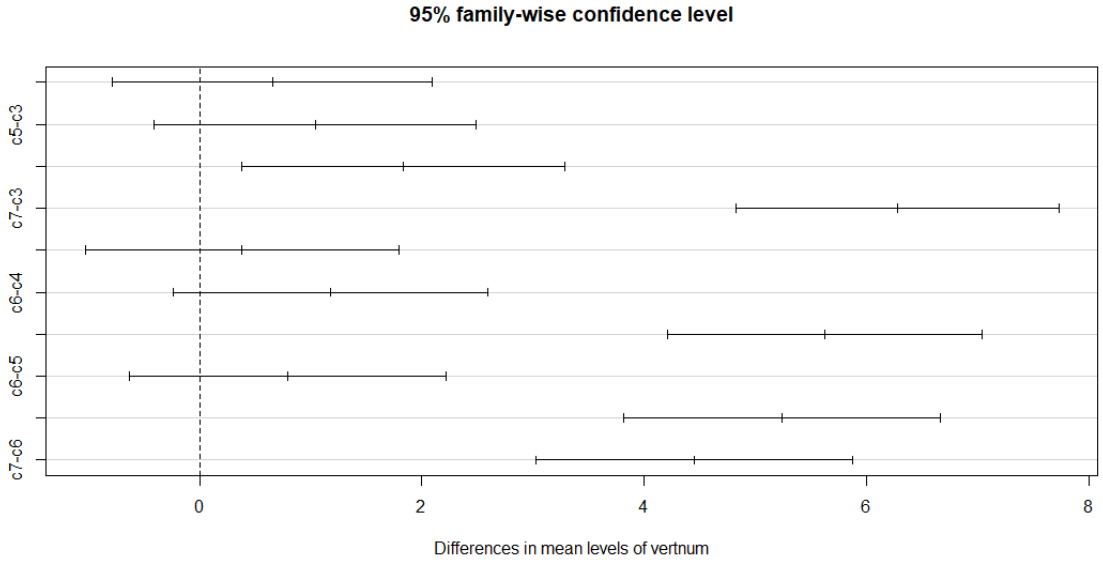


**Figure 18:** Results for the Tukey's HSD illustrating differences among for the cervical vertebrae (C3-C7) Articular Process Height measurement.

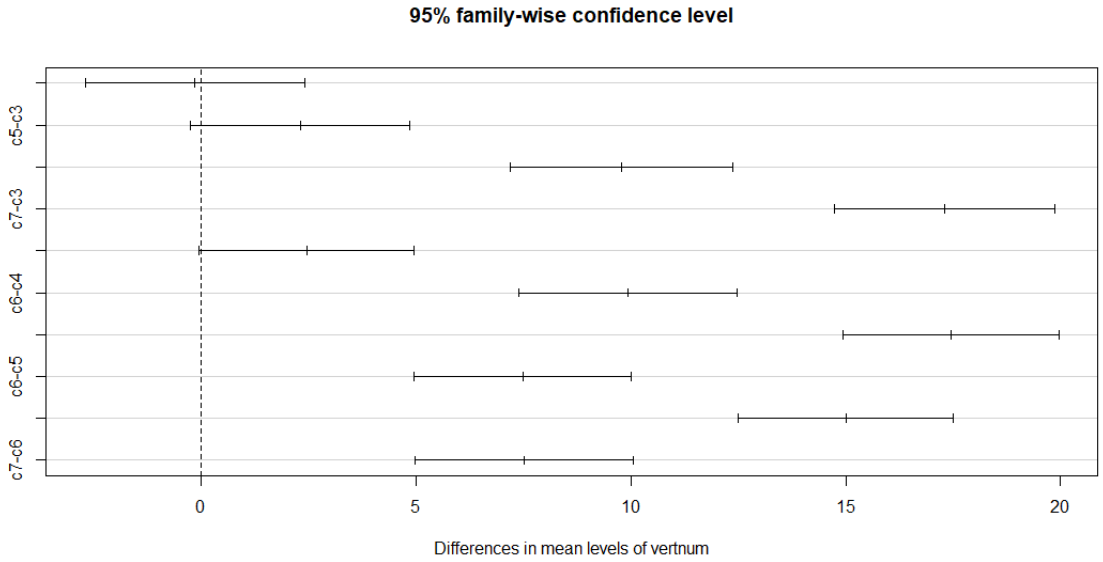


**Figure 19:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Spinous Process Length measurement.

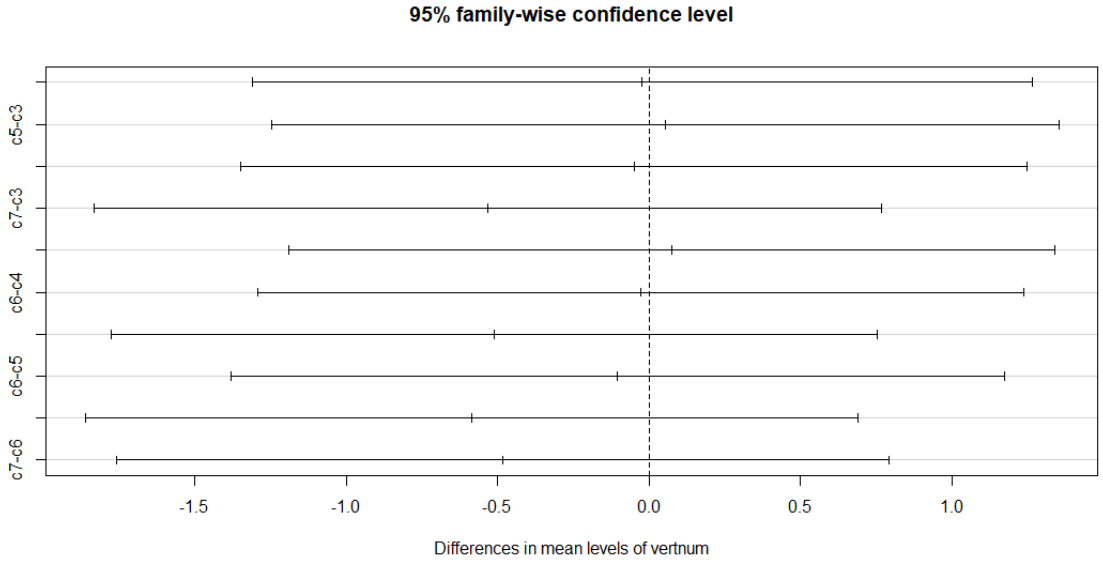


**Figure 20:** Results for the Tukey's HSD illustrating differences among the cervical vertebrae (C3-C7) Maximum Inferior Sagittal Length measurement.

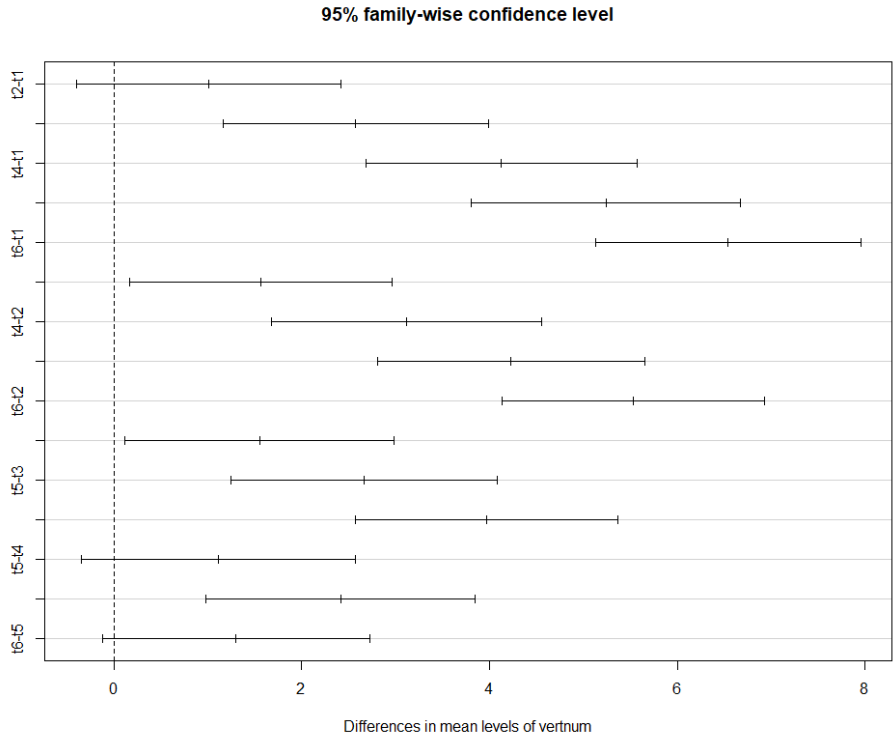


**Figure 21:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Superior Sagittal Length measurement.

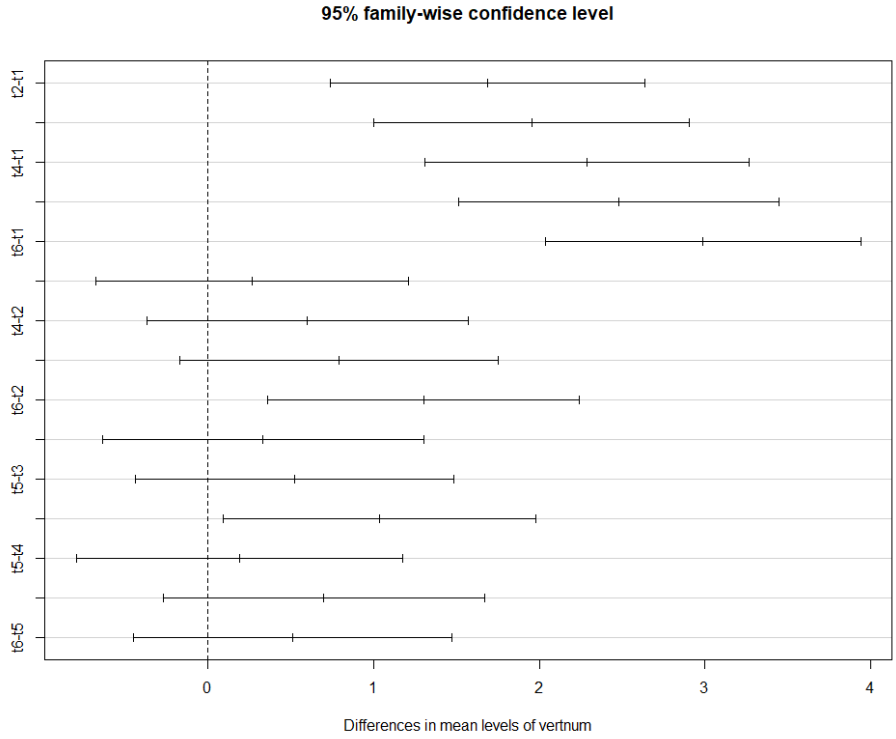


**Figure 22:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Centroid Height measurement.

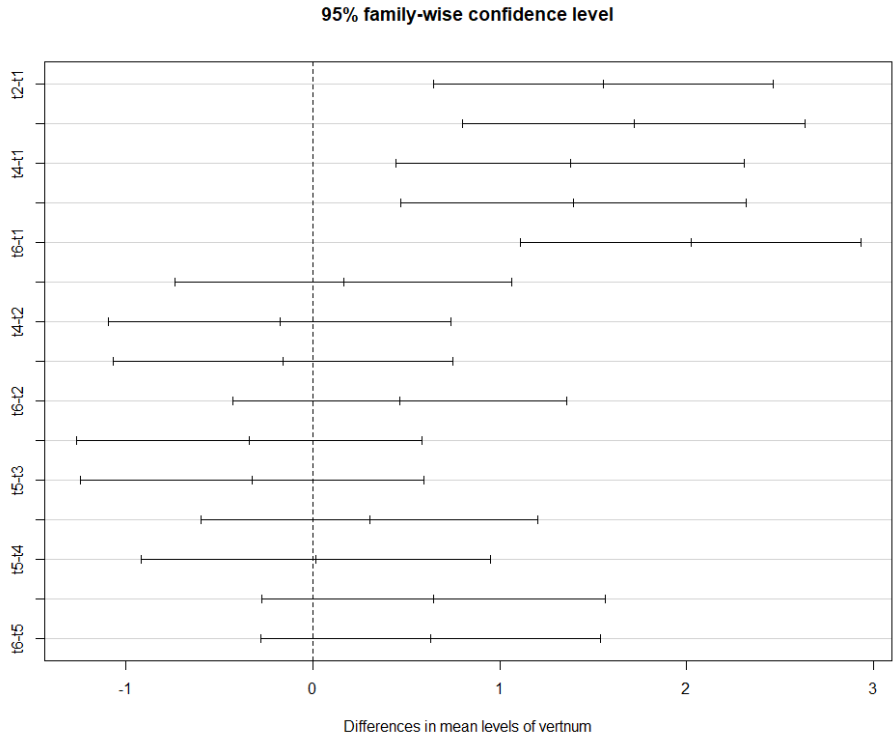


**Figure 23:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Anterior Height measurement.

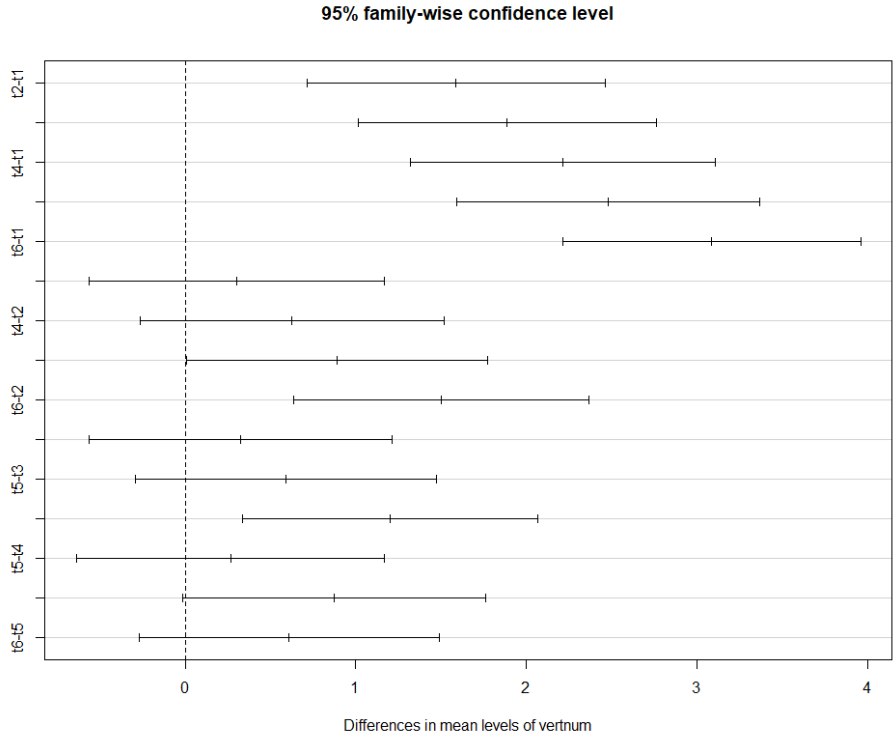


**Figure 24:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Posterior Height measurement.

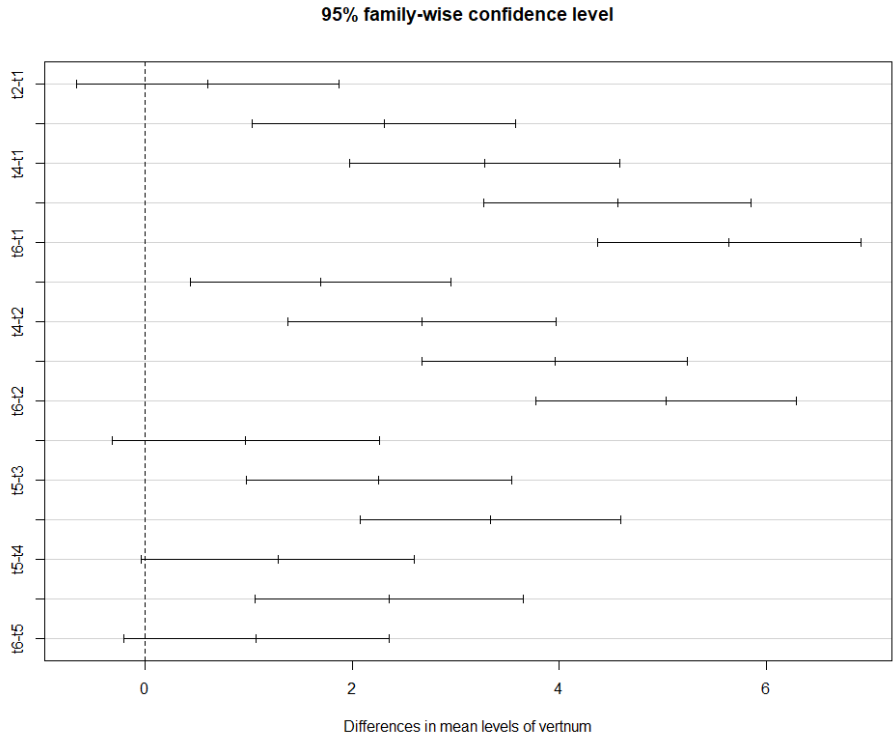


**Figure 25:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Superior Articular Length measurement.

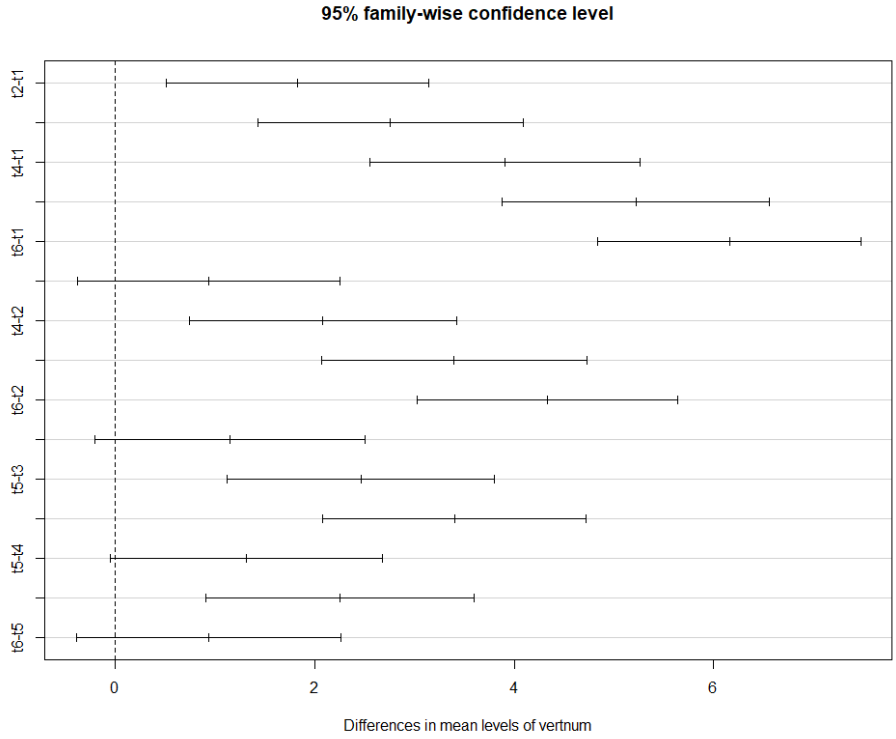


**Figure 26:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Superior Articular Length measurement.

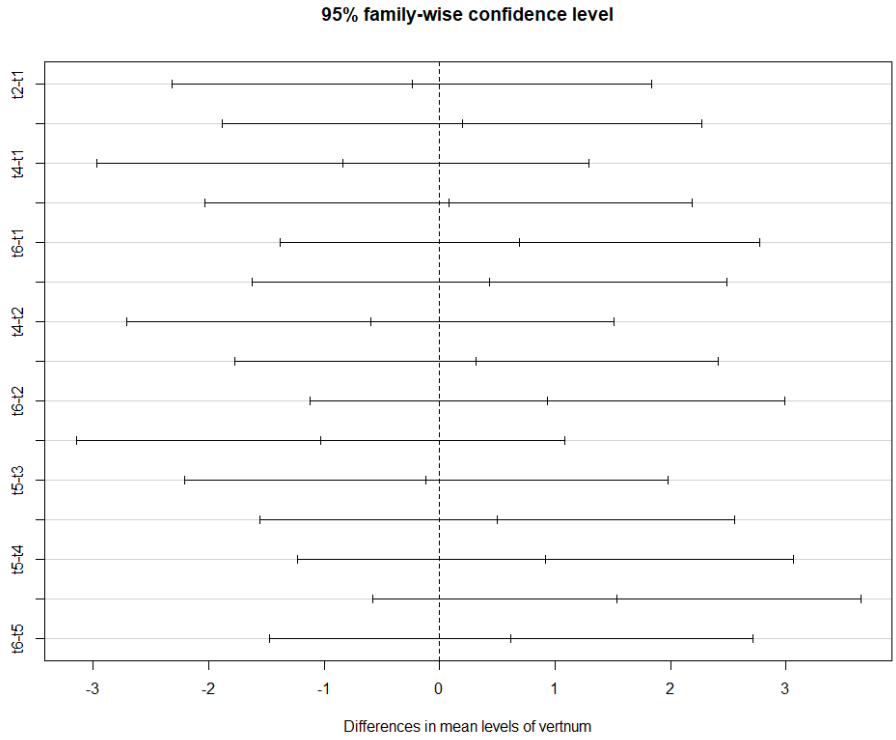


**Figure 27:** Results for the Tukey's HSD differences among the upper thoracic vertebrae (T1-T6) Maximum Superior Articular Width measurement.

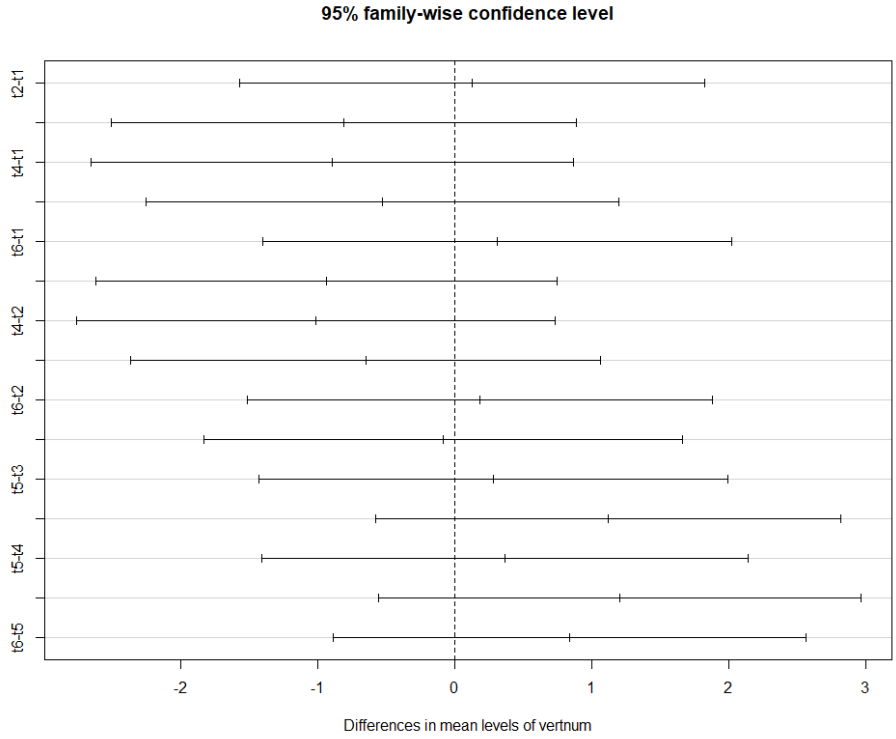


**Figure 28:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Inferior Articular Width measurement.

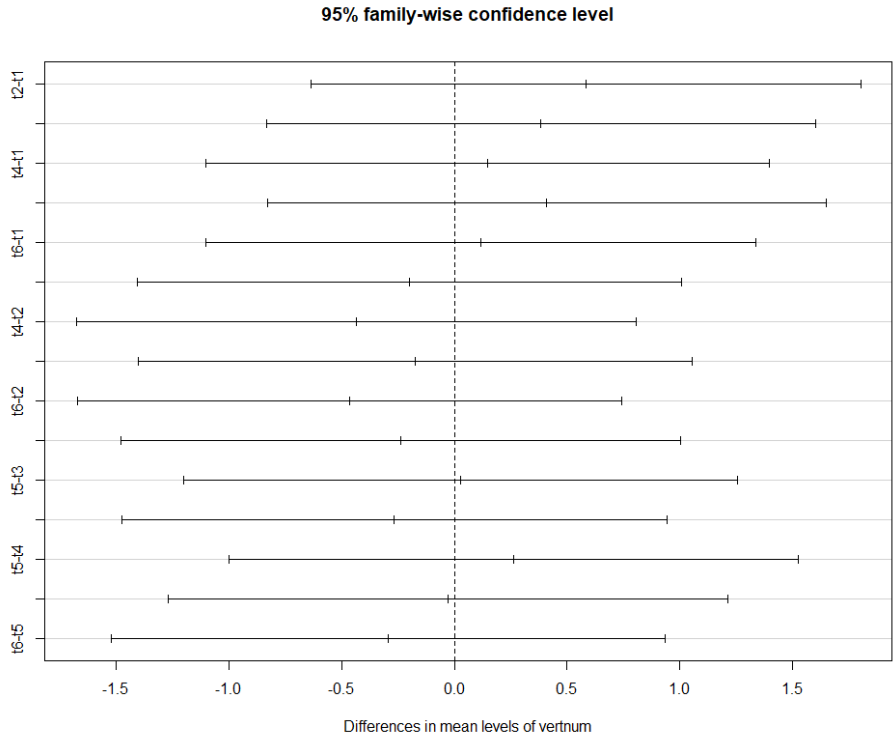


**Figure 29:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Foramen Sagittal Length measurement.

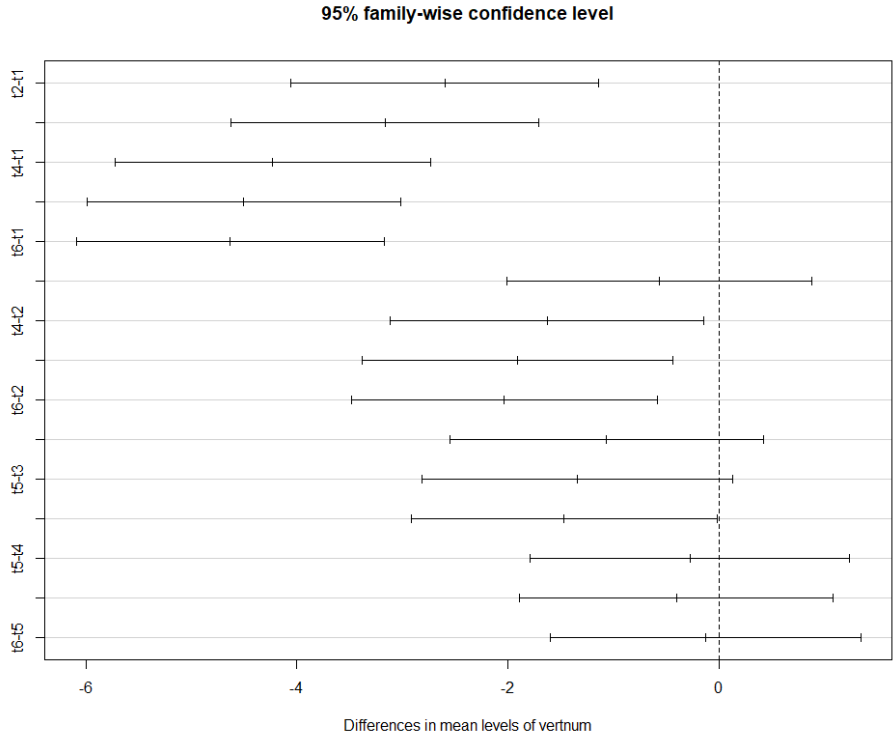


**Figure 30:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Foramen Coronal Width measurement.

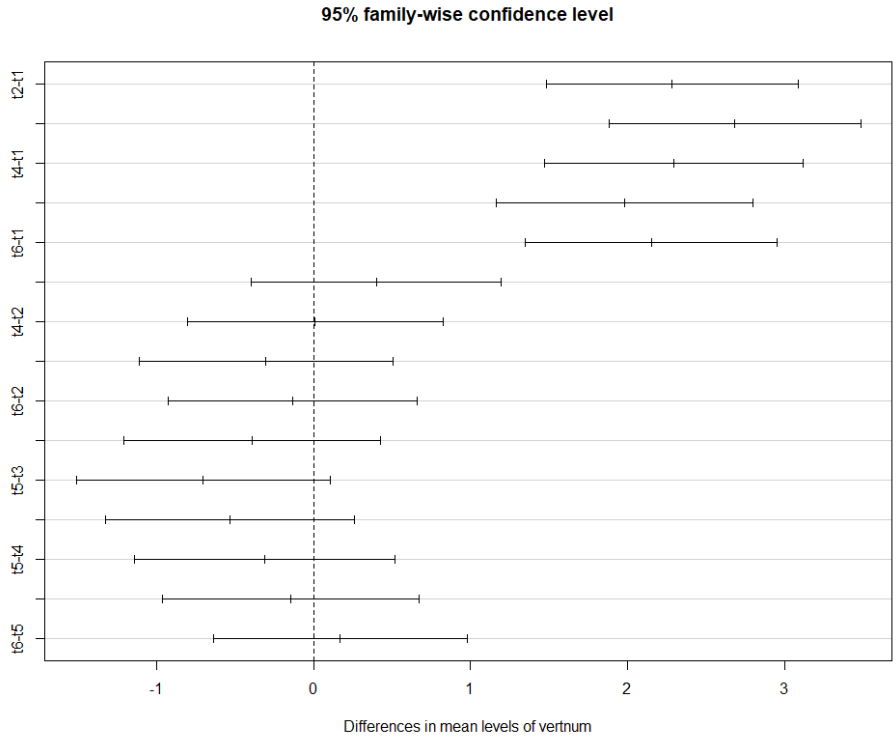


**Figure 31:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Pedicle Height measurement.

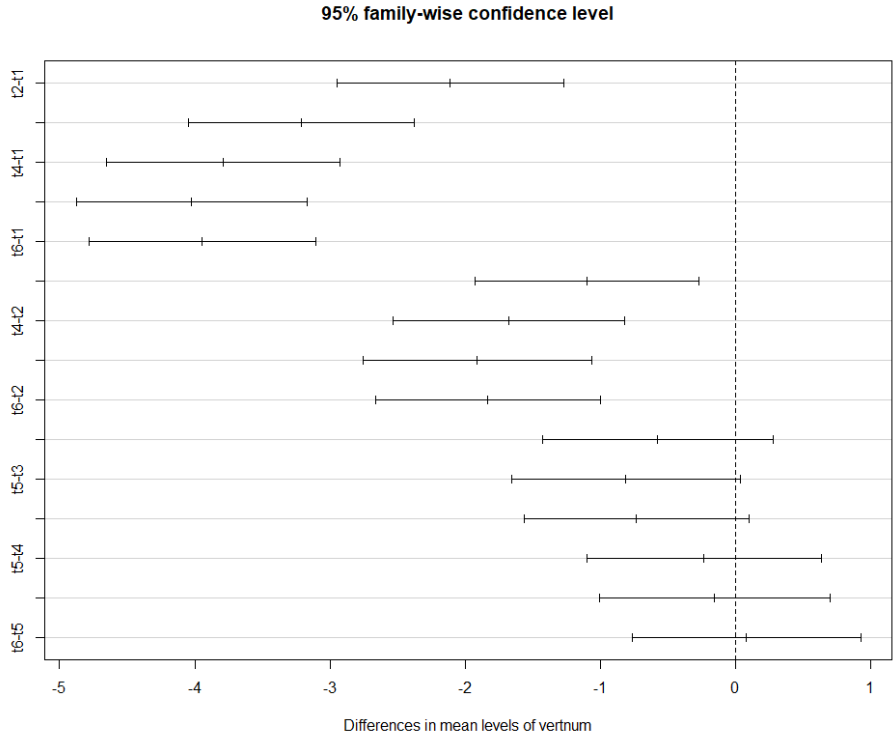


**Figure 32:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Pedicle Width measurement.

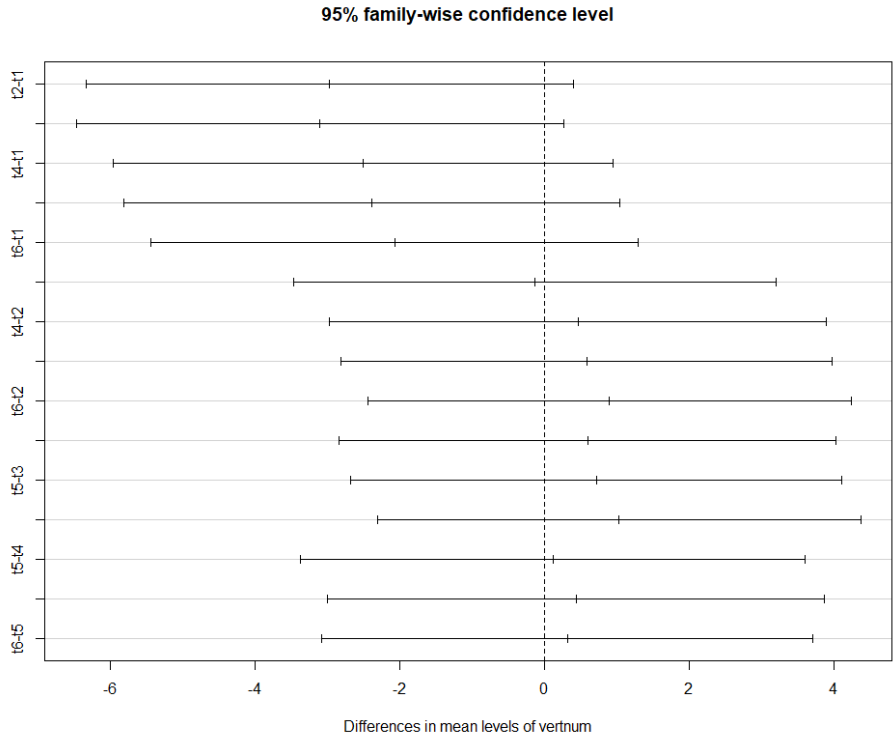


**Figure 33:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Pedicle Length measurement.

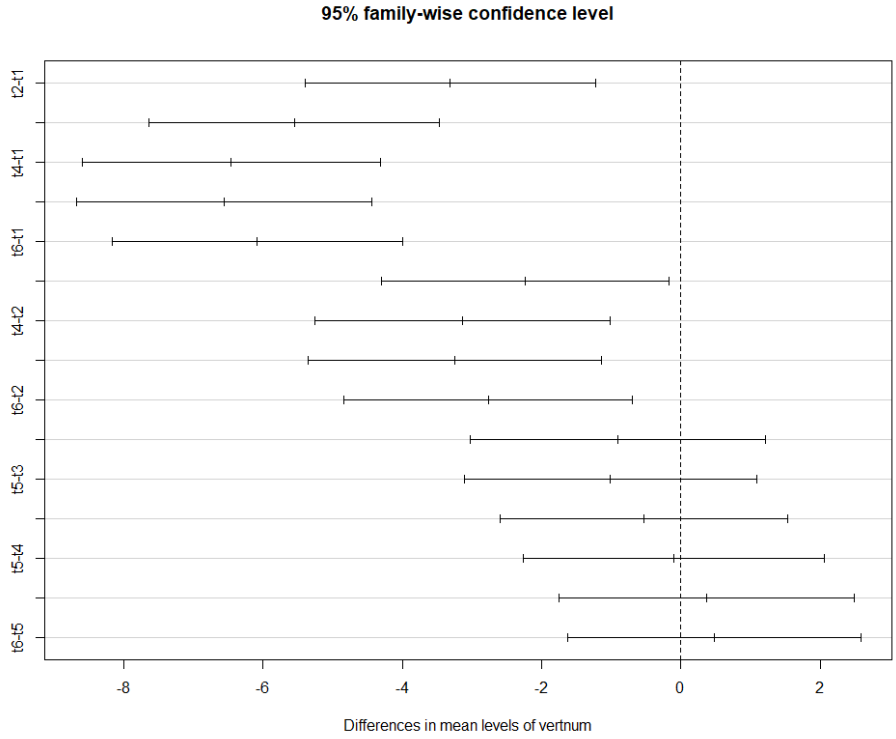


**Figure 34:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Transverse Process Length measurement.

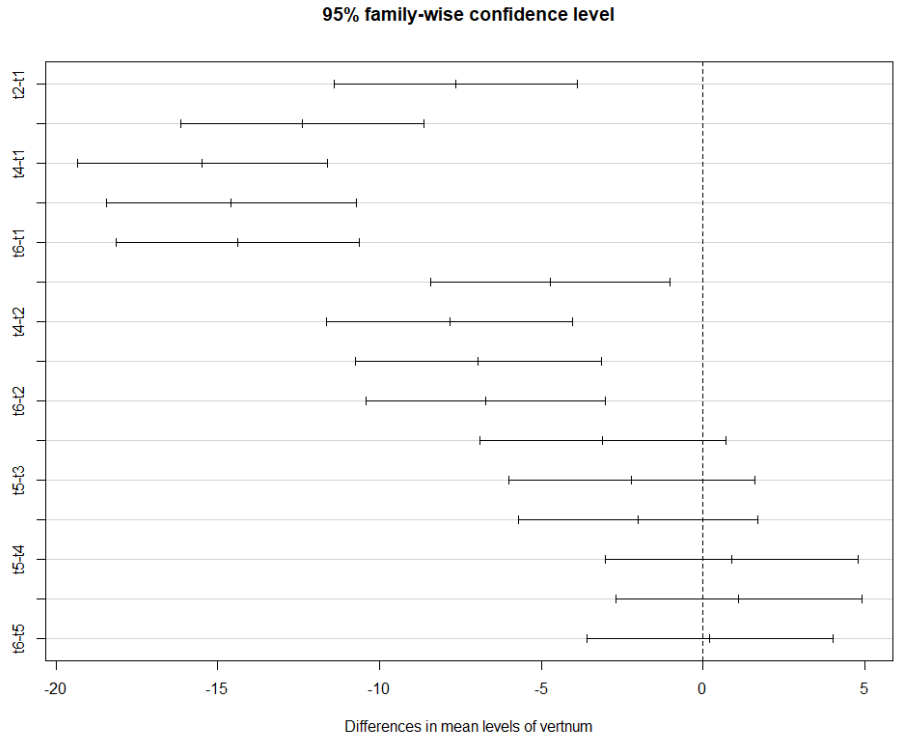


**Figure 35:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Transverse Process Width measurement.

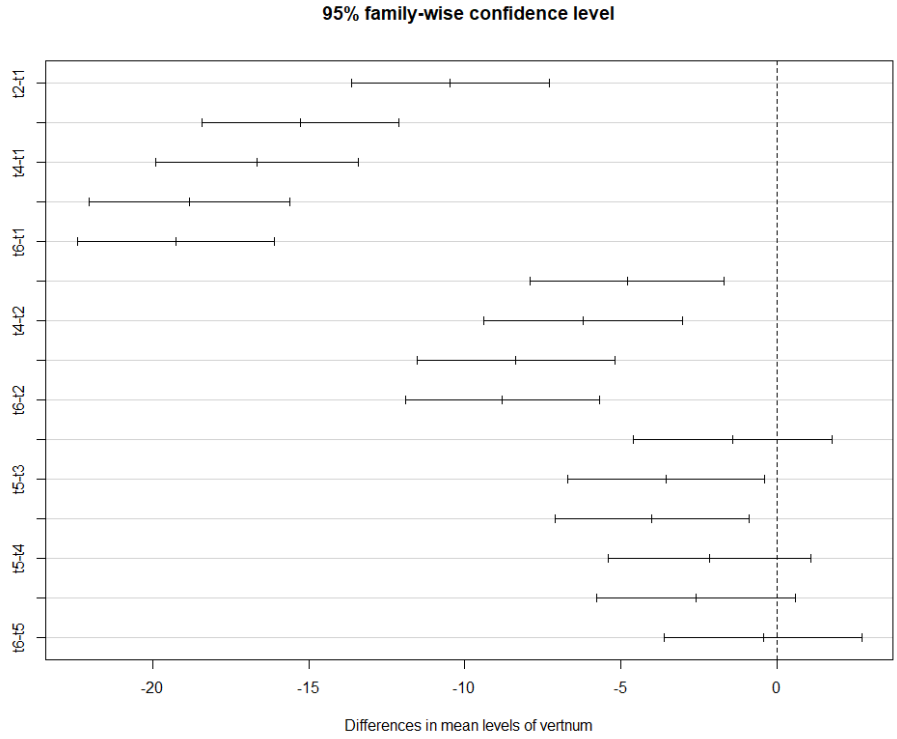


**Figure 36:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Superior Articular Process Width measurement.

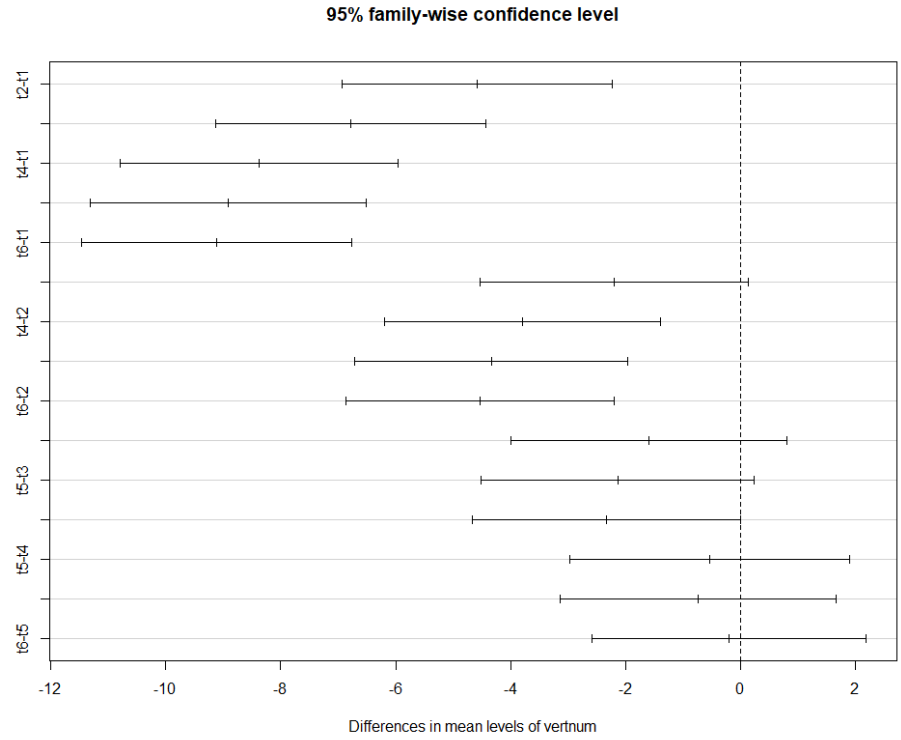


**Figure 37:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Inferior Articular Process Width measurement.

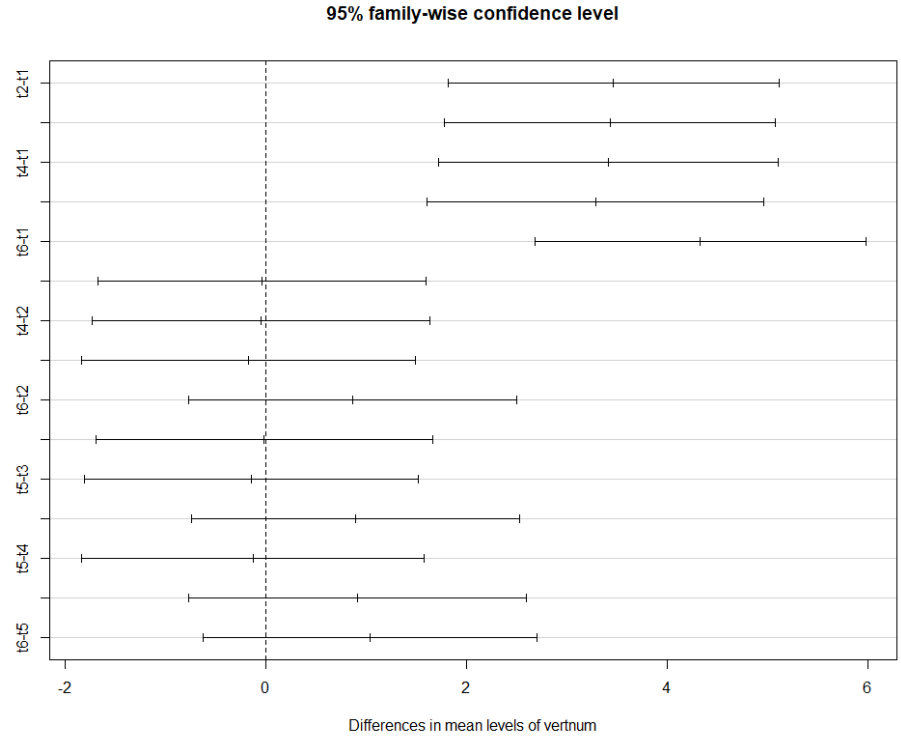


**Figure 38:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Articular Process Height measurement.

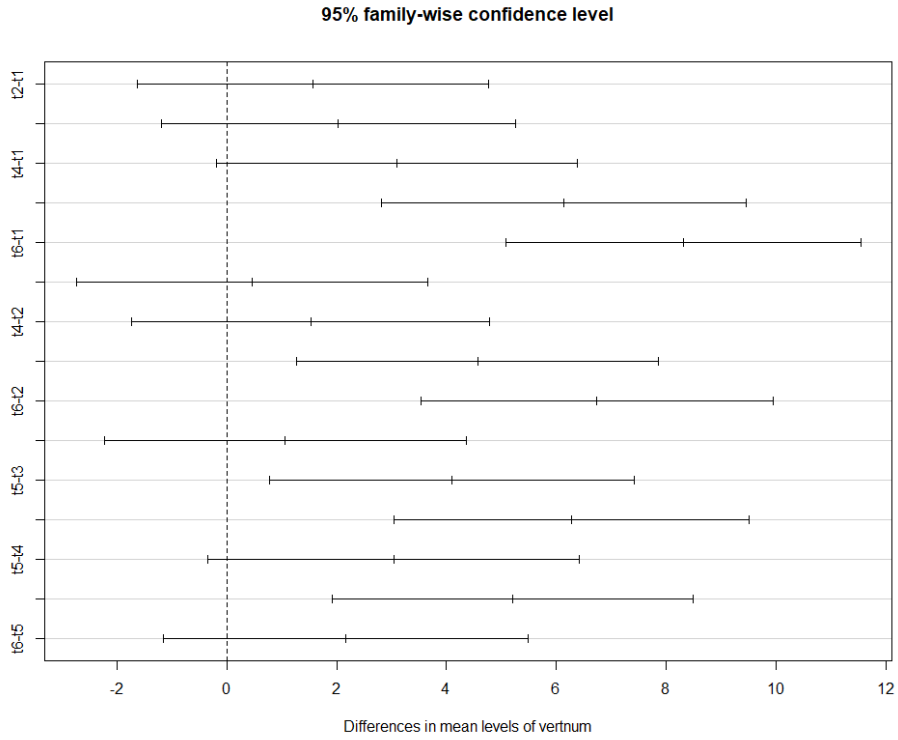


**Figure 39:** Results for the Tukey's HSD illustrating differences among the upper thoracic vertebrae (T1-T6) Maximum Spinous Process Length measurement.

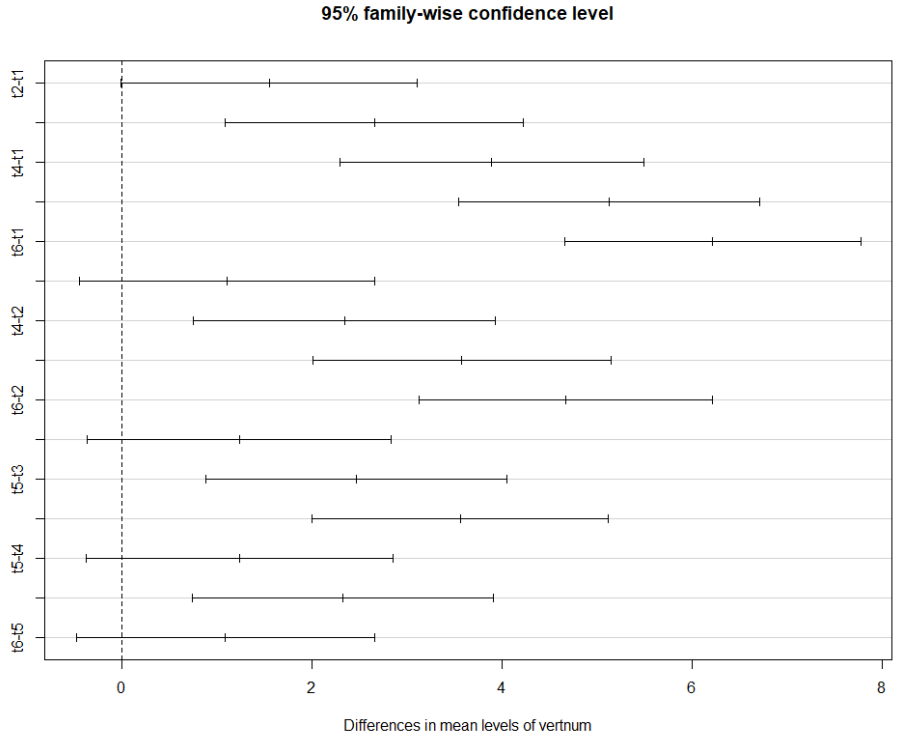


**Figure 40:** Results for the Tukey's HSD illustrating sub-type differences and variable overlap for the upper thoracic vertebrae (T1-T6) Maximum Inferior Sagittal Length measurement.

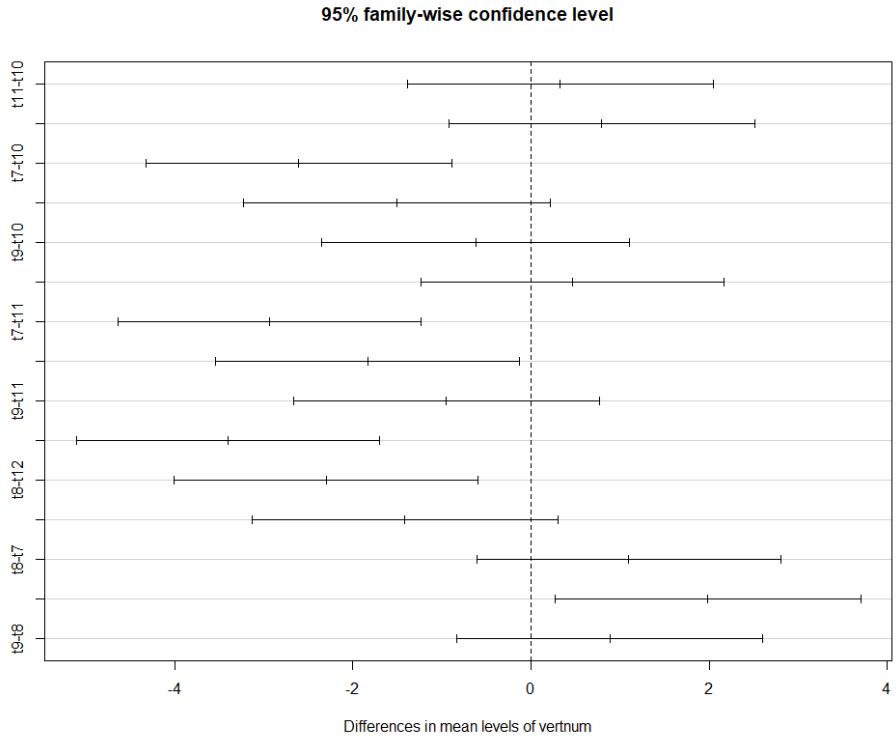


**Figure 41:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Superior Sagittal Length measurement.

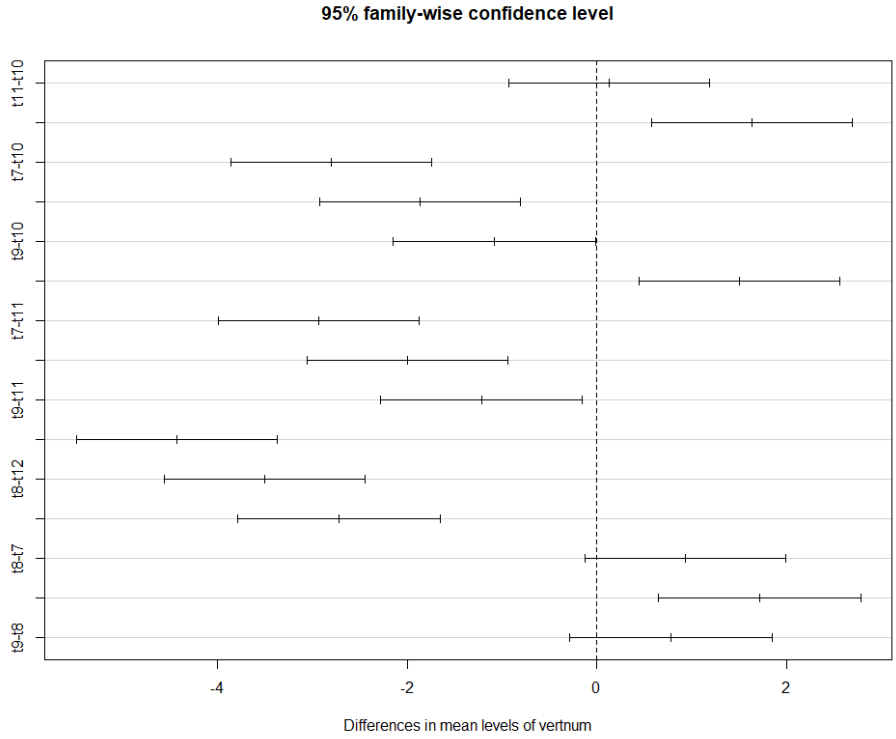


**Figure 42:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Centroid Height measurement.

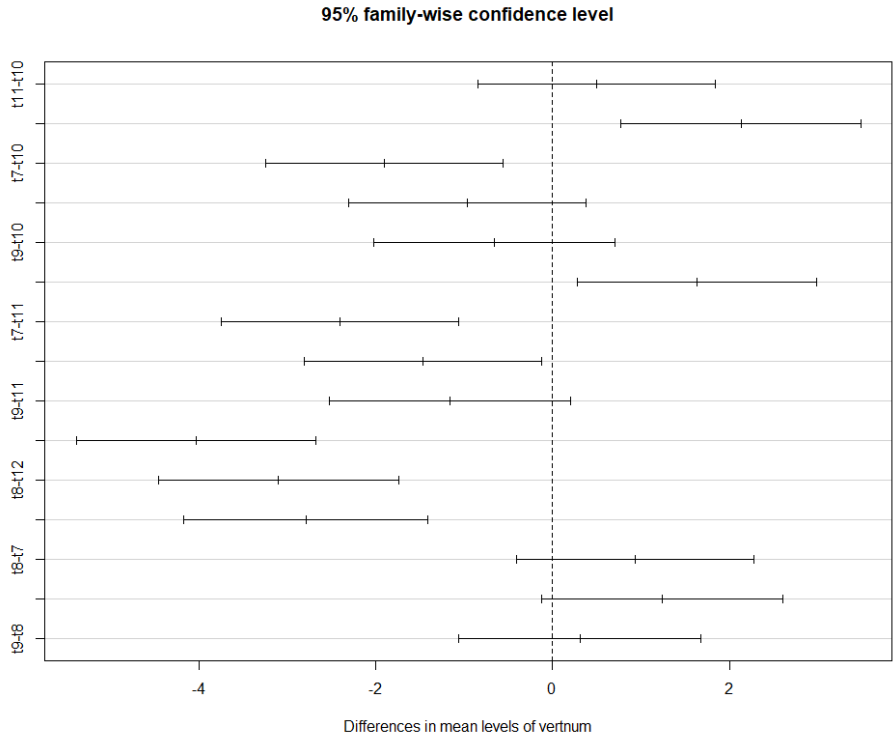


**Figure 43:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Anterior Height measurement.

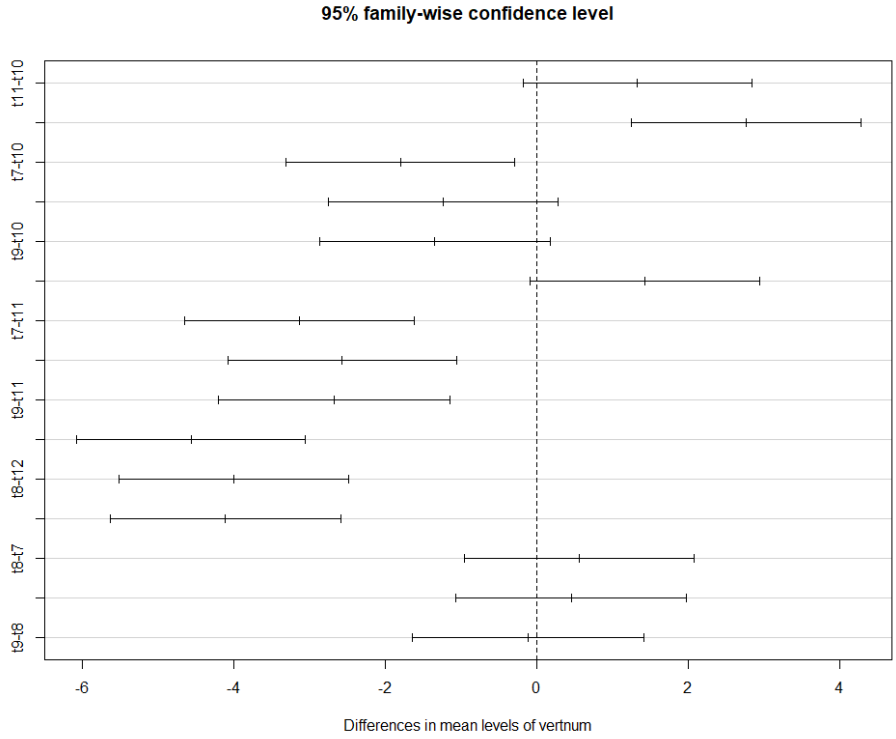


**Figure 44:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Posterior Height measurement.

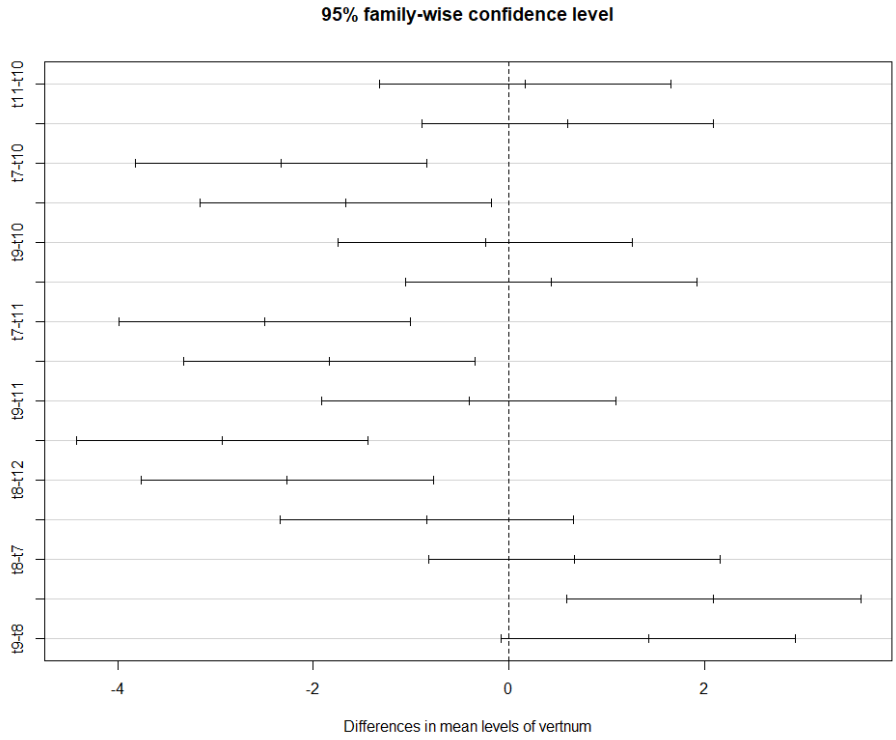


**Figure 45:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Superior Articular Length measurements.

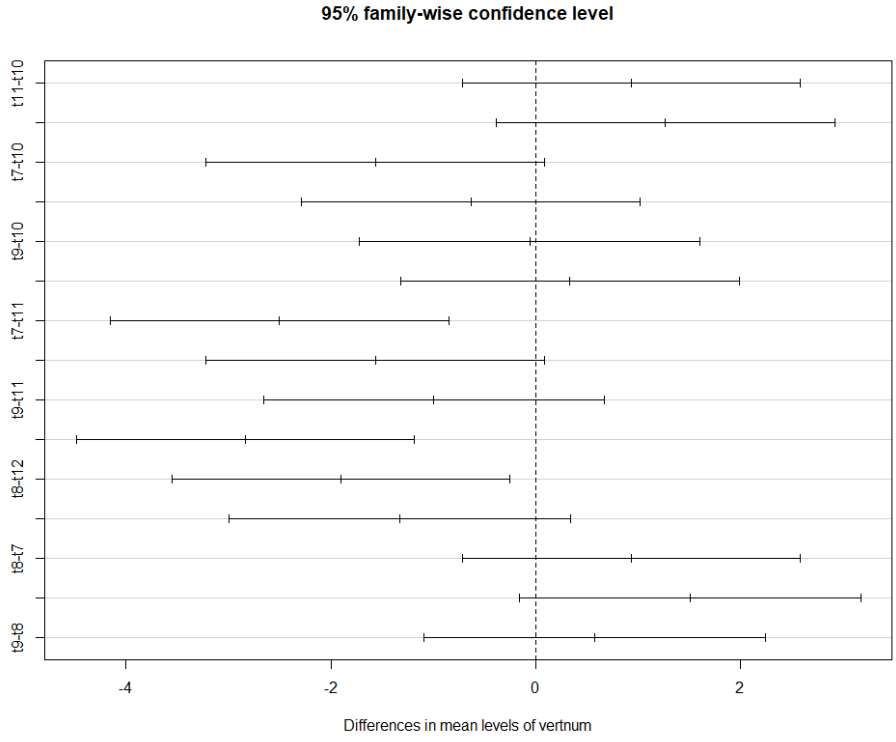


**Figure 46:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Superior Articular Length measurement.

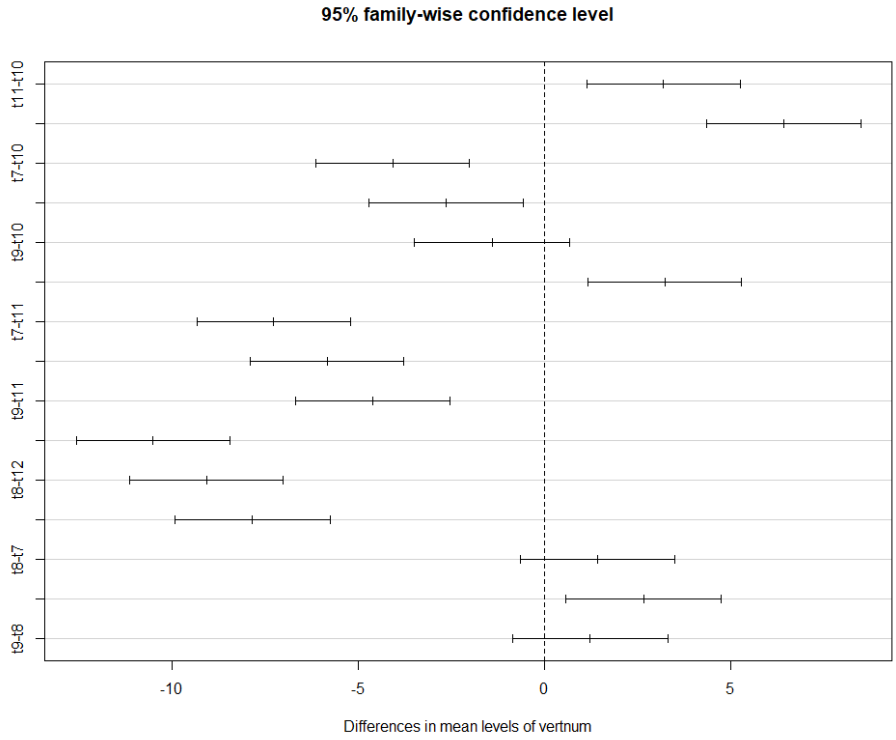


**Figure 47:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Superior Articular Width measurement.

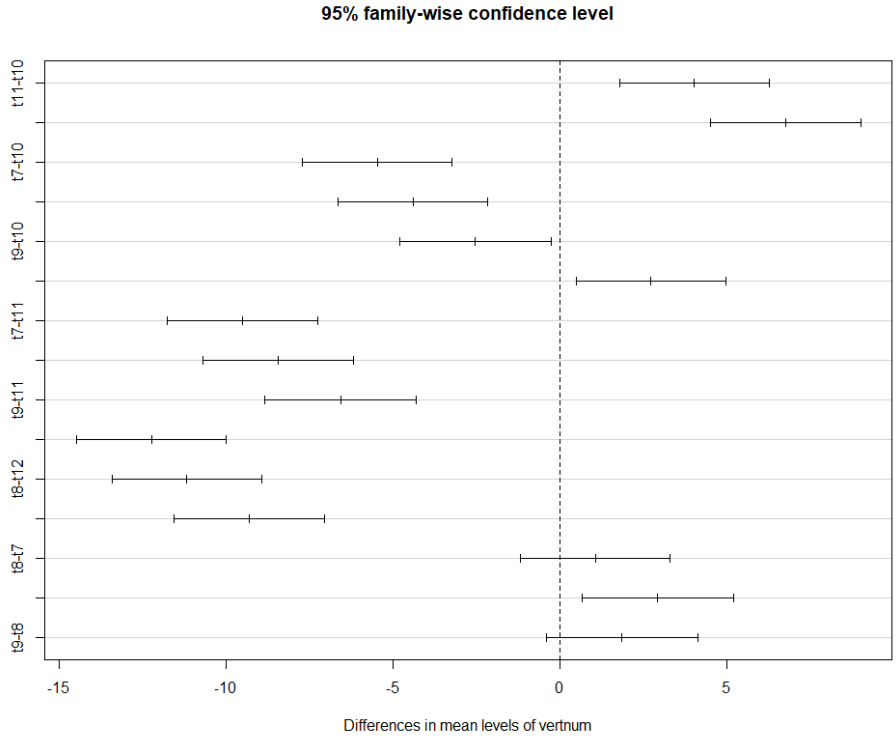


**Figure 48:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Inferior Articular Width measurement.

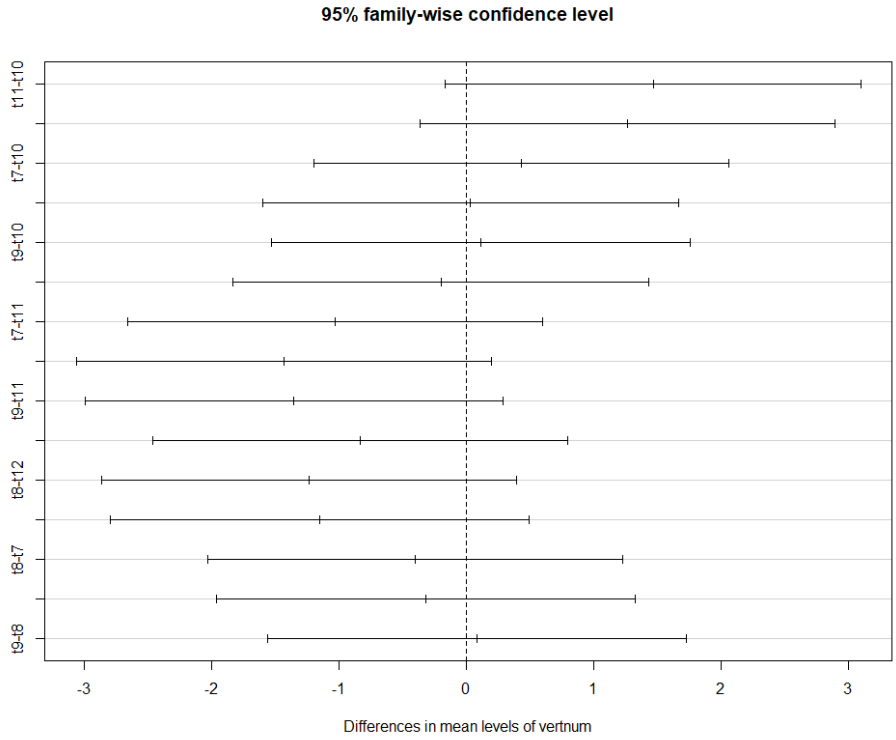


**Figure 49:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Foramen Sagittal Length measurement.

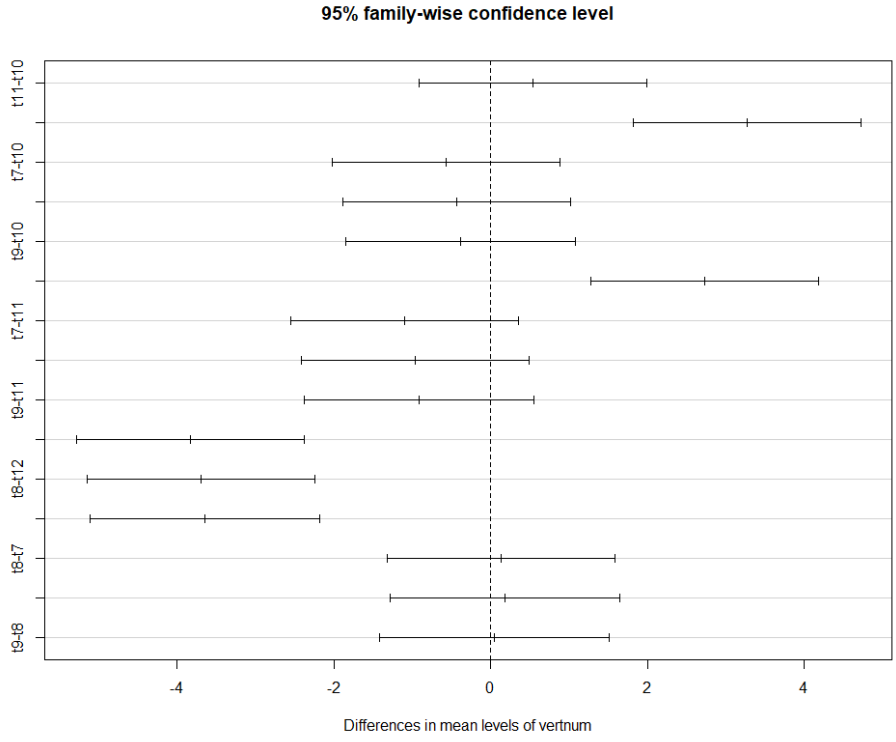


**Figure 50:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Foramen Coronal Width measurement.

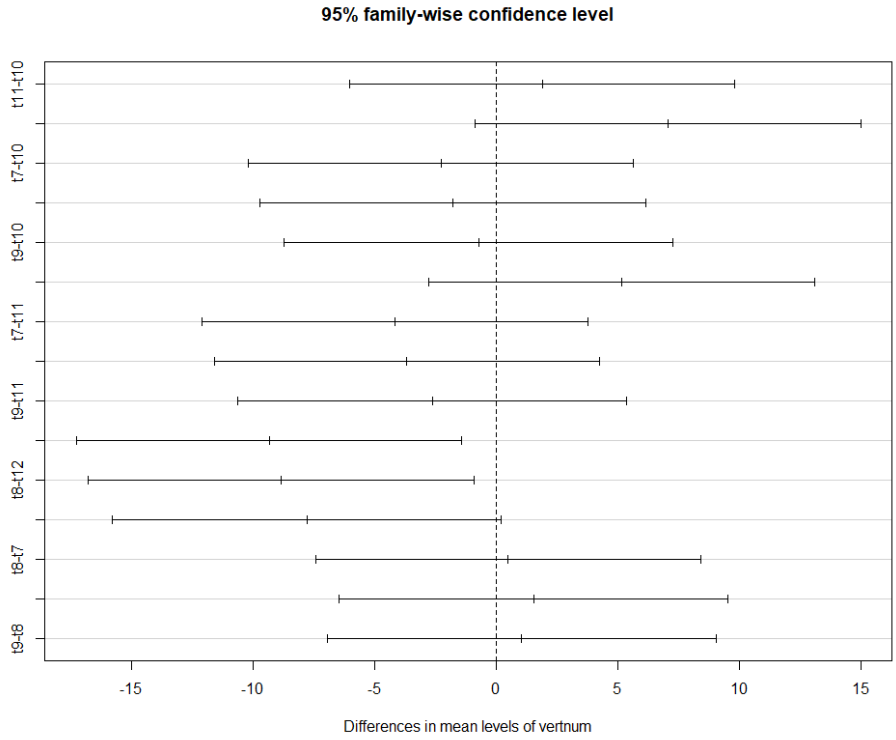


**Figure 51:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Pedicle Height measurement.

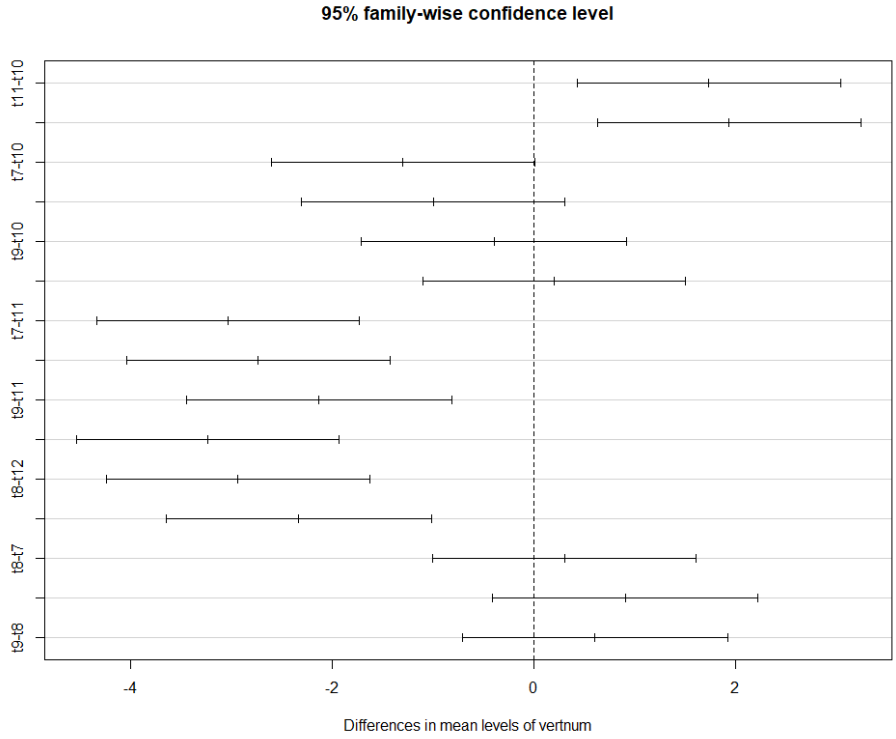


**Figure 52:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Pedicle Width measurement.

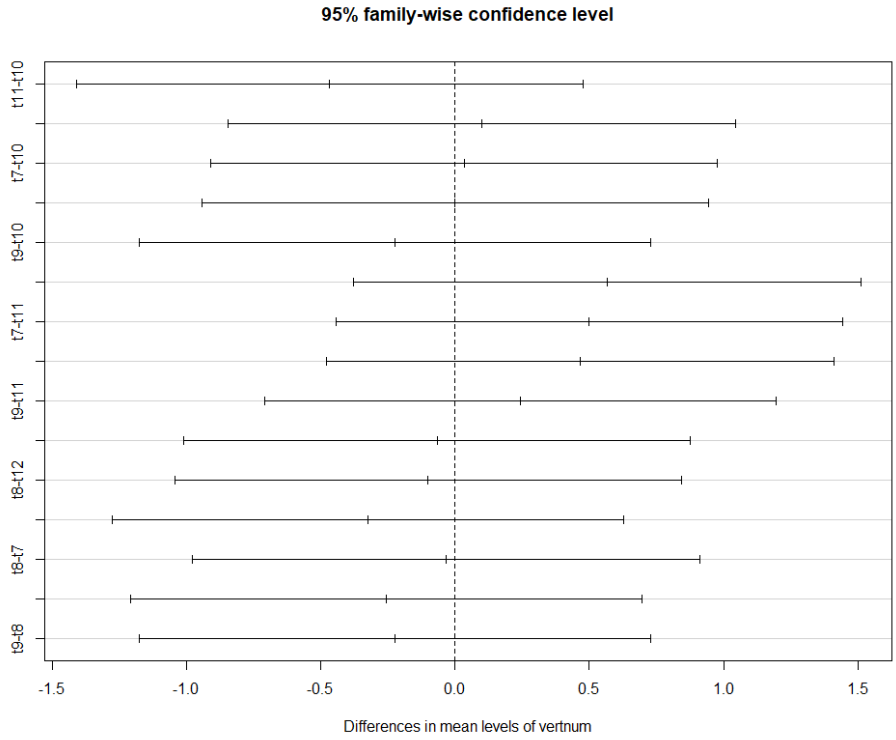


**Figure 53:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Pedicle Length measurement.

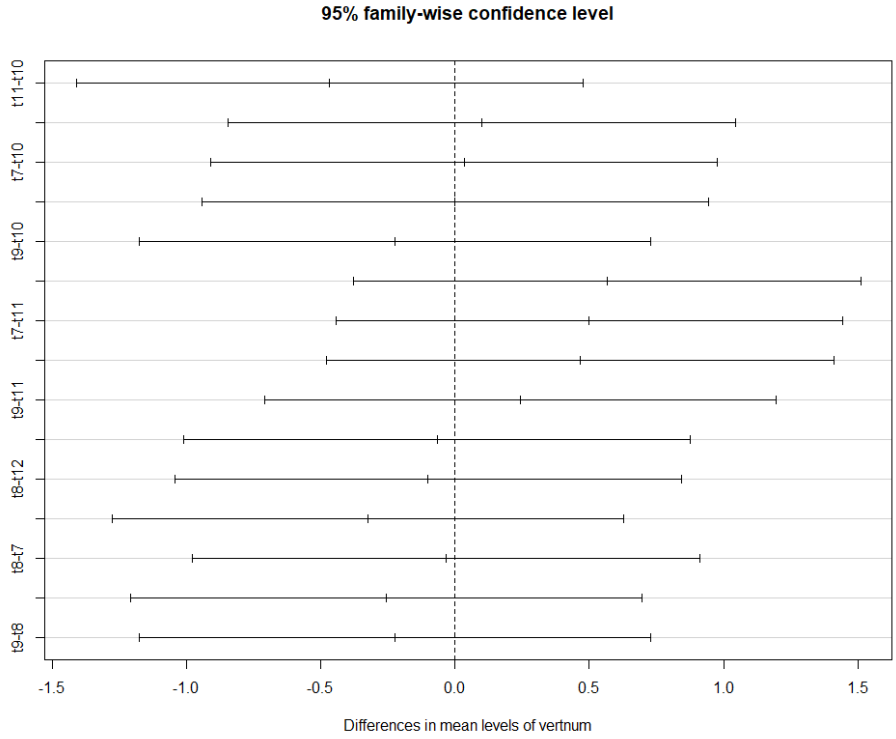


**Figure 54:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Transverse Process Length measurement.

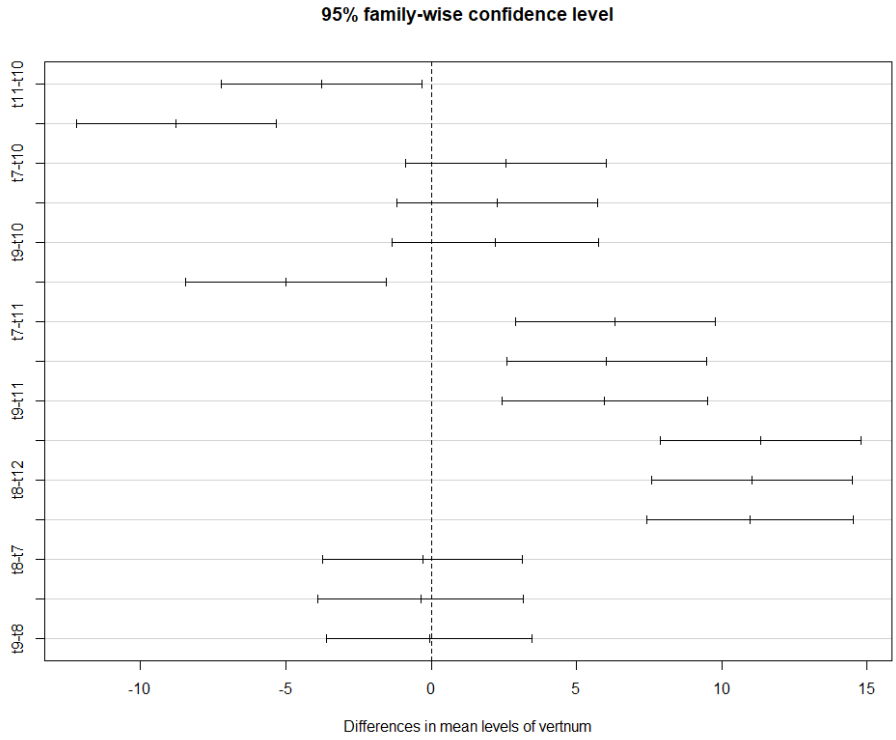


**Figure 55:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Transverse Process Width measurement.

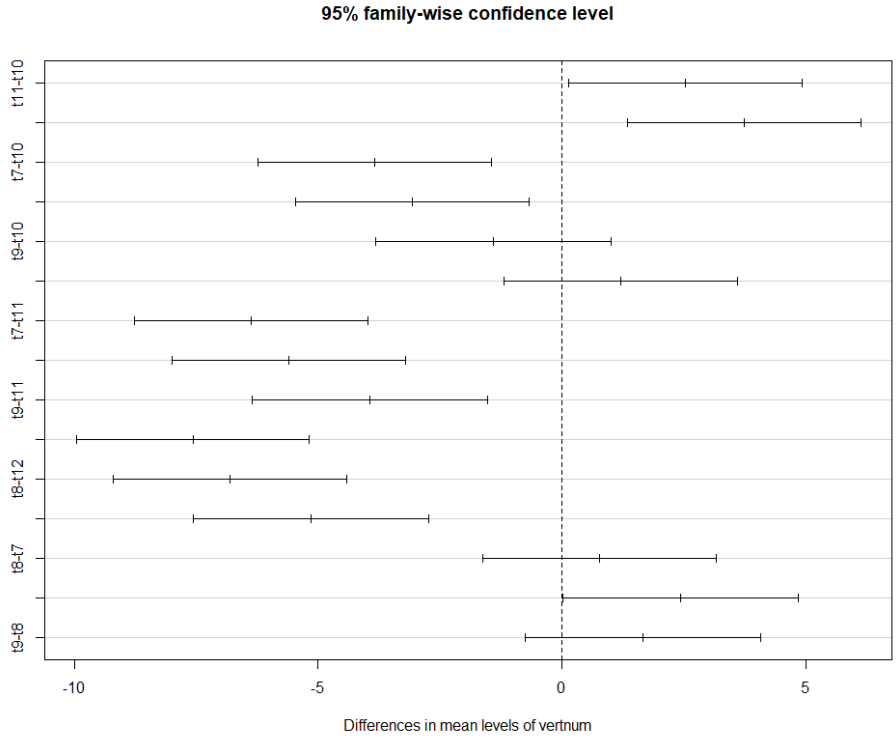


**Figure 56:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Superior Articular Process Width measurement.

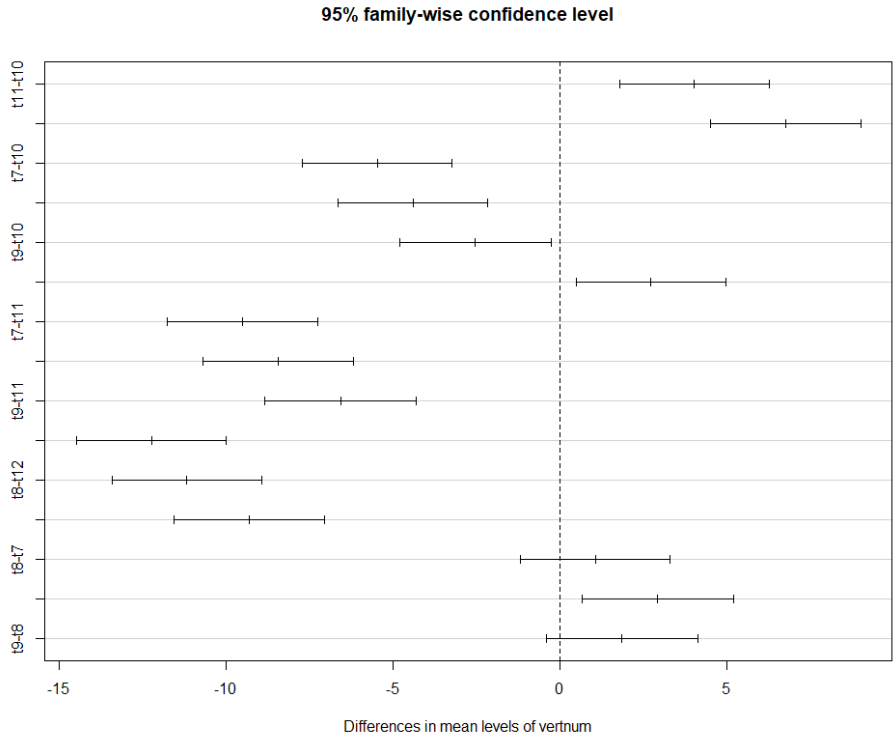


**Figure 57:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Inferior Articular Process Width measurement.

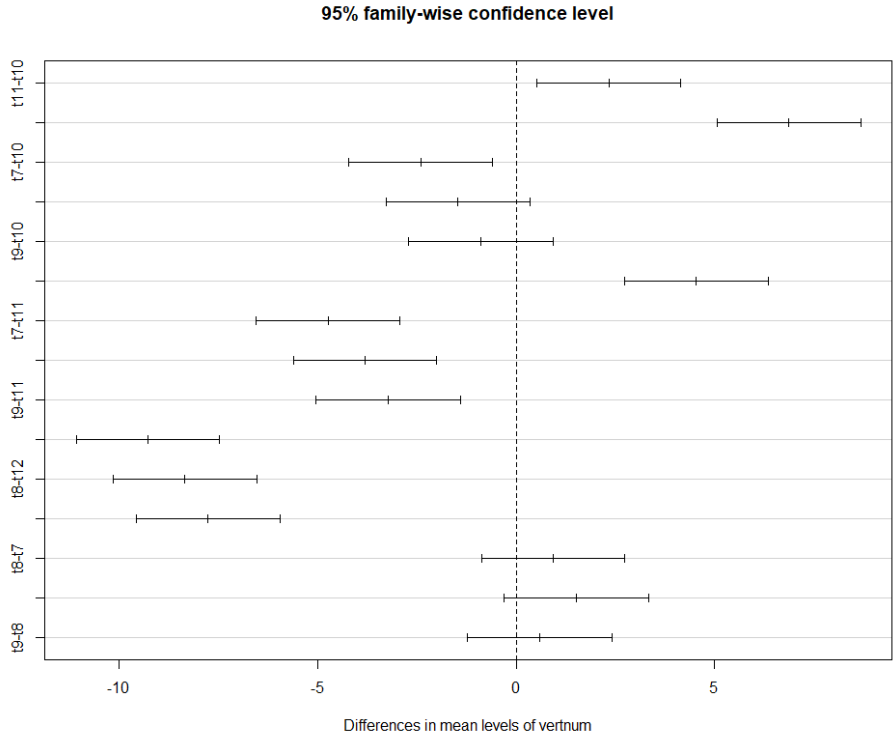


**Figure 58:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Articular Process Height measurement.

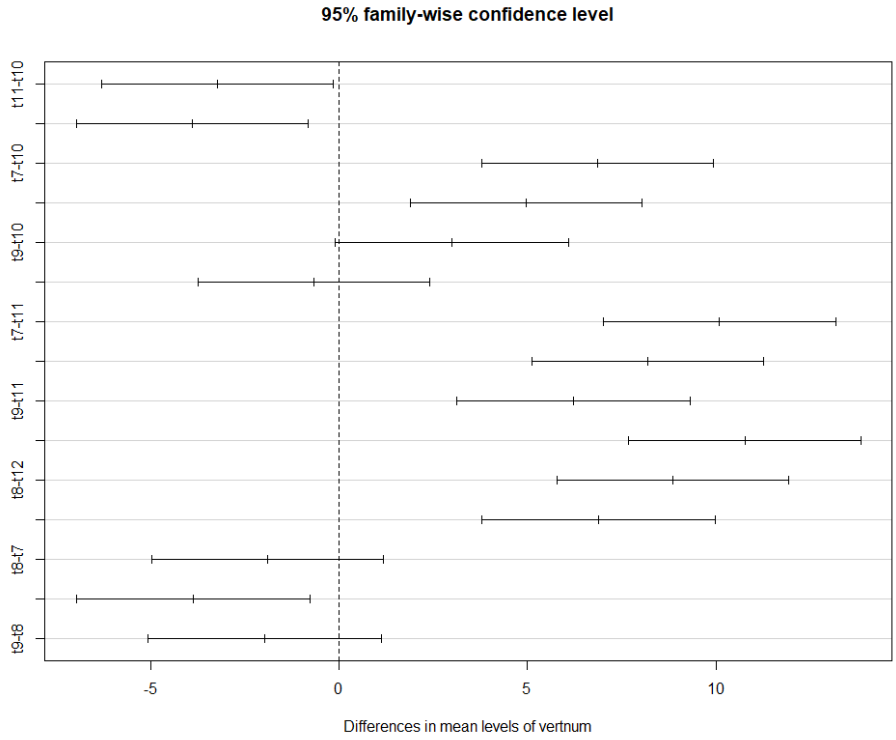


**Figure 59:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Spinous Process Length measurement.

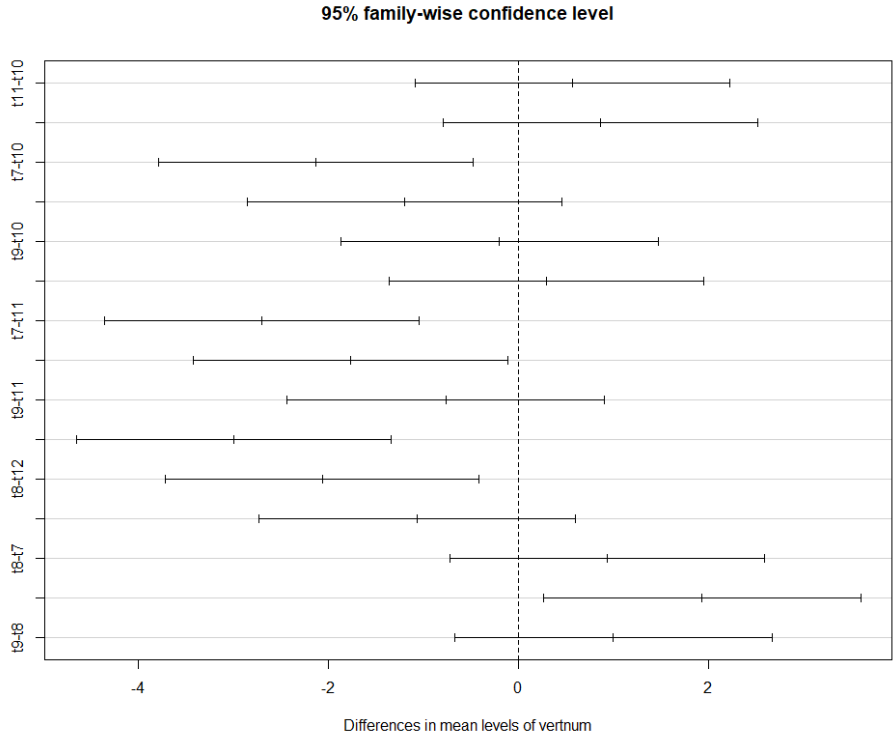


**Figure 60:** Results for the Tukey's HSD illustrating differences among the lower thoracic vertebrae (T7-T12) Maximum Inferior Sagittal Length measurement.

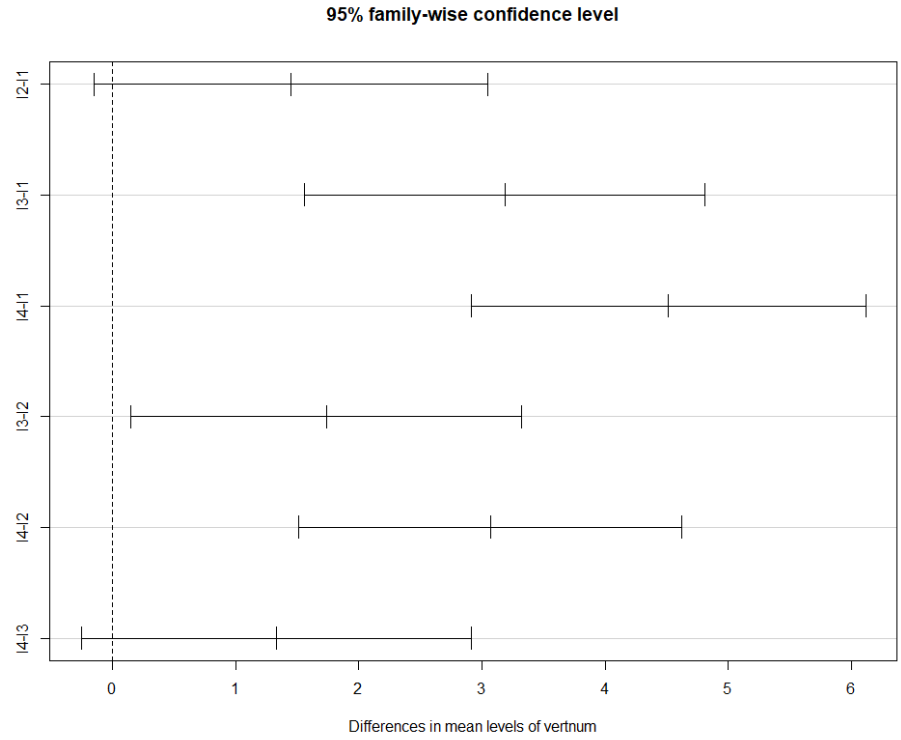


**Figure 61:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Superior Sagittal Length measurement.

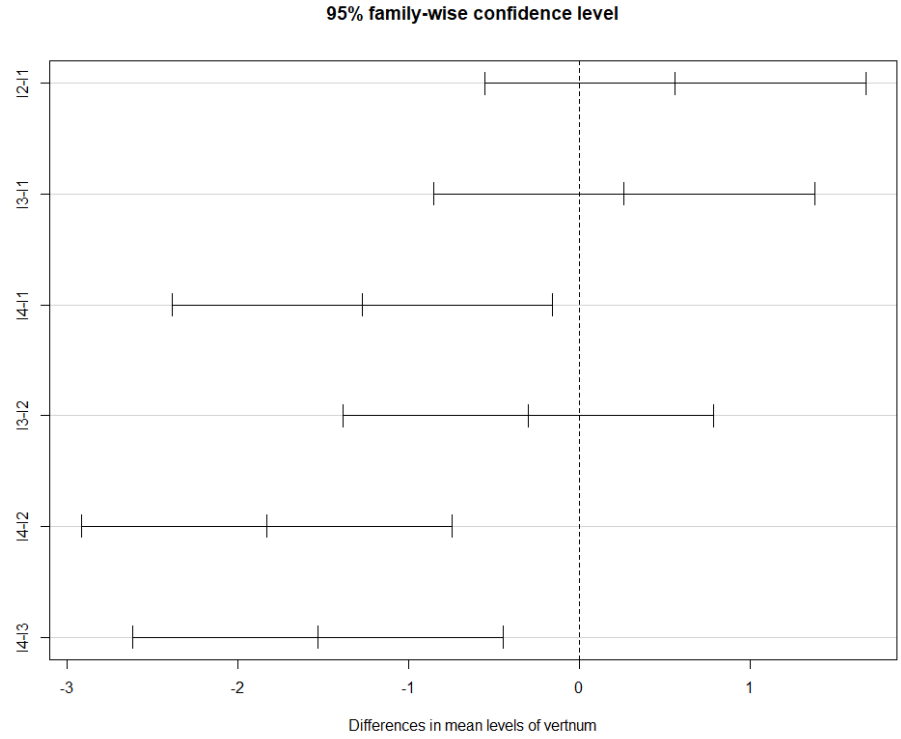


**Figure 62:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Centroid Height measurement.

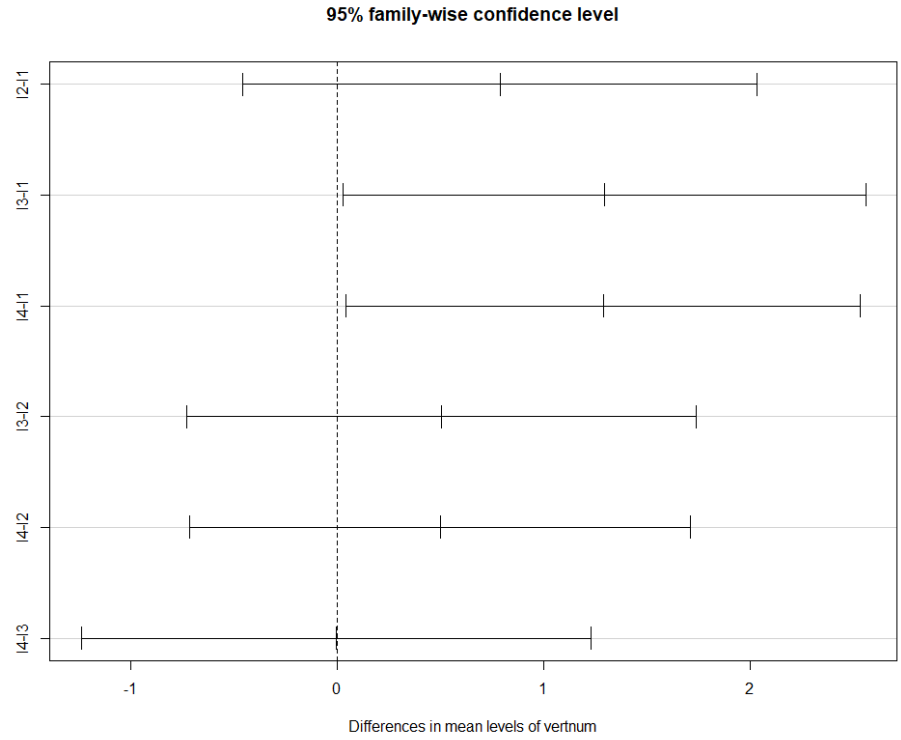


**Figure 63:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Anterior Height measurement.

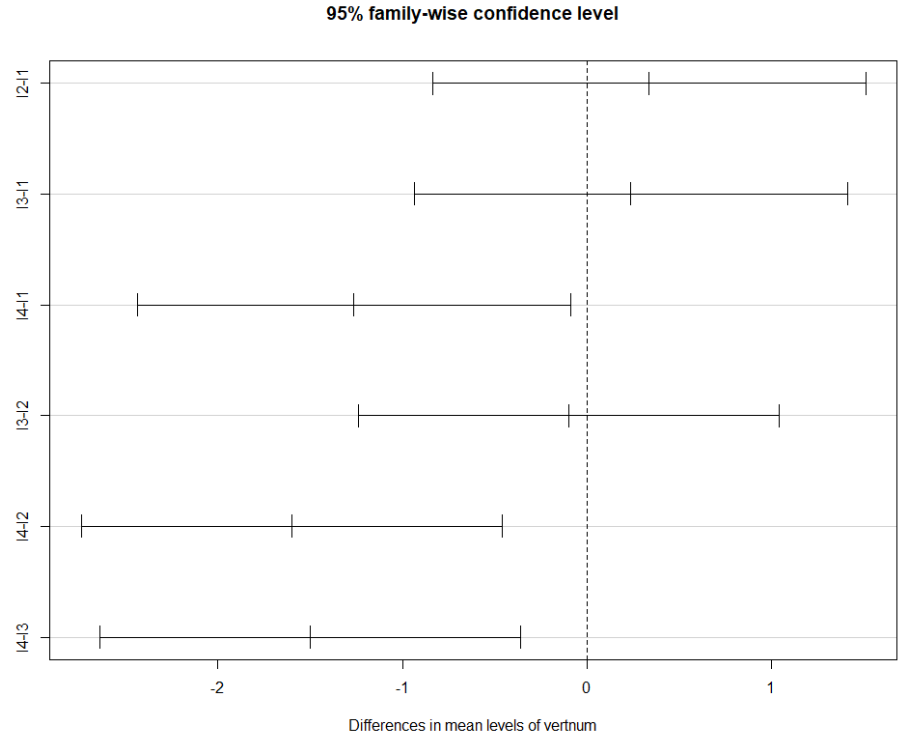


**Figure 64:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Posterior Height measurement.

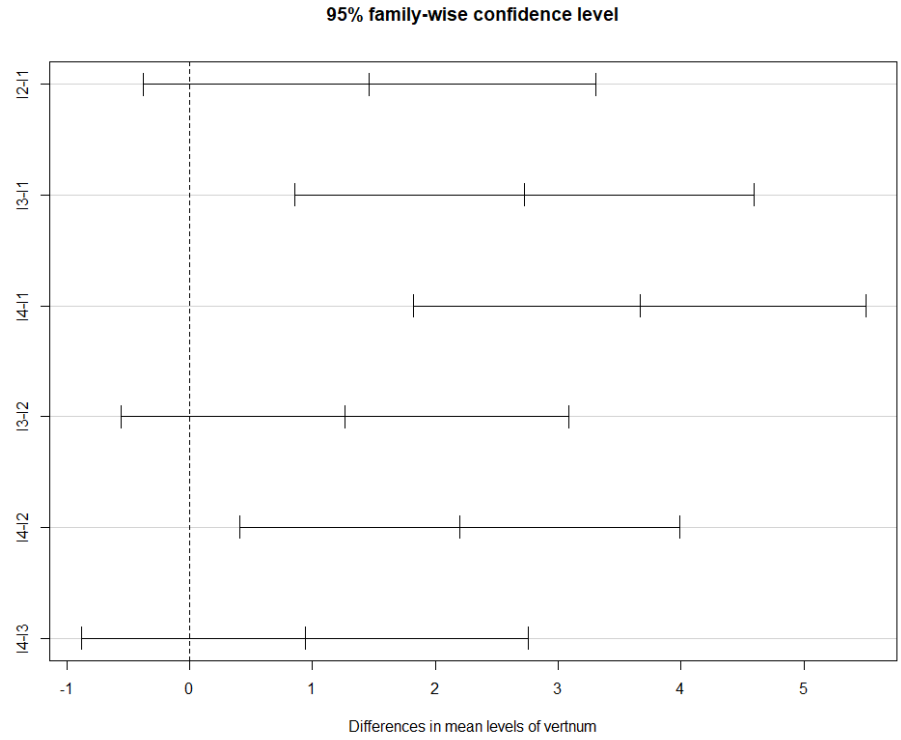


**Figure 65:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Superior Articular Length measurement.

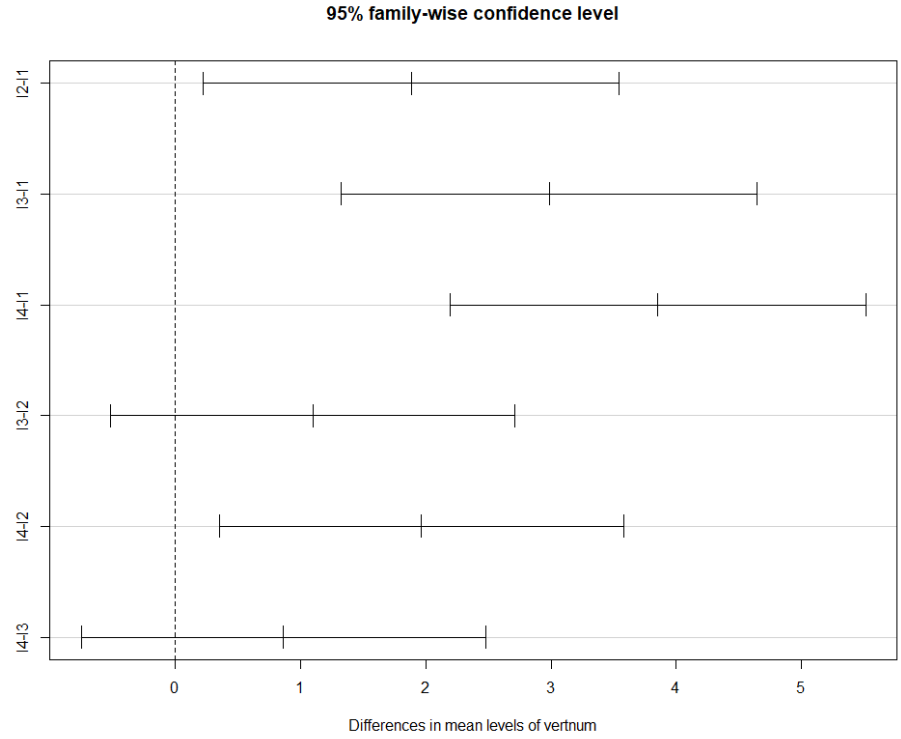


**Figure 66:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Superior Articular Length measurement.

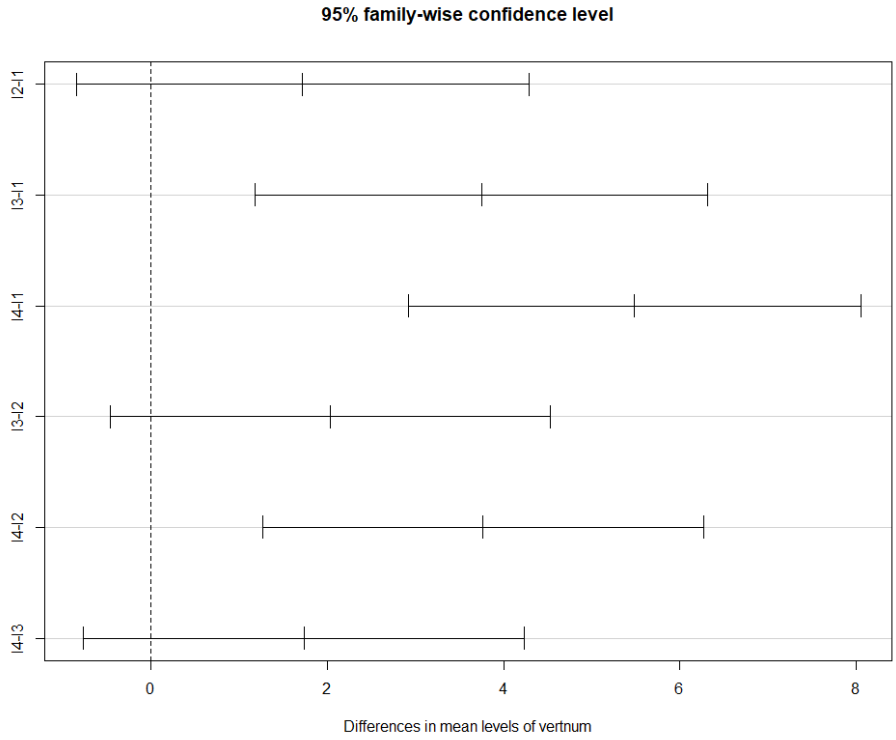


**Figure 67:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Superior Articular Width measurement.

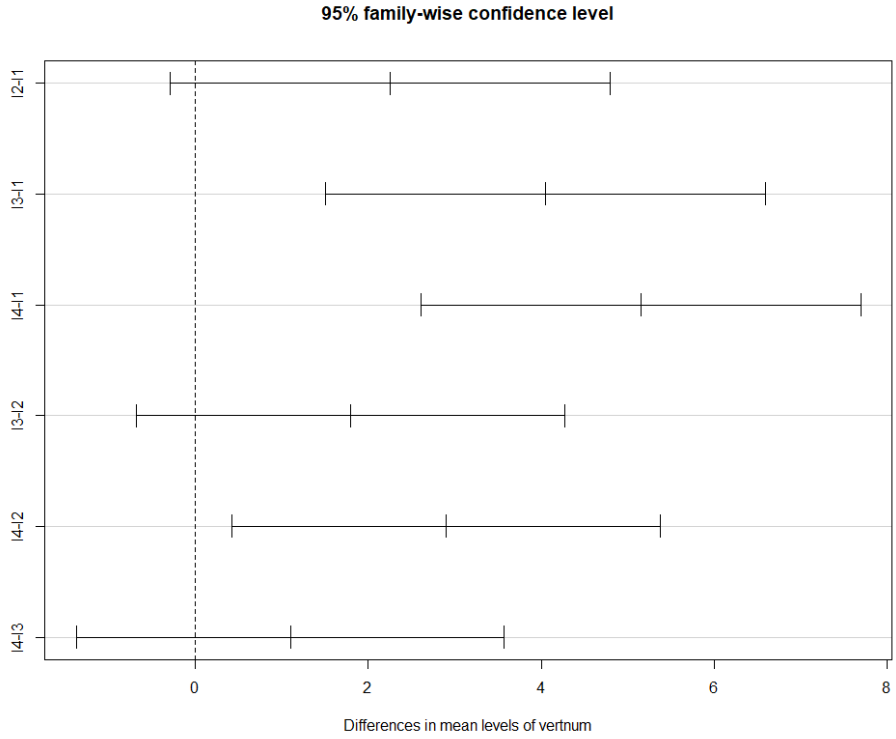


**Figure 68:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Inferior Articular Width measurement.

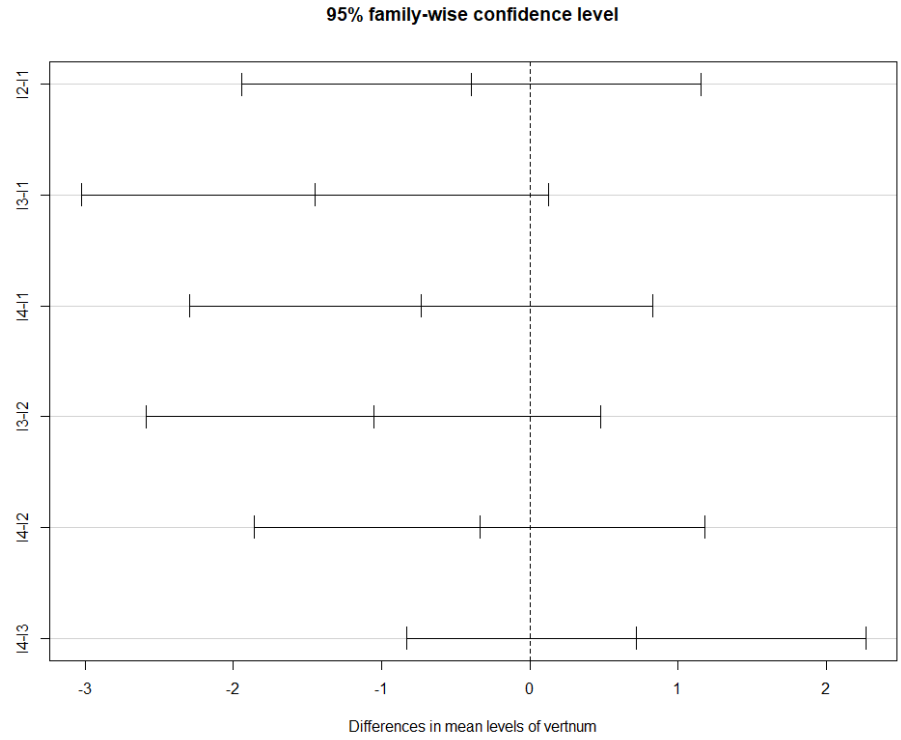


**Figure 69:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Foramen Sagittal Length measurement.

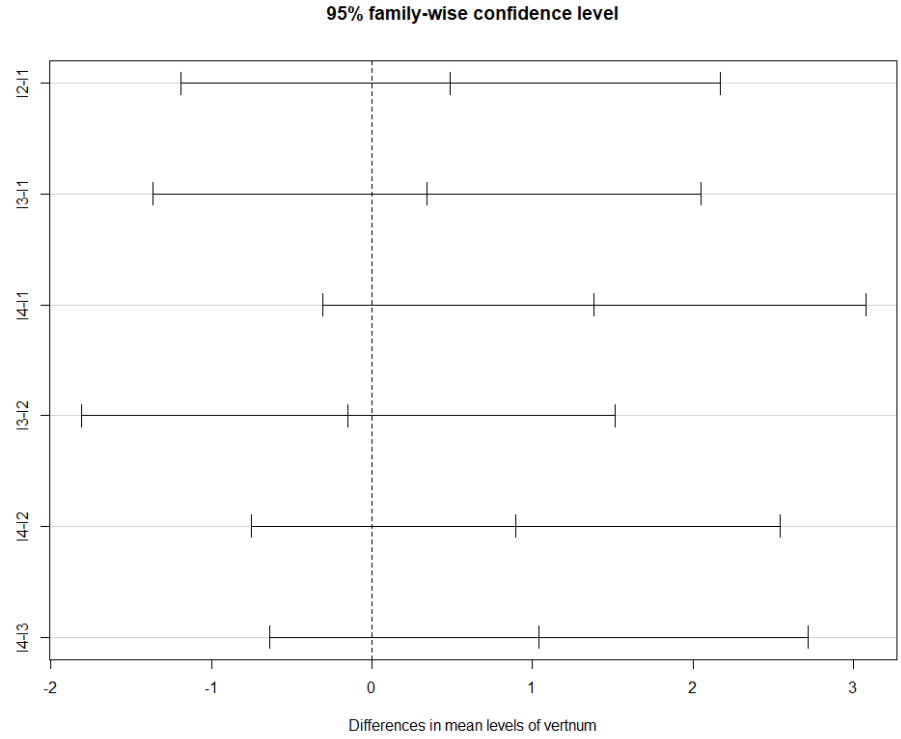


**Figure 70:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Foramen Coronal Width measurement.

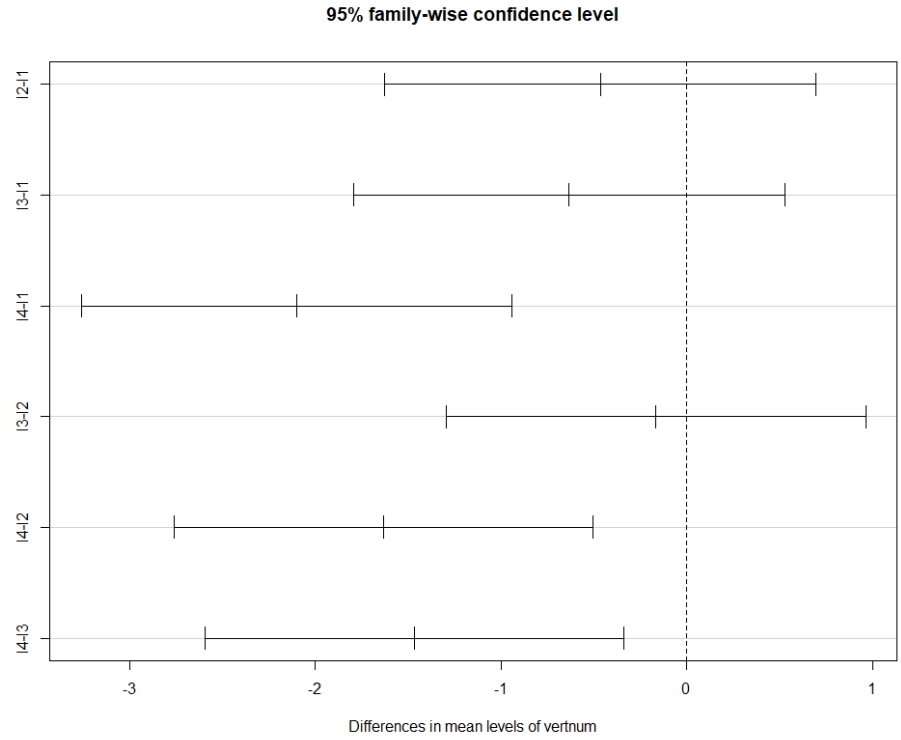


**Figure 71:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Pedicle Height measurement.

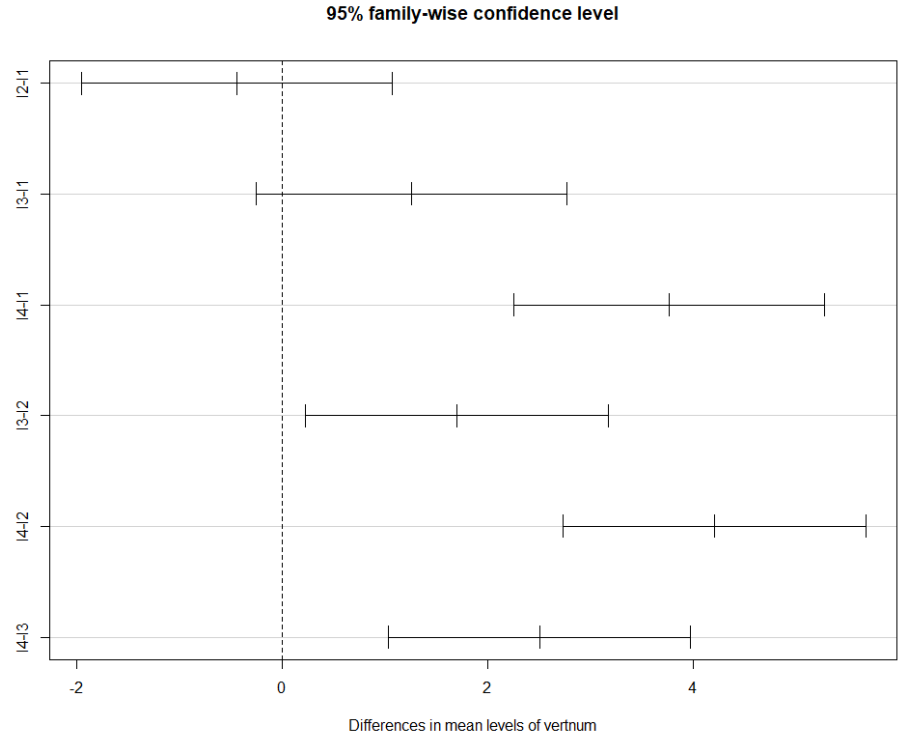


**Figure 72:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Pedicle Width measurement.

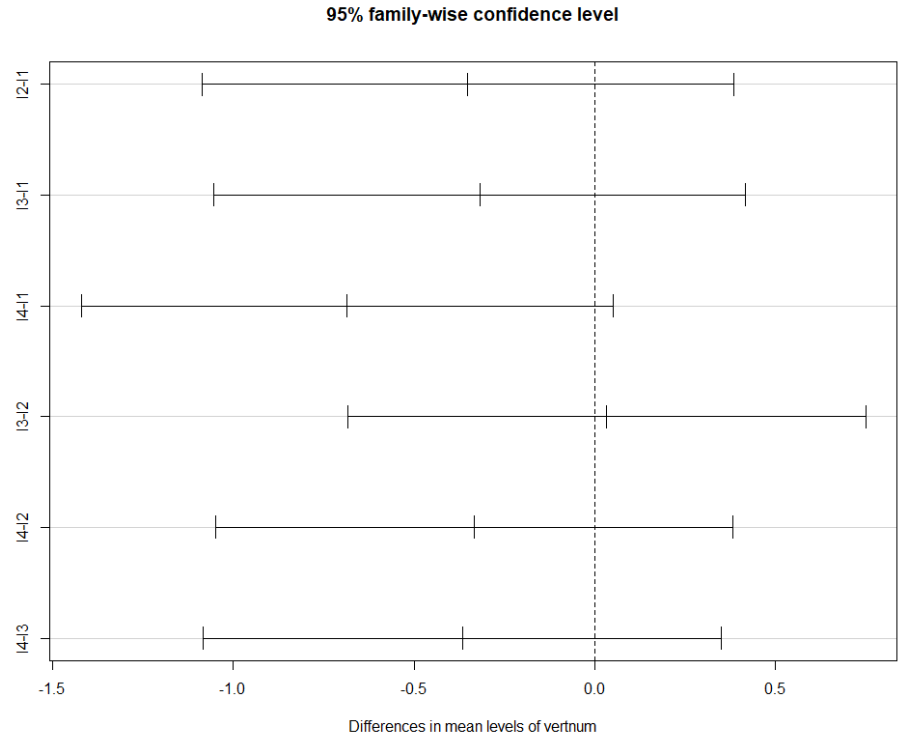


**Figure 73:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Pedicle Length measurement.

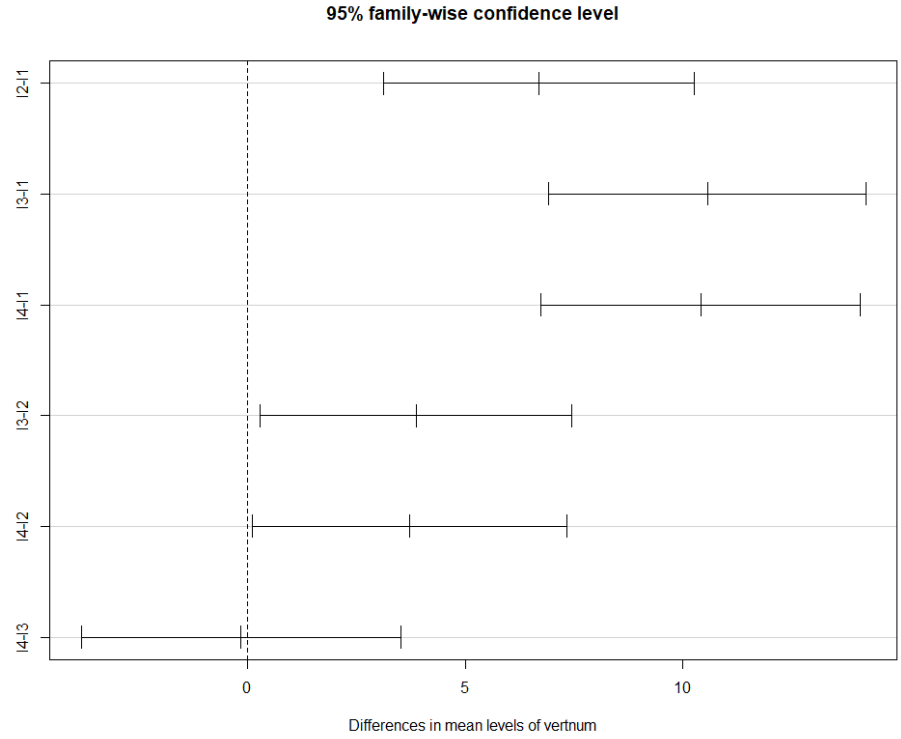


**Figure 74:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Transverse Process Length measurement.

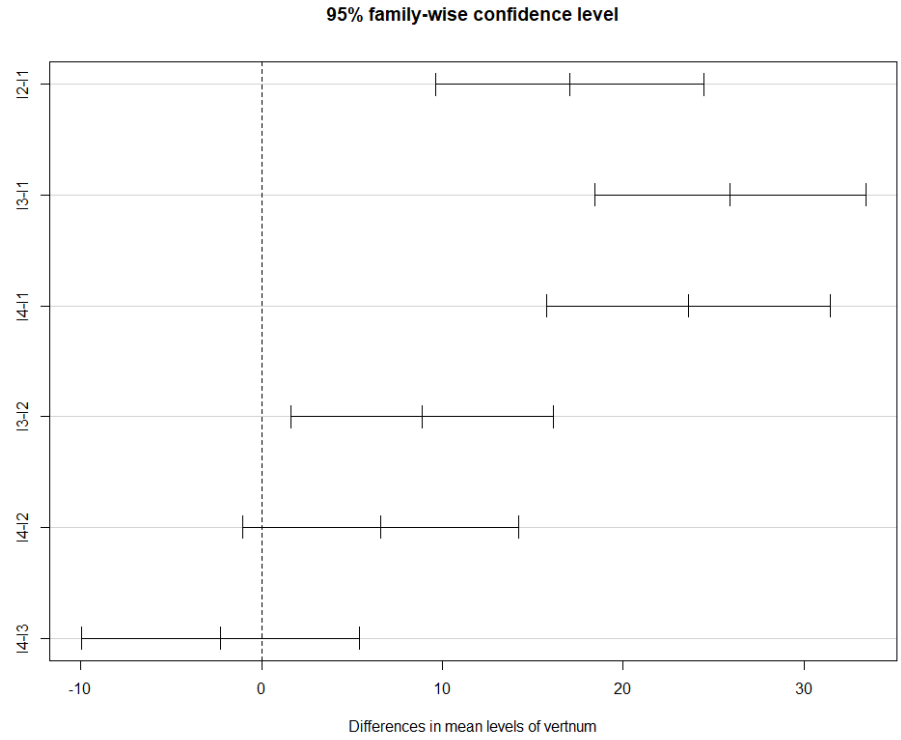


**Figure 75:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Transverse Process Width measurement.

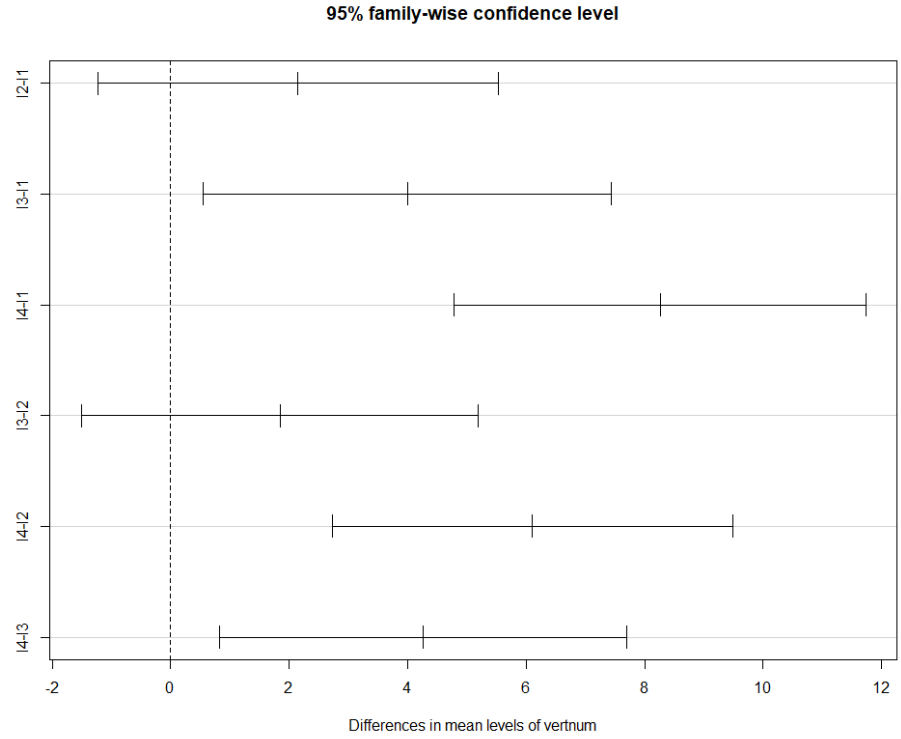


**Figure 76:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Superior Articular Process Width measurement.

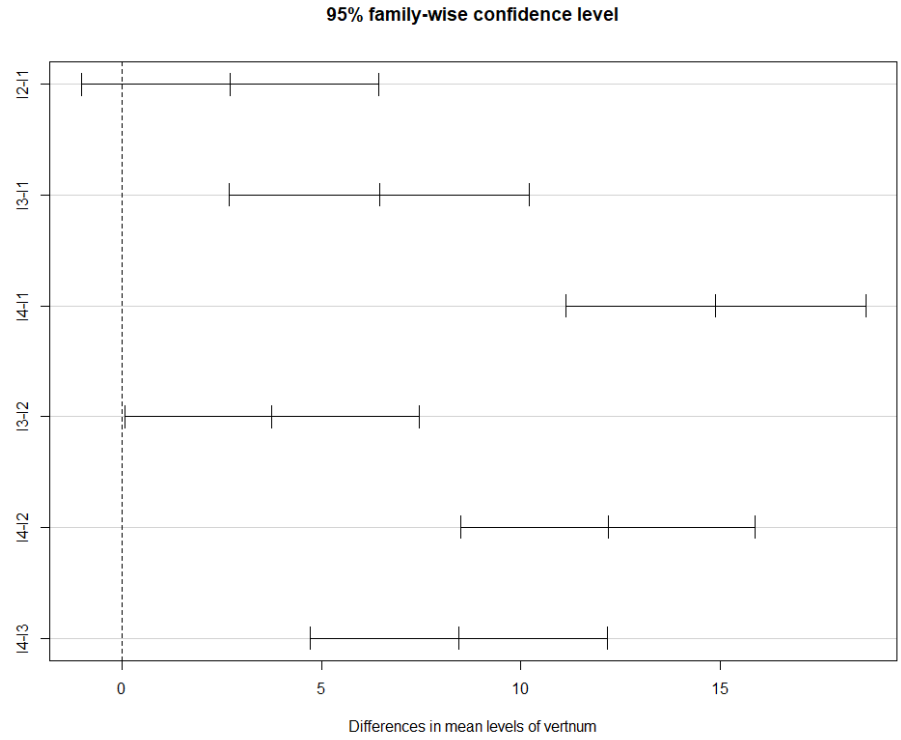


**Figure 77:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Inferior Articular Process Width measurement.

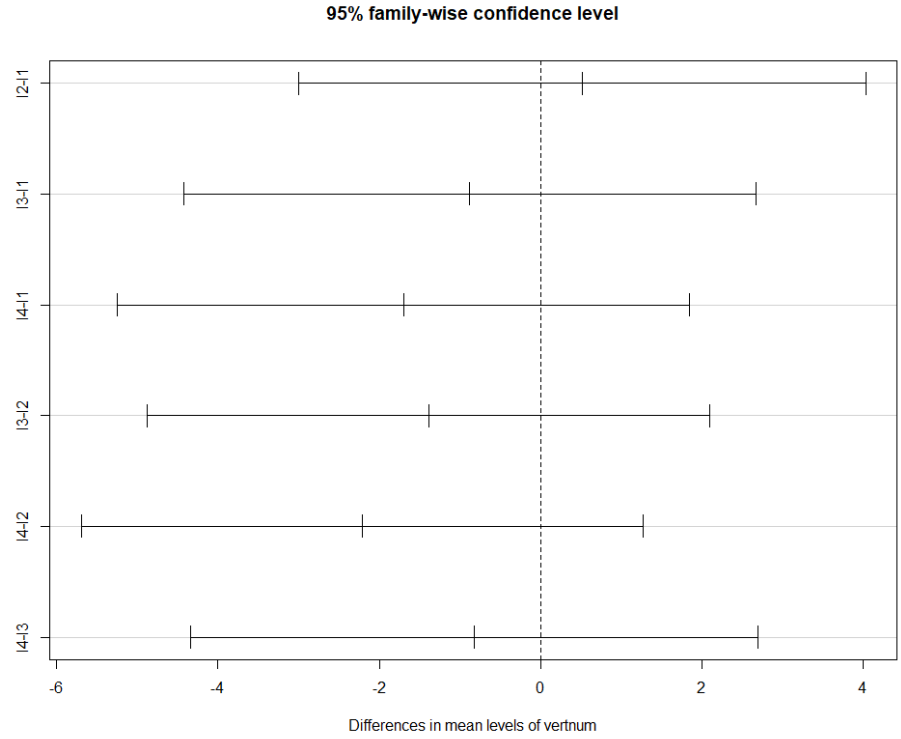


**Figure 78:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Articular Process Height measurement.

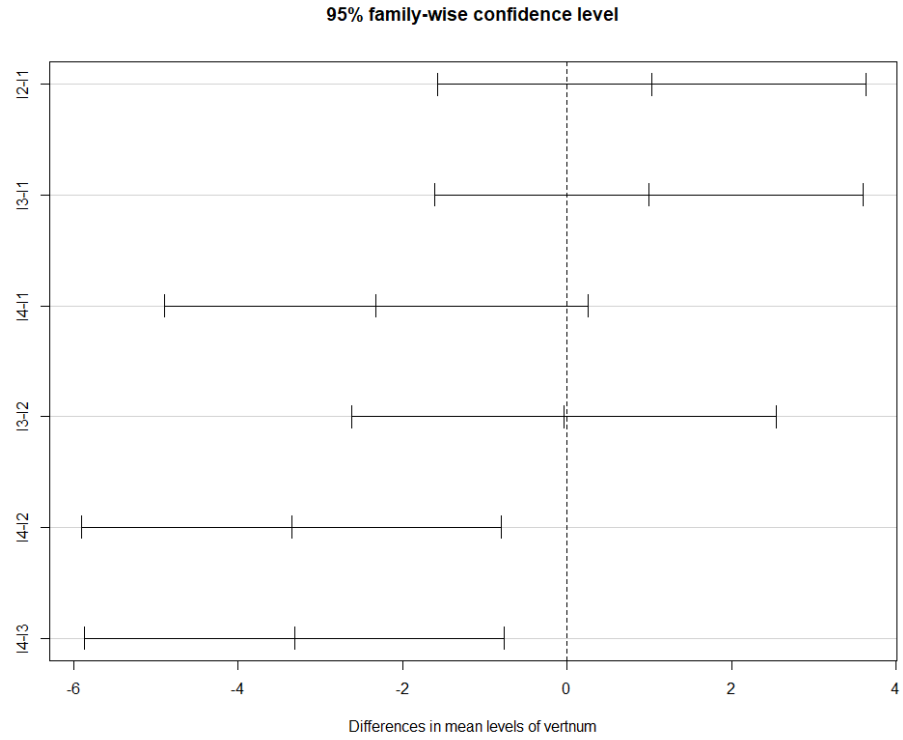


**Figure 79:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Spinous Process Length measurement.

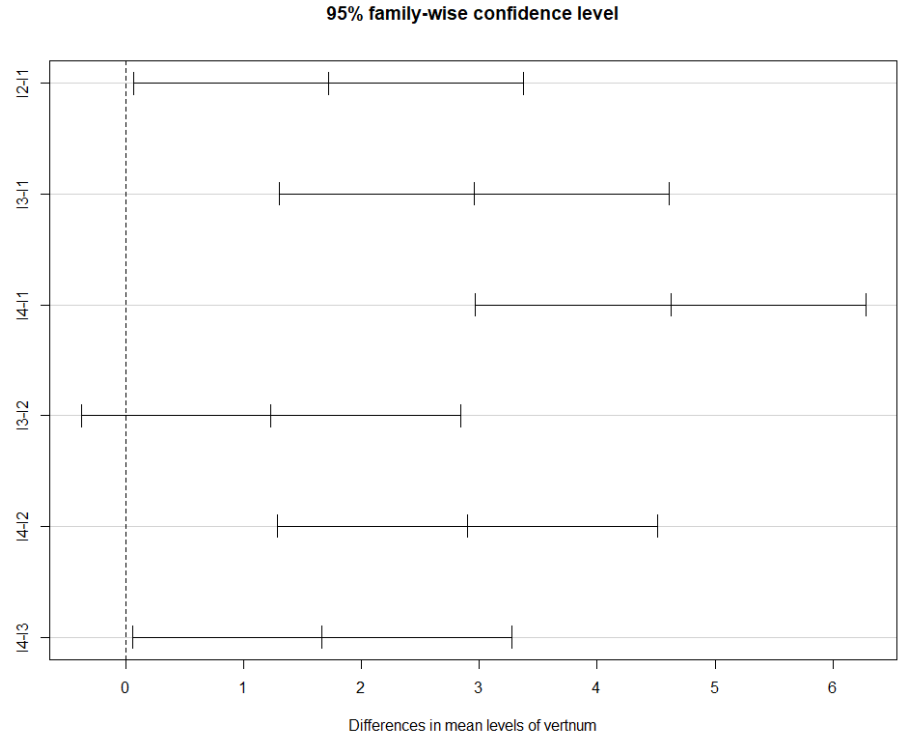


**Figure 80:** Results for the Tukey's HSD illustrating differences among the lumbar vertebrae (L1-L4) Maximum Inferior Sagittal Length measurement.

# APPENDIX IV – DESCRIPTIVE ANALYSIS

**Tables A1 – A4:** Summary statistics of the cervical vertebrae (C3 – C6) showing the means and standard deviations for population affinity and sex.

**Table A1:** Summary statistics of the cervical vertebrae (C3-C6) showing the means and standard deviation for black South Africans. Refer to Appendix I for measurement names and definitions.

| | C3 | | | C4 | | | C5 | | | C6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 55 | 15.24 | 1.51 | 58 | 15.28 | 1.65 | 58 | 15.22 | 1.93 | 55 | 15.69 | 1.78 |
| **XAH** | 55 | 12.60 | 1.47 | 57 | 12.74 | 1.17 | 57 | 11.88 | 1.27 | 55 | 12.04 | 1.05 |
| **XPH** | 55 | 12.85 | 1.19 | 58 | 12.62 | 1.04 | 58 | 12.38 | 1.11 | 55 | 12.55 | 1.12 |
| **XALs** | 54 | 12.43 | 1.31 | 58 | 12.78 | 1.53 | 58 | 12.72 | 1.37 | 56 | 12.98 | 1.46 |
| **XALi** | 55 | 13.20 | 1.38 | 57 | 13.51 | 1.76 | 57 | 13.93 | 1.50 | 55 | 13.76 | 1.53 |
| **XAWs** | 54 | 17.19 | 1.68 | 59 | 18.24 | 1.45 | 58 | 19.26 | 2.00 | 56 | 19.89 | 1.87 |
| **XAWi** | 54 | 16.52 | 1.37 | 58 | 17.14 | 1.49 | 58 | 18.17 | 2.14 | 56 | 19.68 | 2.20 |
| **XPL** | 54 | 4.44 | 0.77 | 58 | 4.50 | 0.73 | 57 | 4.95 | 0.85 | 56 | 5.30 | 0.85 |
| **TPL** | 52 | 31.63 | 2.37 | 57 | 31.79 | 2.40 | 57 | 32.56 | 2.58 | 52 | 34.31 | 2.95 |
| **XTPW** | 49 | 49.98 | 3.89 | 53 | 51.00 | 3.87 | 50 | 53.72 | 4.21 | 39 | 58.38 | 5.14 |
| **XAPi** | 54 | 47.52 | 3.18 | 58 | 49.26 | 3.24 | 58 | 50.88 | 3.38 | 54 | 50.17 | 3.95 |
| **APH** | 54 | 19.91 | 1.93 | 59 | 20.53 | 1.99 | 58 | 20.57 | 2.07 | 55 | 21.95 | 1.85 |
| **XSPL** | 54 | 14.87 | 3.07 | 56 | 14.50 | 2.65 | 58 | 17.29 | 3.24 | 55 | 24.13 | 4.68 |
| **XSLi** | 55 | 16.22 | 1.82 | 58 | 16.38 | 2.05 | 58 | 16.57 | 1.82 | 56 | 16.61 | 1.80 |

**Table A2:** Summary statistics of the cervical vertebrae (C3-C6) showing the means and standard deviation for white South Africans. Refer to Appendix I for measurement names and definitions.

| | C3 | | | C4 | | | C5 | | | C6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 51 | 15.06 | 1.71 | 57 | 15.89 | 1.85 | 56 | 15.91 | 2.01 | 51 | 17.35 | 2.30 |
| **XAH** | 52 | 14.02 | 1.32 | 53 | 13.77 | 1.58 | 54 | 13.43 | 1.44 | 50 | 12.88 | 1.21 |
| **XPH** | 50 | 14.18 | 1.29 | 56 | 13.88 | 1.28 | 56 | 13.84 | 1.36 | 50 | 13.80 | 1.18 |
| **XALs** | 52 | 12.96 | 1.41 | 57 | 13.46 | 1.36 | 54 | 13.54 | 1.67 | 50 | 14.40 | 1.70 |
| **XALi** | 50 | 13.96 | 1.51 | 54 | 14.28 | 1.65 | 55 | 15.11 | 2.42 | 50 | 15.38 | 1.46 |
| **XAWs** | 52 | 18.58 | 1.58 | 58 | 19.78 | 1.81 | 56 | 20.77 | 1.94 | 51 | 22.82 | 2.00 |
| **XAWi** | 52 | 17.71 | 1.93 | 53 | 18.75 | 1.75 | 53 | 19.32 | 2.12 | 50 | 21.68 | 2.00 |
| **XPL** | 51 | 4.65 | 0.80 | 57 | 5.11 | 0.96 | 54 | 5.44 | 1.18 | 52 | 6.04 | 0.95 |
| **TPL** | 48 | 34.10 | 1.95 | 54 | 34.52 | 1.94 | 52 | 34.92 | 2.39 | 37 | 35.03 | 2.32 |
| **XTPW** | 34 | 53.79 | 2.71 | 40 | 54.67 | 3.33 | 34 | 55.91 | 3.64 | 29 | 58.21 | 3.12 |
| **XAPi** | 52 | 52.04 | 3.02 | 57 | 53.19 | 2.82 | 53 | 54.08 | 3.26 | 50 | 53.52 | 3.50 |
| **APH** | 50 | 21.96 | 2.49 | 54 | 23.00 | 2.50 | 53 | 23.11 | 2.75 | 51 | 24.22 | 2.71 |
| **XSPL** | 47 | 17.94 | 3.20 | 50 | 18.82 | 3.61 | 46 | 20.15 | 3.37 | 48 | 24.71 | 3.82 |
| **XSLi** | 49 | 16.27 | 1.75 | 53 | 16.85 | 1.83 | 53 | 17.51 | 2.09 | 49 | 17.98 | 1.98 |

**Table A3:** Summary statistics of the cervical vertebrae (C3-C6) showing the means and standard deviation for males. Refer to Appendix I for measurement names and definitions.

| | C3 | | | C4 | | | C5 | | | C6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 51 | 16.22 | 1.38 | 57 | 16.60 | 1.69 | 57 | 16.33 | 2.00 | 54 | 17.22 | 2.23 |
| **XAH** | 52 | 13.77 | 1.58 | 54 | 13.80 | 1.46 | 57 | 12.91 | 1.56 | 55 | 12.73 | 1.28 |
| **XPH** | 51 | 14.10 | 1.40 | 56 | 13.77 | 1.24 | 57 | 13.56 | 1.50 | 53 | 13.64 | 1.33 |
| **XALs** | 52 | 13.52 | 1.31 | 58 | 13.74 | 1.58 | 56 | 13.79 | 1.69 | 54 | 14.22 | 1.90 |
| **XALi** | 51 | 14.41 | 1.42 | 55 | 14.78 | 1.62 | 58 | 15.53 | 2.19 | 54 | 15.02 | 1.72 |
| **XAWs** | 51 | 18.57 | 1.81 | 58 | 19.34 | 1.98 | 57 | 20.60 | 2.15 | 55 | 21.76 | 2.65 |
| **XAWi** | 50 | 17.88 | 1.78 | 55 | 18.53 | 1.84 | 56 | 19.25 | 2.30 | 55 | 21.40 | 2.48 |
| **XPL** | 51 | 4.67 | 0.82 | 56 | 4.88 | 0.95 | 54 | 5.22 | 1.21 | 55 | 5.73 | 1.06 |
| **TPL** | 49 | 33.59 | 2.32 | 55 | 34.16 | 2.29 | 54 | 34.81 | 2.71 | 44 | 36.09 | 2.59 |
| **XTPW** | 41 | 53.49 | 3.28 | 45 | 54.51 | 3.85 | 45 | 56.67 | 3.86 | 35 | 60.54 | 4.03 |
| **XAPi** | 52 | 51.04 | 3.64 | 57 | 52.37 | 3.39 | 56 | 54.09 | 3.40 | 52 | 54.08 | 3.29 |
| **APH** | 52 | 21.38 | 2.46 | 55 | 22.20 | 2.50 | 54 | 22.65 | 2.62 | 55 | 23.69 | 2.62 |
| **XSPL** | 48 | 17.52 | 3.56 | 51 | 17.67 | 3.94 | 51 | 19.80 | 3.47 | 50 | 25.82 | 4.53 |
| **XSLi** | 49 | 17.20 | 1.65 | 55 | 17.49 | 1.93 | 56 | 17.93 | 1.99 | 53 | 17.77 | 1.85 |

**Table A4:** Summary statistics of the cervical vertebrae (C3-C6) showing the means and standard deviation for females. Refer to Appendix I for measurement names and definitions.

| | C3 | | | C4 | | | C5 | | | C6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 55 | 14.16 | 1.10 | 58 | 14.59 | 1.20 | 57 | 14.79 | 1.67 | 52 | 15.73 | 1.91 |
| **XAH** | 55 | 12.84 | 1.42 | 56 | 12.70 | 1.28 | 54 | 12.33 | 1.50 | 50 | 12.12 | 1.02 |
| **XPH** | 54 | 12.91 | 1.14 | 58 | 12.72 | 1.20 | 57 | 12.63 | 1.20 | 52 | 12.63 | 1.07 |
| **XALs** | 54 | 11.89 | 0.90 | 57 | 12.47 | 1.05 | 56 | 12.45 | 1.09 | 52 | 13.06 | 1.29 |
| **XALi** | 54 | 12.76 | 1.04 | 56 | 13.00 | 1.39 | 54 | 13.41 | 1.22 | 51 | 14.02 | 1.52 |
| **XAWs** | 55 | 17.22 | 1.46 | 59 | 18.66 | 1.56 | 57 | 19.40 | 1.90 | 52 | 20.79 | 2.05 |
| **XAWi** | 56 | 16.41 | 1.45 | 56 | 17.30 | 1.56 | 55 | 18.18 | 1.96 | 51 | 19.78 | 1.84 |
| **XPL** | 54 | 4.43 | 0.74 | 59 | 4.73 | 0.85 | 57 | 5.16 | 0.88 | 53 | 5.58 | 0.86 |
| **TPL** | 51 | 32.08 | 2.46 | 56 | 32.09 | 2.44 | 55 | 32.58 | 2.32 | 45 | 33.16 | 1.95 |
| **XTPW** | 42 | 49.64 | 3.57 | 48 | 50.77 | 3.40 | 39 | 52.23 | 2.99 | 33 | 55.94 | 3.38 |
| **XAPi** | 54 | 48.48 | 3.63 | 58 | 50.07 | 3.49 | 55 | 50.69 | 3.14 | 52 | 49.48 | 3.48 |
| **APH** | 52 | 20.40 | 2.33 | 58 | 21.24 | 2.54 | 57 | 20.96 | 2.58 | 51 | 22.33 | 2.32 |
| **XSPL** | 53 | 15.19 | 3.01 | 55 | 15.49 | 3.37 | 53 | 17.36 | 3.28 | 53 | 23.06 | 3.60 |
| **XSLi** | 55 | 15.38 | 1.43 | 56 | 15.73 | 1.55 | 55 | 16.09 | 1.54 | 52 | 16.71 | 2.02 |

**Table A5:** The mean of all cervical vertebrae (C3-C6) combined for population and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Black** | **White** | **Male** | **Female** |
| **XSLs** | 15.35 | 16.05 | 16.59 | 14.8 |
| **XAH** | 12.31 | 13.53 | 13.29 | 12.51 |
| **XPH** | 12.60 | 13.92 | 13.76 | 12.72 |
| **XALs** | 12.73 | 13.58 | 13.82 | 12.46 |
| **XALi** | 13.60 | 14.68 | 14.95 | 13.28 |
| **XAWs** | 18.66 | 20.46 | 20.09 | 18.99 |
| **XAWi** | 17.88 | 19.34 | 19.3 | 17.88 |
| **XPL** | 4.8 | 5.31 | 5.13 | 4.97 |
| **TPL** | 32.56 | 34.62 | 34.62 | 32.45 |
| **XTPW** | 52.96 | 55.51 | 56.11 | 51.89 |
| **XAPi** | 49.48 | 53.21 | 52.90 | 49.69 |
| **APH** | 20.73 | 23.08 | 22.5 | 21.22 |
| **XSPL** | 17.69 | 20.4 | 20.22 | 17.75 |
| **XSLi** | 16.44 | 17.15 | 17.61 | 15.97 |

**Tables A6-A9:** Summary statistics of the upper thoracic vertebrae (T2-T6) showing the means and standard deviations for population and sex. Refer to Appendix I for measurement names and definitions.

**Table A6:** Summary statistics of the upper thoracic vertebrae (T2-T6) showing the means and standard deviation for black South Africans. Refer to Appendix I for measurement names and definitions.

| | T2 | | | T3 | | | T4 | | | T5 | | | T6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 59 | 16.97 | 1.63 | 60 | 18.53 | 1.83 | 57 | 19.65 | 2.16 | 58 | 20.95 | 1.96 | 59 | 22.32 | 2.05 |
| **XAH** | 58 | 17.17 | 1.35 | 58 | 17.26 | 1.19 | 53 | 17.21 | 1.26 | 55 | 17.15 | 1.16 | 56 | 17.66 | 1.27 |
| **XPH** | 58 | 17.24 | 1.26 | 60 | 17.75 | 1.22 | 57 | 17.96 | 1.22 | 57 | 18.37 | 1.23 | 59 | 18.81 | 1.27 |
| **XALs** | 59 | 13.69 | 1.45 | 60 | 15.20 | 1.88 | 57 | 16.04 | 1.84 | 58 | 17.47 | 1.84 | 59 | 18.58 | 1.98 |
| **XALi** | 58 | 15.31 | 1.64 | 58 | 16.29 | 1.71 | 54 | 17.20 | 1.82 | 56 | 18.62 | 1.93 | 58 | 19.64 | 1.88 |
| **XAWs** | 58 | 22.45 | 2.33 | 60 | 22.15 | 2.39 | 57 | 21.61 | 1.73 | 58 | 22.38 | 1.86 | 59 | 23.07 | 1.75 |
| **XAWi** | 59 | 24.15 | 2.50 | 60 | 23.27 | 2.26 | 56 | 23.23 | 2.40 | 58 | 23.76 | 2.07 | 58 | 24.72 | 1.95 |
| **XPL** | 59 | 4.76 | 1.15 | 60 | 4.18 | 0.98 | 57 | 4.39 | 0.88 | 58 | 4.41 | 0.88 | 59 | 4.64 | 1.01 |
| **TPL** | 59 | 31.22 | 3.59 | 60 | 29.17 | 2.84 | 57 | 28.33 | 2.92 | 58 | 28.34 | 2.89 | 59 | 28.83 | 2.65 |
| **XTPW** | 59 | 63.24 | 7.08 | 60 | 58.17 | 5.60 | 55 | 55.85 | 4.65 | 54 | 56.30 | 5.04 | 56 | 56.80 | 4.89 |
| **XAPi** | 58 | 33.66 | 4.03 | 60 | 31.48 | 3.71 | 56 | 30.27 | 2.96 | 57 | 29.46 | 3.42 | 59 | 29.61 | 3.29 |
| **APH** | 59 | 30.32 | 2.49 | 59 | 30.29 | 2.35 | 56 | 30.16 | 2.43 | 56 | 30.52 | 2.07 | 58 | 31.67 | 2.24 |
| **XSPL** | 56 | 36.32 | 4.23 | 58 | 37.12 | 4.40 | 56 | 37.59 | 5.06 | 53 | 41.02 | 5.20 | 55 | 43.67 | 5.07 |
| **XSLi** | 58 | 18.14 | 1.74 | 59 | 19.25 | 1.86 | 55 | 20.35 | 2.07 | 57 | 21.58 | 2.06 | 58 | 22.67 | 2.16 |

**Table A7:** Summary statistics of the upper thoracic vertebrae (T2-T6) showing the means and standard deviation for whites South Africans. Refer to Appendix I for measurement names and definitions.

| | T2 | | | T3 | | | T4 | | | T5 | | | T6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 54 | 18.00 | 1.97 | 58 | 20.45 | 2.49 | 54 | 23.13 | 2.13 | 56 | 25.00 | 2.44 | 52 | 26.40 | 2.25 |
| **XAH** | 52 | 18.17 | 1.22 | 57 | 18.37 | 1.41 | 53 | 15.62 | 1.13 | 57 | 18.88 | 1.55 | 51 | 18.94 | 1.46 |
| **XPH** | 57 | 18.72 | 1.32 | 59 | 18.92 | 1.35 | 57 | 19.47 | 1.34 | 57 | 20.25 | 1.46 | 52 | 20.88 | 1.38 |
| **XALs** | 53 | 15.45 | 1.87 | 59 | 17.02 | 2.43 | 55 | 19.33 | 2.25 | 57 | 21.02 | 2.45 | 52 | 22.35 | 2.33 |
| **XALi** | 53 | 17.06 | 2.39 | 56 | 19.07 | 2.16 | 54 | 20.85 | 2.07 | 57 | 22.51 | 2.85 | 50 | 23.82 | 2.78 |
| **XAWs** | 56 | 25.02 | 1.77 | 59 | 23.75 | 1.84 | 57 | 23.72 | 1.68 | 57 | 24.42 | 2.09 | 52 | 25.77 | 2.29 |
| **XAWi** | 56 | 26.16 | 1.85 | 58 | 25.10 | 2.12 | 57 | 25.09 | 2.25 | 57 | 26.32 | 2.38 | 51 | 27.73 | 2.60 |
| **XPL** | 58 | 6.60 | 1.43 | 59 | 5.10 | 117 | 57 | 4.56 | 0.91 | 56 | 4.61 | 1.02 | 51 | 4.84 | 1.10 |
| **TPL** | 58 | 35.19 | 3.11 | 59 | 32.31 | 2.90 | 56 | 31.32 | 2.80 | 56 | 31.66 | 2.35 | 51 | 32.10 | 2.14 |
| **XTPW** | 55 | 70.15 | 5.74 | 55 | 64.47 | 5.22 | 55 | 62.60 | 4.56 | 51 | 63.22 | 3.96 | 45 | 64.64 | 4.14 |
| **XAPi** | 58 | 37.19 | 3.56 | 59 | 35.02 | 2.73 | 56 | 34.27 | 2.40 | 57 | 34.19 | 2.51 | 50 | 34.36 | 2.80 |
| **APH** | 58 | 31.64 | 2.33 | 59 | 32.19 | 2.14 | 57 | 32.25 | 2.32 | 56 | 33.02 | 2.48 | 51 | 34.12 | 2.23 |
| **XSPL** | 57 | 39.32 | 4.74 | 56 | 40.14 | 4.96 | 53 | 43.11 | 5.36 | 51 | 47.49 | 6.62 | 50 | 49.58 | 5.79 |
| **XSLi** | 52 | 19.71 | 2.37 | 55 | 22.24 | 2.25 | 54 | 24.31 | 2.12 | 54 | 26.00 | 2.56 | 51 | 27.35 | 2.47 |

**Table A8:** Summary statistics of the upper thoracic vertebrae (T2-T6) showing the means and standard deviation for males. Refer to Appendix I for measurement names and definitions.

| | T2 | | | T3 | | | T4 | | | T5 | | | T6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 58 | 18.31 | 1.91 | 60 | 20.40 | 2.53 | 54 | 22.54 | 2.64 | 57 | 24.26 | 3.10 | 55 | 25.20 | 3.01 |
| **XAH** | 56 | 18.16 | 1.35 | 58 | 18.34 | 1.34 | 53 | 18.42 | 1.23 | 57 | 18.56 | 1.72 | 55 | 18.84 | 1.46 |
| **XPH** | 59 | 18.64 | 1.35 | 60 | 18.88 | 1.39 | 55 | 19.33 | 1.23 | 57 | 19.88 | 1.62 | 55 | 20.40 | 1.51 |
| **XALs** | 58 | 15.47 | 1.83 | 60 | 17.30 | 2.39 | 55 | 18.91 | 2.63 | 57 | 20.58 | 2.93 | 55 | 21.49 | 3.01 |
| **XALi** | 57 | 17.18 | 2.33 | 56 | 18.71 | 2.53 | 54 | 20.17 | 2.69 | 57 | 21.91 | 3.30 | 54 | 22.70 | 3.45 |
| **XAWs** | 59 | 24.69 | 2.21 | 60 | 24.15 | 2.28 | 55 | 23.62 | 2.01 | 57 | 24.56 | 2.15 | 55 | 25.35 | 2.35 |
| **XAWi** | 60 | 26.32 | 2.27 | 60 | 25.50 | 2.34 | 54 | 25.50 | 2.35 | 57 | 26.25 | 2.50 | 53 | 27.26 | 2.90 |
| **XPL** | 60 | 5.60 | 1.89 | 60 | 4.78 | 1.32 | 55 | 4.76 | 0.84 | 57 | 4.88 | 0.96 | 55 | 5.11 | 1.07 |
| **TPL** | 60 | 35.05 | 3.51 | 60 | 32.50 | 2.95 | 54 | 31.46 | 3.00 | 57 | 31.37 | 2.64 | 55 | 31.78 | 2.86 |
| **XTPW** | 57 | 70.02 | 6.73 | 58 | 64.62 | 5.52 | 55 | 62.02 | 5.04 | 56 | 62.55 | 4.56 | 53 | 62.85 | 5.19 |
| **XAPi** | 60 | 37.48 | 3.75 | 60 | 34.83 | 2.98 | 55 | 33.62 | 2.72 | 57 | 33.49 | 3.25 | 55 | 33.36 | 3.52 |
| **APH** | 60 | 31.93 | 2.36 | 60 | 32.23 | 2.07 | 55 | 32.20 | 2.21 | 56 | 32.77 | 2.49 | 55 | 33.45 | 2.49 |
| **XSPL** | 59 | 39.97 | 4.24 | 57 | 40.81 | 4.93 | 53 | 42.57 | 5.83 | 51 | 46.90 | 6.64 | 53 | 48.49 | 5.96 |
| **XSLi** | 57 | 19.86 | 2.28 | 56 | 21.66 | 2.65 | 54 | 23.39 | 2.79 | 56 | 25.04 | 3.24 | 55 | 25.78 | 3.18 |

**Table A9:** Summary statistics of the upper thoracic vertebrae (T2-T6) showing the means and standard deviation for females. Refer to Appendix I for measurement names and definitions.

| | T7 | | | T8 | | | T9 | | | T10 | | | T11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 55 | 16.56 | 1.33 | 58 | 18.52 | 1.76 | 57 | 20.21 | 2.38 | 57 | 21.61 | 2.22 | 56 | 23.29 | 2.60 |
| **XAH** | 54 | 17.11 | 1.21 | 57 | 17.26 | 1.28 | 53 | 17.42 | 1.36 | 55 | 17.47 | 1.30 | 52 | 17.67 | 1.31 |
| **XPH** | 56 | 17.27 | 1.29 | 59 | 17.26 | 1.18 | 59 | 18.15 | 1.48 | 57 | 18.74 | 1.47 | 56 | 19.18 | 1.62 |
| **XALs** | 54 | 13.52 | 1.33 | 59 | 14.88 | 1.54 | 57 | 16.44 | 2.00 | 58 | 17.90 | 1.89 | 56 | 19.21 | 2.20 |
| **XALi** | 54 | 15.06 | 1.41 | 58 | 16.64 | 1.70 | 54 | 17.89 | 2.12 | 56 | 19.23 | 2.22 | 54 | 20.44 | 2.30 |
| **XAWs** | 55 | 22.65 | 2.23 | 59 | 21.71 | 1.49 | 59 | 21.78 | 1.53 | 58 | 22.24 | 1.60 | 56 | 23.34 | 2.07 |
| **XAWi** | 55 | 23.84 | 1.84 | 58 | 22.79 | 1.44 | 59 | 22.95 | 1.95 | 58 | 23.83 | 2.02 | 56 | 25.05 | 2.05 |
| **XPL** | 57 | 5.75 | 1.20 | 59 | 4.49 | 0.99 | 59 | 4.20 | 0.87 | 57 | 4.14 | 0.79 | 55 | 4.36 | 0.91 |
| **TPL** | 57 | 31.23 | 3.28 | 59 | 28.92 | 2.49 | 59 | 28.31 | 2.63 | 57 | 28.58 | 2.93 | 55 | 28.91 | 2.43 |
| **XTPW** | 57 | 63.12 | 6.20 | 57 | 58.23 | 4.95 | 55 | 56.44 | 4.94 | 49 | 56.35 | 5.08 | 48 | 57.48 | 5.60 |
| **XAPi** | 56 | 33.96 | 4.23 | 59 | 31.61 | 3.67 | 57 | 30.96 | 3.41 | 57 | 30.16 | 3.64 | 54 | 30.19 | 3.57 |
| **APH** | 57 | 29.96 | 2.23 | 58 | 30.21 | 2.36 | 58 | 30.28 | 2.58 | 56 | 30.77 | 2.32 | 54 | 32.17 | 2.45 |
| **XSPL** | 54 | 35.50 | 4.10 | 57 | 36.40 | 3.79 | 56 | 38.11 | 5.09 | 53 | 41.58 | 5.79 | 52 | 44.44 | 5.72 |
| **XSLi** | 53 | 17.83 | 1.54 | 58 | 19.76 | 2.05 | 55 | 21.25 | 2.59 | 55 | 22.40 | 2.56 | 54 | 23.93 | 3.16 |

**Table A10:** The mean of all upper thoracic vertebrae (T2-T6) combined for population and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Black** | **White** | **Male** | **Female** |
| **XSLs** | 19.63 | 22.54 | 22.08 | 20.00 |
| **XAH** | 17.31 | 18.60 | 18.46 | 17.40 |
| **XPH** | 18.01 | 19.62 | 19.41 | 18.20 |
| **XALs** | 16.21 | 19.01 | 18.70 | 16.43 |
| **XALi** | 17.43 | 20.64 | 20.11 | 17.87 |
| **XAWs** | 22.36 | 24.51 | 24.47 | 22.36 |
| **XAWi** | 23.84 | 25.96 | 26.15 | 23.61 |
| **XPL** | 4.48 | 5.26 | 5.03 | 4.69 |
| **TPL** | 29.19 | 32.66 | 32.48 | 29.30 |
| **XTPW** | 57.86 | 64.93 | 64.46 | 57.88 |
| **XAPi** | 30.94 | 35.18 | 34.61 | 31.42 |
| **APH** | 30.68 | 32.65 | 32.50 | 30.80 |
| **XSPL** | 38.83 | 43.70 | 43.60 | 38.81 |
| **XSLi** | 20.41 | 23.91 | 23.12 | 21.05 |

**Tables A11-A14:** Summary statistics of the lower thoracic vertebrae (T7-T11) showing the means and standard deviations for population and sex. Refer to Appendix I for measurement names and definitions.

**Table A11:** Summary statistics of the lower thoracic vertebrae (T7-T11) showing the means and standard deviation for black South Africans. Refer to Appendix I for measurement names and definitions.

| | T7 | | | T8 | | | T9 | | | T10 | | | T11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 57 | 23.30 | 2.28 | 57 | 24.61 | 2.51 | 59 | 25.39 | 2.37 | 59 | 26.05 | 2.31 | 56 | 26.12 | 2.78 |
| **XAH** | 57 | 18.14 | 1.38 | 55 | 18.85 | 1.56 | 59 | 19.66 | 1.56 | 59 | 20.92 | 1.69 | 56 | 21.32 | 1.45 |
| **XPH** | 57 | 19.58 | 1.36 | 57 | 20.12 | 1.30 | 58 | 20.71 | 1.56 | 60 | 21.68 | 1.51 | 56 | 23.02 | 1.81 |
| **XALs** | 57 | 19.68 | 2.02 | 57 | 20.58 | 1.82 | 59 | 21.73 | 2.18 | 60 | 22.15 | 2.11 | 56 | 22.11 | 2.20 |
| **XALi** | 57 | 20.77 | 2.18 | 56 | 21.62 | 2.23 | 59 | 22.22 | 2.08 | 59 | 22.34 | 1.93 | 57 | 22.93 | 2.49 |
| **XAWs** | 57 | 24.18 | 2.11 | 57 | 25.72 | 2.05 | 59 | 26.98 | 2.28 | 59 | 22.68 | 1.93 | 56 | 31.39 | 2.61 |
| **XAWi** | 56 | 25.73 | 2.07 | 56 | 27.00 | 2.30 | 58 | 28.98 | 2.56 | 60 | 31.87 | 2.89 | 57 | 34.72 | 3.63 |
| **XPL** | 57 | 4.93 | 1.22 | 57 | 5.05 | 1.19 | 59 | 5.19 | 0.96 | 60 | 5.83 | 1.12 | 57 | 6.11 | 1.62 |
| **TPL** | 57 | 29.00 | 2.67 | 57 | 28.65 | 2.75 | 58 | 28.31 | 2.84 | 59 | 27.10 | 2.99 | 56 | 24.91 | 3.23 |
| **XTPW** | 55 | 56.93 | 4.57 | 56 | 56.23 | 5.11 | 56 | 55.84 | 5.31 | 60 | 53.78 | 5.38 | 56 | 49.93 | 6.28 |
| **XAPi** | 57 | 30.49 | 3.27 | 57 | 31.30 | 3.44 | 59 | 33.75 | 3.57 | 60 | 34.52 | 4.00 | 56 | 34.12 | 4.53 |
| **APH** | 55 | 32.76 | 2.21 | 56 | 33.88 | 2.04 | 58 | 34.59 | 2.38 | 58 | 36.02 | 2.46 | 57 | 38.23 | 2.61 |
| **XSPL** | 53 | 43.13 | 4.65 | 54 | 41.39 | 3.62 | 57 | 38.79 | 3.82 | 60 | 35.78 | 4.09 | 56 | 32.93 | 3.98 |
| **XSLi** | 57 | 23.98 | 2.31 | 56 | 25.00 | 2.33 | 58 | 25.86 | 2.31 | 59 | 25.98 | 2.26 | 57 | 26.42 | 2.54 |

**Table A12:** Summary statistics of the lower thoracic vertebrae (T7-T11) showing the means and standard deviation for whites South Africans. Refer to Appendix I for measurement names and definitions.

| | T7 | | | T8 | | | T9 | | | T10 | | | T11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 52 | 27.63 | 2.94 | 54 | 29.11 | 3.13 | 56 | 29.88 | 3.20 | 55 | 30.58 | 3.07 | 55 | 31.27 | 2.98 |
| **XAH** | 52 | 19.23 | 1.72 | 53 | 19.40 | 1.59 | 56 | 20.32 | 1.85 | 56 | 21.73 | 1.84 | 54 | 22.44 | 1.93 |
| **XPH** | 52 | 21.17 | 1.70 | 55 | 21.58 | 1.57 | 56 | 22.29 | 1.49 | 55 | 23.33 | 1.87 | 56 | 25.12 | 1.81 |
| **XALs** | 51 | 23.82 | 2.81 | 54 | 24.80 | 2.83 | 57 | 26.14 | 3.24 | 55 | 26.95 | 2.95 | 55 | 27.05 | 2.98 |
| **XALi** | 51 | 24.88 | 2.99 | 53 | 26.26 | 3.28 | 54 | 27.15 | 3.24 | 55 | 27.78 | 3.25 | 56 | 28.27 | 3.31 |
| **XAWs** | 52 | 27.44 | 2.59 | 54 | 29.06 | 2.86 | 56 | 30.34 | 2.74 | 55 | 32.25 | 2.72 | 56 | 35.00 | 3.16 |
| **XAWi** | 52 | 29.23 | 3.10 | 54 | 30.74 | 2.97 | 58 | 32.86 | 3.12 | 54 | 35.43 | 2.98 | 57 | 38.11 | 3.55 |
| **XPL** | 52 | 5.06 | 1.35 | 55 | 5.22 | 1.30 | 58 | 5.74 | 1.16 | 57 | 6.49 | 1.57 | 56 | 7.34 | 1.91 |
| **TPL** | 51 | 31.90 | 2.59 | 53 | 31.09 | 2.61 | 55 | 30.80 | 2.56 | 53 | 29.04 | 3.08 | 52 | 27.08 | 3.25 |
| **XTPW** | 50 | 63.38 | 4.90 | 50 | 62.42 | 5.02 | 52 | 61.17 | 4.47 | 49 | 58.49 | 5.10 | 50 | 54.14 | 6.14 |
| **XAPi** | 52 | 34.98 | 2.69 | 55 | 36.29 | 2.55 | 56 | 36.75 | 2.42 | 57 | 37.40 | 3.15 | 57 | 35.72 | 4.91 |
| **APH** | 52 | 34.67 | 2.37 | 54 | 35.54 | 2.21 | 57 | 36.19 | 2.49 | 54 | 38.04 | 2.96 | 55 | 40.98 | 3.41 |
| **XSPL** | 43 | 49.47 | 5.82 | 49 | 46.78 | 5.47 | 50 | 42.94 | 4.78 | 54 | 38.85 | 5.34 | 55 | 35.22 | 5.07 |
| **XSLi** | 51 | 28.55 | 2.90 | 53 | 29.85 | 3.50 | 54 | 30.65 | 3.19 | 57 | 31.37 | 3.40 | 56 | 31.96 | 3.44 |

**Table A13:** Summary statistics of the lower thoracic vertebrae (T7-T11) showing the means and standard deviation for males. Refer to Appendix I for measurement names and definitions.

| | T7 | | | T8 | | | T9 | | | T10 | | | T11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 55 | 26.53 | 3.30 | 57 | 27.91 | 3.55 | 58 | 29.05 | 3.64 | 56 | 29.61 | 3.65 | 58 | 29.98 | 3.62 |
| **XAH** | 55 | 19.24 | 1.68 | 56 | 19.62 | 1.43 | 57 | 20.42 | 1.75 | 57 | 21.89 | 1.69 | 57 | 22.11 | 1.83 |
| **XPH** | 55 | 21.05 | 1.67 | 57 | 21.42 | 1.51 | 57 | 22.09 | 1.69 | 57 | 22.88 | 1.96 | 58 | 24.52 | 2.05 |
| **XALs** | 55 | 22.98 | 3.31 | 57 | 23.75 | 3.42 | 58 | 25.60 | 3.69 | 57 | 25.77 | 3.66 | 58 | 26.00 | 3.63 |
| **XALi** | 54 | 24.00 | 3.61 | 56 | 25.25 | 3.94 | 56 | 26.18 | 3.95 | 58 | 26.47 | 3.98 | 57 | 27.11 | 4.09 |
| **XAWs** | 55 | 26.98 | 2.91 | 57 | 28.60 | 2.92 | 58 | 30.00 | 3.12 | 55 | 31.38 | 3.43 | 57 | 34.65 | 3.45 |
| **XAWi** | 54 | 28.78 | 3.23 | 56 | 30.23 | 3.40 | 58 | 32.31 | 3.67 | 58 | 34.83 | 3.70 | 58 | 38.33 | 3.86 |
| **XPL** | 55 | 5.62 | 1.16 | 57 | 5.61 | 1.26 | 58 | 5.72 | 1.21 | 58 | 6.21 | 1.55 | 57 | 6.28 | 2.09 |
| **TPL** | 55 | 31.93 | 2.60 | 56 | 31.52 | 2.55 | 57 | 31.21 | 2.40 | 55 | 29.93 | 2.66 | 55 | 27.67 | 2.80 |
| **XTPW** | 54 | 62.83 | 5.16 | 56 | 62.32 | 5.11 | 53 | 61.57 | 4.51 | 54 | 59.07 | 4.76 | 54 | 55.06 | 5.44 |
| **XAPi** | 55 | 34.05 | 3.56 | 57 | 35.44 | 3.39 | 57 | 39.91 | 2.86 | 58 | 38.12 | 2.78 | 58 | 36.74 | 4.28 |
| **APH** | 55 | 34.55 | 2.22 | 57 | 35.58 | 2.37 | 58 | 36.07 | 2.59 | 56 | 37.62 | 3.10 | 57 | 40.16 | 3.56 |
| **XSPL** | 48 | 48.69 | 6.20 | 56 | 45.55 | 5.25 | 53 | 42.68 | 4.98 | 56 | 39.52 | 4.89 | 56 | 35.84 | 4.79 |
| **XSLi** | 55 | 27.31 | 3.51 | 56 | 28.59 | 3.94 | 56 | 29.50 | 3.56 | 58 | 30.21 | 3.93 | 57 | 30.63 | 4.04 |

**Table A14:** Summary statistics of the lower thoracic vertebrae (T7-T11) showing the sample size, means and standard deviation for females. Refer to Appendix I for measurement names and definitions.

| | T7 | | | T8 | | | T9 | | | T10 | | | T11 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 54 | 24.19 | 3.09 | 54 | 25.63 | 3.04 | 57 | 26.07 | 2.85 | 58 | 26.91 | 2.84 | 53 | 27.25 | 3.62 |
| **XAH** | 54 | 18.07 | 1.39 | 52 | 18.58 | 1.58 | 58 | 19.55 | 1.61 | 58 | 20.74 | 1.75 | 53 | 21.62 | 1.72 |
| **XPH** | 54 | 19.61 | 1.46 | 55 | 20.24 | 1.49 | 57 | 20.88 | 1.51 | 58 | 22.07 | 1.71 | 54 | 23.59 | 2.05 |
| **XALs** | 53 | 20.25 | 2.35 | 54 | 21.44 | 2.38 | 58 | 22.19 | 2.34 | 58 | 23.14 | 2.79 | 53 | 22.98 | 2.86 |
| **XALi** | 54 | 21.43 | 2.38 | 53 | 22.43 | 2.60 | 57 | 23.00 | 2.49 | 56 | 23.41 | 2.89 | 56 | 24.02 | 3.16 |
| **XAWs** | 54 | 24.46 | 2.17 | 54 | 26.02 | 2.44 | 57 | 27.21 | 2.14 | 59 | 29.37 | 2.44 | 55 | 31.69 | 2.63 |
| **XAWi** | 54 | 26.06 | 2.39 | 54 | 27.39 | 2.32 | 58 | 29.53 | 2.57 | 56 | 32.23 | 2.48 | 56 | 34.43 | 2.99 |
| **XPL** | 54 | 4.35 | 1.07 | 55 | 4.64 | 1.01 | 59 | 5.20 | 0.91 | 59 | 6.10 | 1.23 | 56 | 7.16 | 1.51 |
| **TPL** | 53 | 28.75 | 2.50 | 54 | 28.07 | 2.21 | 56 | 27.80 | 2.47 | 57 | 26.18 | 2.46 | 53 | 24.17 | 3.05 |
| **XTPW** | 51 | 57.00 | 4.66 | 50 | 55.60 | 4.64 | 55 | 55.36 | 4.79 | 55 | 52.78 | 4.85 | 52 | 48.65 | 5.99 |
| **XAPi** | 54 | 31.19 | 3.38 | 55 | 32.00 | 3.70 | 58 | 33.53 | 3.06 | 59 | 33.76 | 3.59 | 55 | 33.02 | 4.55 |
| **APH** | 52 | 32.79 | 2.42 | 53 | 33.74 | 1.73 | 57 | 34.68 | 2.33 | 56 | 36.36 | 2.53 | 55 | 38.98 | 2.95 |
| **XSPL** | 48 | 43.25 | 4.57 | 47 | 42.04 | 4.77 | 54 | 38.81 | 3.65 | 58 | 35.03 | 3.92 | 55 | 32.25 | 4.62 |
| **XSLi** | 53 | 24.92 | 2.98 | 53 | 26.06 | 3.24 | 56 | 26.84 | 3.26 | 58 | 27.05 | 3.29 | 56 | 27.68 | 3.62 |

**Table A15:** The mean of all lower thoracic vertebrae (T7-T11) combined for population and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Black** | **White** | **Male** | **Female** |
| **XSLs** | 19.62 | 22.55 | 22.09 | 19.99 |
| **XAH** | 17.31 | 18.62 | 18.48 | 17.41 |
| **XPH** | 18.01 | 19.62 | 19.41 | 18.20 |
| **XALs** | 16.23 | 19.01 | 18.71 | 16.45 |
| **XALi** | 17.44 | 20.66 | 20.12 | 17.90 |
| **XAWs** | 22.31 | 24.49 | 24.46 | 22.30 |
| **XAWi** | 23.59 | 25.89 | 26.08 | 23.36 |
| **XPL** | 4.88 | 5.41 | 5.17 | 5.10 |
| **TPL** | 29.30 | 32.60 | 32.50 | 29.31 |
| **XTPW** | 57.66 | 64.69 | 64.23 | 57.70 |
| **XAPi** | 31.12 | 35.27 | 34.72 | 31.58 |
| **APH** | 30.66 | 32.71 | 32.55 | 30.79 |
| **XSPL** | 38.78 | 43.58 | 43.49 | 37.74 |
| **XSLi** | 20.39 | 23.98 | 23.18 | 21.04 |

**Tables A16-A19:** Summary statistics of the lumbar vertebrae (L1-L4) showing the means and standard deviations for population and sex. Refer to Appendix I for measurement names and definitions.

**Table A16:** Summary statistics of the lumbar vertebrae (L1-L4) showing the means and standard deviation for black South Africans. Refer to Appendix I for measurement names and definitions.

| | L1 | | | L2 | | | L3 | | | L4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 57 | 27.26 | 2.30 | 59 | 29.05 | 2.35 | 56 | 30.88 | 2.55 | 53 | 32.00 | 2.85 |
| **XAH** | 56 | 24.48 | 1.80 | 58 | 25.62 | 1.68 | 56 | 26.05 | 1.79 | 53 | 26.00 | 1.88 |
| **XPH** | 57 | 26.40 | 1.92 | 59 | 26.86 | 1.69 | 58 | 26.67 | 1.89 | 54 | 25.41 | 1.92 |
| **XALs** | 57 | 23.05 | 2.47 | 59 | 24.93 | 2.31 | 55 | 26.09 | 2.15 | 53 | 27.42 | 2.55 |
| **XALi** | 56 | 24.66 | 2.38 | 58 | 26.84 | 2.63 | 58 | 27.71 | 2.78 | 53 | 28.87 | 2.56 |
| **XAWs** | 56 | 37.23 | 3.23 | 59 | 39.64 | 3.40 | 58 | 41.95 | 3.92 | 54 | 43.56 | 2.91 |
| **XAWi** | 57 | 39.65 | 3.89 | 59 | 42.10 | 3.78 | 58 | 44.29 | 3.46 | 54 | 45.57 | 3.31 |
| **XPL** | 57 | 6.96 | 1.24 | 59 | 6.76 | 1.34 | 58 | 7.64 | 2.13 | 54 | 7.89 | 2.68 |
| **TPL** | 56 | 31.86 | 5.55 | 54 | 38.33 | 3.82 | 49 | 42.94 | 4.69 | 45 | 42.96 | 4.88 |
| **XTPW** | 47 | 62.45 | 10.30 | 41 | 77.10 | 6.03 | 41 | 86.83 | 8.94 | 30 | 87.03 | 10.46 |
| **XAPWi** | 57 | 26.82 | 3.90 | 58 | 29.52 | 4.16 | 54 | 33.17 | 4.82 | 50 | 40.34 | 6.40 |
| **APH** | 57 | 44.54 | 2.92 | 53 | 46.13 | 2.50 | 50 | 45.02 | 3.49 | 51 | 43.45 | 2.54 |
| **XSPL** | 56 | 33.30 | 3.61 | 56 | 34.73 | 3.63 | 51 | 34.67 | 4.52 | 52 | 32.08 | 3.25 |
| **XSLi** | 55 | 28.33 | 2.57 | 58 | 30.24 | 2.64 | 58 | 31.64 | 2.61 | 53 | 33.17 | 2.99 |

**Table A17:** Summary statistics of the lumbar vertebrae (L1-L4) showing the means and standard deviation for whites South Africans. Refer to Appendix I for measurement names and definitions.

| | L1 | | | L2 | | | L3 | | | L4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 56 | 31.93 | 2.92 | 59 | 33.36 | 3.35 | 55 | 34.45 | 2.87 | 53 | 35.23 | 2.91 |
| **XAH** | 56 | 26.09 | 2.07 | 56 | 27.96 | 2.04 | 54 | 28.78 | 2.06 | 55 | 29.13 | 2.13 |
| **XPH** | 57 | 28.35 | 1.73 | 57 | 28.88 | 1.81 | 53 | 28.72 | 1.95 | 55 | 28.04 | 2.20 |
| **XALs** | 57 | 28.60 | 3.19 | 59 | 29.88 | 3.26 | 55 | 30.58 | 3.22 | 53 | 31.19 | 2.67 |
| **XALi** | 56 | 29.23 | 2.97 | 54 | 30.15 | 3.08 | 53 | 30.72 | 2.79 | 52 | 31.62 | 2.87 |
| **XAWs** | 58 | 40.71 | 3.48 | 58 | 42.66 | 3.66 | 54 | 44.44 | 3.66 | 56 | 46.61 | 3.83 |
| **XAWi** | 56 | 43.64 | 3.69 | 56 | 42.20 | 3.66 | 56 | 47.38 | 3.74 | 55 | 49.45 | 3.81 |
| **XPL** | 57 | 7.65 | 1.47 | 59 | 7.85 | 1.40 | 57 | 9.19 | 1.56 | 56 | 11.38 | 1.86 |
| **TPL** | 47 | 35.36 | 6.74 | 37 | 39.65 | 4.57 | 42 | 43.19 | 5.02 | 35 | 43.31 | 4.80 |
| **XTPW** | 32 | 67.12 | 13.30 | 25 | 78.48 | 6.65 | 21 | 84.67 | 5.01 | 16 | 86.06 | 11.13 |
| **XAPi** | 57 | 28.63 | 3.15 | 55 | 31.49 | 3.85 | 52 | 34.23 | 4.77 | 53 | 43.57 | 6.68 |
| **APH** | 53 | 47.26 | 3.60 | 53 | 48.49 | 3.30 | 47 | 48.55 | 3.81 | 49 | 45.73 | 3.87 |
| **XSPL** | 55 | 35.89 | 2.79 | 50 | 38.36 | 3.19 | 45 | 40.49 | 3.31 | 47 | 38.32 | 4.27 |
| **XSLi** | 56 | 32.88 | 3.05 | 56 | 33.73 | 3.17 | 53 | 34.23 | 2.71 | 53 | 34.75 | 2.74 |

**Table A18:** Summary statistics of the lumbar vertebrae (L1-L4) showing the means and standard deviation for males. Refer to Appendix I for measurement names and definitions.

| | L1 | | | L2 | | | L3 | | | L4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 54 | 31.24 | 3.31 | 59 | 32.73 | 3.54 | 54 | 33.78 | 3.15 | 58 | 34.90 | 3.14 |
| **XAH** | 55 | 25.44 | 2.16 | 57 | 26.72 | 2.08 | 55 | 27.53 | 2.51 | 59 | 27.76 | 2.87 |
| **XPH** | 55 | 28.05 | 2.02 | 57 | 28.32 | 1.91 | 55 | 28.20 | 2.04 | 59 | 27.36 | 2.50 |
| **XALs** | 55 | 27.78 | 3.84 | 59 | 29.14 | **3.97** | 54 | 29.72 | 3.73 | 59 | 30.44 | 3.30 |
| **XALi** | 55 | 28.69 | 3.37 | 56 | 29.95 | 3.32 | 57 | 30.79 | 2.94 | 57 | 31.65 | 3.02 |
| **XAWs** | 55 | 41.33 | 3.43 | 59 | 43.14 | 3.69 | 56 | 44.96 | 4.25 | 59 | 46.92 | 3.50 |
| **XAWi** | 54 | 44.06 | 4.15 | 57 | 45.77 | 3.79 | 57 | 47.82 | 3.96 | 58 | 49.40 | 3.98 |
| **XPL** | 55 | 7.44 | 1.50 | 59 | 7.29 | 1.64 | 58 | 7.93 | 2.15 | 59 | 8.93 | 3.46 |
| **TPL** | 51 | 35.57 | 6.81 | 45 | 41.00 | 3.68 | 48 | 45.15 | 4.47 | 47 | 44.87 | 4.55 |
| **XTPW** | 38 | 67.32 | 12.73 | 33 | 80.06 | 4.68 | 33 | 89.15 | 7.84 | 29 | 89.07 | 10.19 |
| **XAPi** | 55 | 28.71 | 3.88 | 55 | 31.38 | 3.95 | 53 | 34.26 | 4.76 | 56 | 44.05 | 6.55 |
| **APH** | 52 | 47.13 | 3.45 | 54 | 48.13 | 2.71 | 51 | 47.67 | 3.84 | 54 | 45.17 | 3.42 |
| **XSPL** | 54 | 36.07 | 3.23 | 52 | 37.85 | 3.93 | 52 | 38.52 | 4.54 | 59 | 36.04 | 5.25 |
| **XSLi** | 55 | 32.33 | 3.25 | 56 | 33.29 | 3.04 | 56 | 34.23 | 2.80 | 57 | 35.42 | 2.69 |

**Table A19:** Summary statistics of the lumbar vertebrae (L1-L4) showing the means and standard deviation for females. Refer to Appendix I for measurement names and definitions.

| | L1 | | | L2 | | | L3 | | | L4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** | ***n*** | ***mean*** | ***sd*** |
| **XSLs** | 59 | 28.05 | 2.98 | 59 | 29.68 | 2.98 | 57 | 31.58 | 2.99 | 48 | 32.06 | 2.79 |
| **XAH** | 57 | 25.14 | 2.04 | 57 | 26.82 | 2.34 | 55 | 27.25 | 2.21 | 49 | 27.39 | 2.10 |
| **XPH** | 59 | 26.75 | 1.91 | 59 | 27.41 | 2.03 | 56 | 27.11 | 2.16 | 50 | 26.00 | 2.18 |
| **XALs** | 59 | 24.00 | 3.17 | 59 | 25.68 | 2.56 | 56 | 27.00 | 2.76 | 47 | 27.87 | 2.46 |
| **XALi** | 57 | 25.26 | 2.80 | 56 | 26.93 | 2.49 | 54 | 27.41 | 2.37 | 48 | 28.54 | 2.04 |
| **XAWs** | 59 | 36.83 | 2.62 | 58 | 39.10 | 2.77 | 56 | 41.34 | 2.70 | 51 | 43.02 | 2.78 |
| **XAWi** | 59 | 39.41 | 3.02 | 58 | 41.48 | 3.02 | 57 | 43.79 | 2.61 | 51 | 45.41 | 2.97 |
| **XPL** | 59 | 7.19 | 1.29 | 59 | 7.32 | 1.29 | 57 | 8.89 | 1.76 | 51 | 10.51 | 1.69 |
| **TPL** | 52 | 31.38 | 5.10 | 46 | 36.78 | 3.53 | 43 | 40.72 | 4.11 | 33 | 40.61 | 4.08 |
| **XTPW** | 41 | 61.59 | 10.16 | 33 | 75.18 | 6.74 | 29 | 82.62 | 6.38 | 17 | 82.65 | 10.29 |
| **XAPi** | 59 | 26.81 | 3.18 | 58 | 29.62 | 4.12 | 53 | 33.11 | 4.82 | 47 | 39.55 | 6.12 |
| **APH** | 58 | 44.71 | 3.20 | 52 | 46.46 | 3.36 | 46 | 45.70 | 4.04 | 46 | 43.87 | 3.36 |
| **XSPL** | 57 | 33.18 | 3.09 | 54 | 35.09 | 3.32 | 44 | 36.07 | 5.10 | 46 | 33.89 | 4.20 |
| **XSLi** | 56 | 28.95 | 3.17 | 58 | 30.67 | 3.22 | 55 | 31.49 | 2.42 | 49 | 32.27 | 2.30 |

**Table A20:** The means of all lumbar vertebrae (L1-L4) combined for population and sex. Refer to Appendix I for measurement names and definitions.

| | Population | | Sex | |
|---|---|---|---|---|
| | **Black** | **White** | **Male** | **Female** |
| **XSLs** | 29.78 | 33.73 | 33.20 | 30.28 |
| **XAH** | 25.55 | 27.97 | 26.87 | 26.63 |
| **XPH** | 26.36 | 28.51 | 27.99 | 26.84 |
| **XALs** | 25.36 | 30.02 | 29.27 | 26.07 |
| **XALi** | 26.98 | 30.49 | 30.37 | 26.95 |
| **XAWs** | 40.36 | 43.58 | 44.14 | 39.74 |
| **XAWi** | 42.86 | 46.22 | 46.63 | 42.41 |
| **XPL** | 7.72 | 8.97 | 7.87 | 8.83 |
| **TPL** | 38.23 | 39.93 | 41.38 | 36.35 |
| **XTPW** | 76.68 | 77.01 | 80.42 | 72.84 |
| **XAPi** | 32.17 | 34.29 | 34.59 | 31.84 |
| **APH** | 44.75 | 47.49 | 46.99 | 45.15 |
| **XSPL** | 33.76 | 38.22 | 37.18 | 34.55 |
| **XSLi** | 30.85 | 33.89 | 33.81 | 30.82 |