STATURE ESTIMATION FROM FRAGMENTS OF THE TIBIA IN BLACK SOUTH AFRICANS

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A dissertation submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in fulfilment for the requirements of the degree Master of Science (Medicine).

Johannesburg, 2018

DECLARATION

I, Amy Joy Spies, declare that this dissertation is my own work. It is being submitted for the degree of Master of Science (Medicine) at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination, at this or any other University.

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____07____day of ____Nov____20____18____in__Parktown

Presentations arising from this dissertation:

- Spies, A. J., Bidmos, M. A., and Brits, D. (2018). Reconstructing total skeletal height and tibial length of black South Africans from tibial fragments. Oral presentation at the 46th Annual Conference of the Anatomical Society of Southern Africa, Johannesburg, South Africa.

- Spies, A. J., Bidmos, M. A., and Brits, D. (2018). Stature estimation from fragments of the tibia in black South Africans. Poster presentation at the 87th Annual Meeting of the American Association of Physical Anthropologists, Texas, United States of America.

- Spies, A. J., Bidmos, M. A., and Brits, D. (2018). Estimating stature of black South Africans from fragmentary tibiae. Oral presentation at the 21st Annual Congress of the European Anthropological Association, Odense, Denmark.

Publications arising from this dissertation:

- Spies, A. J., Bidmos, M. A., and Brits, D. Using tibial fragments to reconstruct the stature of black South African adults. In preparation.

- Spies, A. J., Bidmos, M. A., and Brits, D. An evaluation of the direct and indirect methods of stature estimation from tibial fragments. In preparation.

ABSTRACT

Stature is an important component of the biological profile of unknown skeletal remains and regression equations for estimating stature have been derived for both intact and fragmentary bones. These equations are population-specific and therefore need to be derived for various populations. The aim of this study was therefore to establish regression equations for estimating both total skeletal height (TSH) and tibial length (TL) from tibial fragments in black South Africans, which previously did not exist. These equations can then be used in conjunction with established equations or soft tissue correction factors to estimate stature.

TSH was calculated for one hundred male and one hundred female skeletons from the Raymond A. Dart Collection of Human Skeletons. Eleven measurements representing tibial fragments were taken on each tibia, and univariate and multivariate equations were derived for the estimation of both TSH and TL from these measurements.

All tibial variables were significantly correlated with both TSH and TL, and regression equations were therefore derived for all variables. The range of standard error of estimates for multivariate equations (3.43-5.06 cm) was only slightly higher than those reported for intact tibiae (2.59-3.16) in black South Africans, and all equations estimated TSH and TL with moderate to high accuracy, with a range of 40-100 %. The direct method, whereby fragments are used to estimate TSH directly, was more accurate than the indirect method, in which TL is first estimated using fragments and this estimated TL is then used to estimate TSH. Equations using tibial fragments derived for South African whites and North American blacks both significantly overestimated stature in black South Africans, with an average overestimation of 9.17 cm using white South African equations, and a mean overestimation of 13.21 cm using equations specific for black North Americans. These results further confirm the population-specificity of these equations.

When intact tibiae are not available for analysis in forensic cases, regression equations using tibial fragments can accurately estimate stature in black South Africans.

ACKNOWLEDGEMENTS

I would like to sincerely thank my supervisors, Dr Desiré Brits and Professor Mubarak A. Bidmos. This research would not be the success it is without all of your invaluable advice and knowledge, endless patience and guidance, and unconditional encouragement and support. Thank you, thank you, thank you.

Thank you to the School of Anatomical Sciences at the University of the Witwatersrand, for access to the Raymond A. Dart Collection of Human Skeletons and for the opportunity to work in one of the largest skeletal collections in the world. Thank you to Mr Brendon Billings, Mr Nicholas Bacci and Mr Daigo Shangase for your assistance in the skeletal collection.

I would sincerely like to thank my friends and family, especially my wonderful Mum, without whose support, encouragement, understanding and love, this would not be possible.

Lastly, thank you to God for giving me strength in times of weakness, endurance in times of exhaustion and peace in times of confusion.

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

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CHAPTER ONE

Introduction

1.1. Introduction

Forensic anthropology deals with the examination of decomposed and skeletonized remains to aid in the possible identification of unknown individuals in both forensic and archaeological cases (Stewart, 1979; Mysorekar *et al.,* 1980; Raxter *et al.,* 2006). In recent years, the expertise of forensic anthropologists has been relied upon more and more in the analysis of forensic cases (Wilson *et al.,* 2010). In 2016, 51 242 of the recorded 456 612 deaths that occurred in South Africa were classified as non-natural, which include deaths related to causes such as violence or accidents (Statistics South Africa, 2017). Individuals whose deaths are classified as non-natural must, according to the Inquest Act of South Africa (No. 58 of 1959), undergo an autopsy. In cases where forensic pathologists cannot assess certain demographics from the soft tissue as a result of decomposition or other taphonomic processes, a skeletal analysis of the remains is required in order to describe these characteristics (Chibba and Bidmos, 2007; Brits *et al.,* 2017).

The aim of a forensic anthropological analysis is to compile a biological profile of the individual, which includes demographics such as age, sex, ancestry and living stature, as well as any other individuating factors that could lead to a possible identification of the deceased (Stewart, 1979; Krogman and İşcan, 1986; Klepinger, 2006; Dayal *et al.,* 2008; Brits *et al.,* 2017). Living stature is a characteristic that is unique to an individual, and thus is classified as a factor of individualization which can be used to aid in the identification of unknown remains, or the exclusion of individuals that do not fit this criterion (Ryan and Bidmos, 2007; İşcan and Steyn, 2013; Brits *et al.,* 2017).

Stature is also an important tool in analysing health and nutrition (Perkins *et al.,* 2016), stress (Sheppard *et al.,* 2015), social and economic conditions (Rah *et al.,* 2015; Zong *et al.,* 2015), climate (Bharati *et al.,* 2010), changes in body proportions over time and between populations (Nyati *et al.,* 2006; Myburgh *et al.,* 2017), and genetic variation (Hur *et al.,* 2008).

There are two methods that can be employed to estimate the living stature of individuals, namely the anatomical (Fully, 1956) and mathematical (Pearson, 1899) methods. The mathematical method, which includes regression equations, is the most commonly used method as it is quick and easy and does not require a complete or intact skeleton (Lundy, 1985; Mays, 2016). This method can also be used to estimate stature from fragmentary remains which is important since skeletal remains are rarely recovered intact (Bidmos, 2006; İşcan and Steyn, 2013; Moore and Ross, 2013). Regression equations for intact and fragmentary bones, including fragmentary femora and tibiae, are available for a number of populations (Trotter and Gleser, 1952; Holland, 1992; Chibba and Bidmos, 2007; Bidmos, 2008a, 2008b; Dayal *et al.,* 2008; Gocha *et al.,* 2013 Mandela *et al.,* 2013; Abledu *et al.,* 2016a; Ugochukwu *et al.,* 2018). However, regression equations for fragmentary tibiae do not exist for black South Africans. Since these formulae are population-specific and either underestimate or overestimate the stature of individuals from populations other than the reference population (Lundy, 1985; Bidmos, 2006), those derived for other populations or even white South Africans cannot simply be used for black South Africans. It is therefore imperative to derive regression equations specific for the black South African population.

1.2. Study aims and objectives

The overall aim of this study was to establish regression equations for estimating both total skeletal height and tibial length from tibial fragments in black South Africans. These equations can then be used together with established equations or soft tissue correction values for estimating stature in black South Africans. This is extremely important since skeletal remains are often received in forensic laboratories in South Africa in fragmentary states (Asala *et al.,* 2004).

The objectives of the study were to:

1. Confirm the population-specificity of regression equations by testing the reliability of formulae for estimating stature from tibial fragments derived for South African whites and North American blacks in a sample of black South Africans;
2. Develop new regression equations specific for black South Africans for estimating both total skeletal height (direct method of stature estimation) and tibial length (indirect method of stature estimation) from individual and a combination of variables of the tibia;
3. Test the accuracy of these newly derived regression equations;
4. Compare the accuracies of the direct and indirect methods of estimating total skeletal height, and thereby stature, from tibial fragments.

It is expected that the outcomes of this research will confirm the need for population-specific standards for estimating stature, and thus, with the establishment of equations specific for black South Africans using tibial fragments, this research will aid in improving stature estimation methods in South African forensic practice.

CHAPTER TWO

Literature Review

2.1. Introduction

During a forensic anthropological analysis, characteristics such as age, sex, ancestry and living stature are ascertained from skeletal remains (Krogman and İşcan, 1986; Klepinger, 2006). Living stature is an important component of the biological profile as it is tool that can aid in the identification of individuals or the exclusion of those that do not match the demographics of the biological profile (İşcan and Steyn, 2013). Therefore, much emphasis has been placed on refining the methods used to estimate stature, as well as developing regression equations for various bones and various population groups. The two methods that are available for estimating stature include the anatomical (Fully, 1956) and mathematical (Pearson, 1899) methods.

2.2. The anatomical method

The anatomical method of stature estimation, also known as the complete skeleton method or Fully's method, was first introduced by Dwight in 1894 (as cited by Lundy in 1985) and was then improved upon by Fully (1956) in order to obtain a more accurate stature estimate. Dwight's method (as cited by Lundy in 1985) involved laying out the skeleton in anatomical position and articulating it with clay as a representation of soft tissue and cartilage between bones. The articulated skeleton was then measured to obtain an estimated stature. Fully's (1956) method was based on Dwight's method, but instead of rearticulating the skeleton, rather makes use of a total skeletal height (TSH) calculated by summing the heights of all the individual bones that contribute directly towards stature (Lundy, 1985). These skeletal elements include the cranium, vertebrae (C2-S1), femur, tibia, talus and calcaneus. An appropriate soft tissue correction factor, which accounts for the scalp, intervertebral discs and soles of the feet, is then added to the TSH to estimate living stature (Ghosh *et al.*, 2015). Fully (1956) proposed a universal soft tissue correction factor of 10.5 cm for individuals of average height, and 10 cm and 11.5 cm for short and tall individuals respectively. However, these correction factors have been shown to underestimate living stature (King, 2004; Bidmos, 2005; Raxter *et al.,* 2006; Maijanen, 2009; Bidmos and Manger, 2012; Brits *et al.,* 2017). This may be the result of "gaps" and "overlaps" previously unaccounted for, including the distance between basion and the dens of the axis, and between S1 and the roof of the acetabulum, as well as an overlap between the medial malleolus of the tibia and the calcaneus (Raxter *et al.,* 2006). The effect of the curvature of the spine on stature was also previously unaccounted for (Bidmos and Manger, 2012). In addition, there is a lack of certainty regarding how some measurements should be taken, such as vertebral height, tibial length, and the talocalcaneal height (Formicola, 1993; Raxter *et al.,* 2006). Furthermore, Fully's (1956) universal soft tissue correction factor was calculated based on the skeletal remains of French males, not taking into account potential differences in the proportion of soft tissue between the sexes and between population groups (Stewart, 1979; King, 2004; Bidmos, 2005). In an attempt to overcome these shortfalls in Fully's (1956) method, Raxter *et al.* (2006) clarified measurement descriptions and procedures and proposed a new soft tissue correction factor that accounted for all the "gaps" and "overlaps" previously overlooked by Fully (1956). This soft tissue correction factor is considered universal and can be applied to any individual irrespective of sex or ancestry. However, several researchers have found this soft tissue correction factor to either significantly overestimate or underestimate stature in various populations or between the sexes (King, 2004; Bidmos, 2005; Bidmos and Manger, 2012; Brits *et al.,* 2017). Bidmos and Manger (2012) found that the soft tissue correction factor proposed by Raxter *et al.* (2006) underestimated stature by an average of 14.8 cm in South African black males, while Brits *et al.* (2017) found the soft tissue correction factor specific for black South African males (Bidmos and Manger, 2012) overestimated the stature of black South African females by an average of 7.8 cm. These authors have therefore proposed new soft tissue correction factors for these groups.

The anatomical method is widely considered to be the most accurate method of stature estimation (Lundy, 1985; Ousley, 1995; Raxter *et al.,* 2006; Baines *et al.,* 2011; Raxter and Ruff, 2017), as it includes all the skeletal elements that contribute directly towards stature (Raxter *et al.,* 2006; Dayal *et al.,* 2008), thus taking into account variations in body proportions (Maijanen, 2009). Fully (1956) found that using the anatomical method, stature estimation errors fell within 2-3 cm, while errors associated with the mathematical method were between 8 and 9 cm. However, the consistent underestimation of stature as a result of universally applicable soft tissue correction factors, which have subsequently been suggested to be both sex- and population-specific (King, 2004; Bidmos, 2005; Bidmos and Manger, 2012; Brits *et al.,* 2017), has affected the reliability of this method. In addition, the large number of measurements required for this method may increase the chance of measurement error (Dong and Peng, 2013), further reducing the reliability of this method. Furthermore, this method requires a complete and intact skeleton which is not always available (Lundy, 1985; Bidmos, 2006; Dayal *et al.,* 2008). In fact, skeletal remains are rarely recovered intact and are often missing elements, which means that the anatomical method cannot be used (Lundy, 1985; Bidmos, 2006). In these cases, the mathematical method, which does not require the complete skeleton, can be used (Dayal *et al.,* 2008).

2.3. The mathematical method

The mathematical method is based on the correlations between various bones and stature and involves using the lengths of individual bones or a combination of bones to estimate stature (Lundy, 1985; Krogman and İşcan, 1986; Tatarek *et al.,* 2005; Moore and Ross, 2013). The main advantage of the mathematical method is that stature can be estimated using only those bones that are available, or a selection of bones, and does not require a complete skeleton (Lundy, 1985; Dayal *et al.*, 2008; Mays, 2016). In fact, this method does not even require complete or intact bones and can be used on fragmentary remains (Holland, 1992; Bidmos, 2008a). The mathematical method is therefore more practical than the anatomical method and is more commonly used since complete skeletons or bones are rarely available in both forensic and archaeological contexts (Lundy, 1985; Mays, 2016). However, the mathematical method does not take into consideration differing body proportions and thus this method may not be as accurate as the anatomical method (Lundy, 1985; Raxter *et al.,* 2006; Maijanen and Niskanen, 2010), with errors of between 8 and 9 cm as opposed to errors of 2-3 cm using the anatomical method (Fully, 1956). The mathematical method includes the bone:stature ratio and regression analyses.

2.3.1. Bone:stature ratio

The bone/stature ratio is based on the principle that certain bones have a constant relationship with stature (Stewart 1979; Pininski and Brits, 2014; Yadav *et al.,* 2016). This method involves multiplying the length of a long bone by a constant factor in order to obtain an estimated living stature (İşcan and Steyn, 2013; Moore and Ross, 2013). These ratios have been published for various bones including the humerus, radius and tibia, with each bone contributing 20.0 %, 14.3 % and 22.1 % of stature respectively (Stewart, 1979). However, the most significant relationship between bone length and stature was that found for the femur, with the femur contributing 26.7 % of adult stature (Feldesman, 1992). The femur:stature ratio was originally thought to be independent of both sex and population (Feldesman, 1992), however, significant differences in the ratio between population groups have been found (Feldesman and Fountain, 1996). While the femur:stature ratio is relatively reliable for estimating the stature of individuals of average height, with a mean error of 2.15-3.4 cm, it has been shown to underestimate the stature of short individuals while overestimating the stature of taller individuals (Feldesman and Fountain, 1996; Sjøvold, 2000). The standard error of estimate (SEE), which gives an indication of the accuracy of a stature estimate obtained using a particular method, is also rarely available for bone:stature ratios (İşcan and Steyn, 2013). In addition, when SEEs are available, they are much larger than those associated with regression analyses, indicating a lower accuracy for the bone:stature method (Krishan *et al.,* 2012). Krishan et al. (2012) found that estimate errors using bone:stature ratios were between 2.17 and 16.32 cm greater than errors associated with the regression method. Bone:stature ratios are therefore not regularly used in forensic contexts and regression analysis is the more commonly used method (Moore and Ross, 2013; Brits *et al.,* 2017).

2.3.2. Regression analyses

In regression analyses, the lengths of one or a combination of bones are used in conjunction with regression equations to estimate stature (Stewart, 1979; Krogman and İşcan, 1986; Ozaslan *et al.,* 2003; Dayal *et al.,* 2008; Cardoso *et al.,* 2016). This is a very quick and easy method of stature estimation which does not require a complete skeleton, but the equations are both sex- and population-specific (Lundy, 1985; Dayal *et al.,* 2008; Gocha *et al.,* 2013; Cardoso *et al.,* 2016). Since populations vary significantly in their statures, equations used to estimate stature are therefore also very different between populations (Lundy, 1985; Cardoso *et al.,* 2016). Using equations specific for one population to estimate the statures of a different population may result in either an underestimation or overestimation of stature, as shown by Gocha *et al.* (2013) in Thai individuals using equations specific for North Americans, and by Bidmos (2006) in South African whites using equations specific for South African blacks. Therefore, equations should not be used to estimate the stature of individuals from populations different from the reference population (Konigsberg *et al.,* 1998; Khanal *et al.,* 2017a; Shukla *et al.,* 2017). Stature estimates obtained using regression equations have been shown to be very accurate, however this method tends to overestimate and underestimate the stature of short and tall individuals respectively (Sjøvold, 2000).

The first regression equations for stature estimation were derived by Pearson in 1899 (as cited by Stewart, 1979) and regression equations have subsequently been established for a number of populations (Table 1).

It is important to note, however, that not all skeletal elements, although showing a statistical relationship with stature, are biologically relevant (Fedak *et al*., 2015). Therefore, skeletal elements that contribute directly towards stature are the most appropriate for estimating stature as it is expected that there is both a statistical and a biological relationship between these two variables (Khanal *et al*., 2017a).

Measurements of long bones have been shown to be the most reliable for the estimation of stature (Trotter and Gleser, 1952; Didia *et al.,* 2009; Gaur *et al.,* 2016), with the long bones of the lower limb yielding the most accurate stature estimates as a result of their high correlation with stature (Lundy and Feldesman, 1987; Duyar *et al.,* 2006; Dayal e*t al.,* 2008; Chandran and Kumar, 2012; Khanal *et al.,* 2017a). For example, Dayal *et al.* (2008) cited SEEs of 2.64 and 2.86 cm for the femur and tibia respectively, while equations using the bones of the upper limb ranged between 3.05 and 3.77 cm. In addition, the femur and tibia had correlations of 0.93 and 0.91 respectively with stature, while correlations for the humerus, ulna and radius ranged between 0.83-0.84 (Dayal *et al.,* 2008). The femur and the tibia are also more useful in stature estimation since they are very robust bones which generally resist erosion and retain their shape, and thus are likely to be available for analysis in forensic cases (Krici and Ozan, 1999; Bakar *et al.,* 2017; Khanal *et al.,* 2017b). In the event of the long bones being unavailable, several other skeletal elements can be used to estimate stature, including the skull (Ryan and Bidmos, 2007; Torimitsu *et al.,* 2016), clavicle (Rani *et al.,* 2011; Torimitsu *et al.,* 2017), scapula (Giurazza *et al.,* 2013; Zhang *et al.,* 2016), sternum (Zhang *et al.,* 2015a; Tumram *et* *al.*, 2016), vertebrae (Zhang *et al.*, 2015b; Milani *et al.*, 2017), sacrum (Pelin *et al.*, 2005; Pininski and Brits, 2014), pelvis (Macaluso, 2015; Torimitsu *et al.*, 2015), calcaneus (Bidmos and Asala, 2005; Bidmos, 2006; Zhang *et al.*, 2017), metatarsals (Bidmos, 2008c; Ibrahim *et al.*, 2017), metacarpals (Musgrave and Harneja, 1978; Zaher *et al.*, 2011) and phalanges (Habib and Kamal, 2010; Pal *et al.*, 2016) to name but a few.

Table 1. Populations with regression equations for the estimation of stature using various skeletal elements

Population	Reference	Bones used	SEE (± cm)
North American	Trotter and Gleser (1952, 1958)	Long bones	2.88-5.05
Guatemalan	Wright and Vásquez (2003)	Long bones	0.33-1.84
Mexican	Garmendia *et al.* (2018)	Long bones	3.80-5.89
Spanish	Muñoz *et al.* (2001	Long bones	3.03-5.18
Portuguese	Cordeiro *et al.* (2009)	Metatarsals	4.35-5.70
Croatian	Petrovečki *et al.* (2007)	Long bones	2.00-5.21
Greek	Nikita and Chovalopoulou (2017)	Long bones	2.13-2.97
Polish	Hauser *et al.* (2005)	Femur	1.77-3.05
Turkish	Sargin *et al.* (2012)	Ulna and tibia	-
Italian	Giurazza *et al.* (2013)	Scapula	-
Bulgarian	Radoinova *et al.* (2002)	Long bones	1.45-2.91
Iranian	Poorhassan *et al.* (2017)	Forearm	4.08-6.21
Saudi Arabian	Kornieieva and Elelemi (2016)	Hands	3.36-5.97
Egyptian	Ibrahim *et al.* (2017)	Metatarsals	4.71-5.60
Korean	Jeong and Jantz (2016)	Long bones and lumbar spine	1.55-3.30
Japanese	Torimitsu *et al.* (2017)	Clavicle	3.43-4.88

Table 1 (continued). Populations with regression equations for the estimation of stature using various skeletal elements

Thai	Mahakkanukrauh *et al.* (2011); Gocha *et al.* (2013)	Long bones and vertebrae	2.40-6.05
Indian	Anirban *et al.* (2013); Gaur *et al.* (2016)	Tibia and fibula	-
Nepalese	Shrestha *et al.* (2015)	Skull	5.54-7.43
Nigerian	Okubike *et al.* (2018)	Footprint	4.46-8.13
Ghanian	Abledu *et al.* (2016b)	Footprint	6.64-8.66
South African	Dayal *et al.* (2008)	Long bones and lumbar spine	1.75-5.54

Even if long bones are present and available for analysis, they are rarely recovered intact and are often fragmentary (Holland, 1992; Chibba and Bidmos, 2007; Bidmos, 2008a). This may be due to various taphonomic processes such as scavenging (Pokines and Tersigni-Tarrant, 2017), weathering (Urbanová *et al.,* 2017) or burning of the remains (Waterhouse, 2013), all of which can result in highly fragmented bones. Additionally, in cases of violent crimes or natural disasters, the incidence of trauma and dismemberment is extremely high which often results in only fragmentary remains being available for analysis (Bidmos, 2006; Yadav *et al.,* 2016; Khanal *et al.,* 2017b). As a result, regression equations for the estimation of stature using fragmentary remains are required (Bidmos, 2008a; Khanal *et al.,* 2017b).

Estimating stature using fragments of bones was first attempted by Gertrude Müller using the radius, humerus and tibia (as cited by Steele and McKern, 1969). These bones were divided into segments and the proportion of each segment to the maximum length of the bone was calculated (Steele and McKern, 1969). These proportions then allowed for the length of the long bone, and subsequently stature, to be estimated from the segments (Chibba and Bidmos, 2007). Steele and McKern (1969) and Steele (1970) then used fragments of the femur, tibia and humerus to estimate stature in a similar manner. This method was later revised by

Simmons *et al.* (1990) who developed new regression equations using more easily reproducible measurements of the femur which could be taken between standardized landmarks. This reduced bias as anatomical landmarks could be easily identified and located, and also improved accuracy by reducing SEEs from a range of 1.57-3.02 cm (Steele, 1970) to a range of 1.99-2.59 cm.

Total skeletal height (TSH) can be estimated from fragments of bones in one of two ways. In the direct method, TSH is estimated directly from measurements of fragments of long bones, while in the indirect method, fragment measurements are first used to estimate the length of the long bone, and this estimated long bone length is then used to estimate TSH (Chibba and Bidmos, 2007; Bidmos, 2009; Khanal *et al.*, 2017b). TSH can then be converted to an estimated living stature (ELS) using appropriate equations or soft tissue correction values (Fully, 1956; Raxter *et al.,* 2006). While the direct method is a much quicker and less complicated way of estimating TSH (Bidmos, 2009; Khanal *et al.,* 2017b), there is debate regarding which method has smaller SEEs and therefore is more accurate. Steele and McKern (1969) concluded that the indirect method has smaller SEE values, but Simmons *et al.* (1990) reported that more accurate estimates are obtained using the direct approach. Bidmos (2009) compared the direct and indirect methods using fragmentary femora in South Africans and reported that the direct method yielded much more accurate estimates of TSH than the indirect method. Additionally, due to the fact that the indirect approach involves two steps in the estimation of TSH, the SEE, which gives an indication of the accuracy of the method, needs to be adjusted to account for both steps of the process (Steele, 1970; Bidmos, 2009). As a result, SEEs are much higher for the indirect (1.33-2.21 cm) compared to the direct method (3.71-5.31 cm), which indicates that this approach is much less accurate (Bidmos, 2009). Fongkete *et al.* (2016) also concluded that the direct method (SEEs of 5.15-6.71 cm) yielded more accurate TSH estimates than the indirect approach (SEEs of 5.59-6.98 cm) using fragments of the femur and tibia in Thai individuals. However, many forensic anthropologists still prefer using the indirect method to estimate the stature of unknown remains (Khanal *et al.*, 2017b). One reason for this may be the fact that equations for converting maximum bone length to TSH or stature already exist for several populations (Trotter and Gleser, 1952; Dayal *et al.*, 2008).

Regression equations for estimating stature from fragmentary femora and tibiae have been derived for numerous populations (Table 2), however, no formulae using tibial fragments exist for black South Africans and due to the population-specificity of these equations, those derived from the white South African or black north American populations cannot be used for black South Africans (Bidmos, 2008b). Therefore, regression formulae for tibial fragments specific for black South Africans need to be established.

2.4. Factors affecting stature

Stature is a multifactorial trait which is affected by both genetics and environmental conditions (Czerwinski *et al.*, 2007; Jelenkovic *et al.*, 2016). Approximately 80-90 % of stature is genetically determined (Ogata, 2006; Hirschhorn and Lettre, 2009), with genetic variation between populations contributing a large portion of population differences in stature (Dauber *et al.*, 2014). The remaining 10 % of stature is influenced by environmental conditions, which include nutrition (Perkins *et al.*, 2016), health (Hwang *et al.*, 2013), stress (Sheppard *et al.*, 2015), hygiene (Rah *et al.*, 2015), climate (Bharati *et al.*, 2010) and socioeconomic status (Zong *et al.*, 2015). Changes in these environmental conditions results in changes in stature over time, a phenomenon known as secular change (Cole, 2000; Moore and Ross, 2013; Myburgh *et al.*, 2017). For example, a decline in nutrition causes stunting and delayed growth (dos Santos *et al.*, 2014; de Onis and Branca, 2016), and therefore results in a decline in stature of the population over time, as seen in Guatemalan (Keep and Bogin, 1999) and Venezuelan (Bogin, 1999) populations during periods of low nutrition. In addition, populations living in colder temperatures or at higher altitudes tend to have shorter limbs and are therefore shorter in stature (Mueller *et al.*, 1980; Katzmarzyk and Leonard, 1998). Different populations are subject to very different environmental conditions, resulting in variations in stature between these populations (Cardoso, 2009; Baines *et al.*, 2011). As such, methods used to estimate stature, particularly regression equations, are population-specific and should not be applied to populations different from the reference population (Trotter and Gleser, 1951; Bidmos, 2008b; Dayal *et al.*, 2008; Cardoso *et al.*, 2016; Khanal *et al.*, 2017a).

Table 2. Populations with regression equations for the estimation of stature from fragmentary femora.

Population	Reference	SEE (± cm)
Indian	Ghosh *et al.* (2015)	-
Nepalese	Khanal *et al.* (2017a)	1.65-2.39
Thai	Fongkete *et al.* (2016)	5.15-6.42
Korean	Lee *et al.* (2014)	2.91-5.83
North American	Simmons *et al.* (1990)	5.47-7.16
Black and white South African	Bidmos (2008a, 2008b)	3.71-5.31

Stature is also largely influenced by age (Trotter and Gleser, 1951; Raxter *et al.*, 2006). Stature increases during childhood and adolescence, remains relatively stable during adulthood and then begins to decline with increasing age (Trotter and Gleser, 1951; Galloway, 1988; Cline *et al.*, 1989; Sjøvold, 2000; Raxter *et al.*, 2006; Fernihough and McGovern, 2015). This decline in stature is a result of compression of both the intervertebral discs and vertebral bodies, as well as a loss of elasticity of soft tissues (Galloway, 1988; Sjøvold, 2000; Raxter *et al.*, 2006; Niskanen *et al.*, 2013; Fernihough and McGovern, 2015).

Table 3. Populations with regression equations for the estimation of stature from fragmentary tibiae.

Population	Reference	SEE (± cm)
Kenyan	Mandela *et al.* (2013)	1.87-2.51
Nigerian	Ugochukwu *et al.* (2016)	3.42-4.05
Thai	Fongkete *et al.* (2016)	5.79-6.71
North American	Holland (1992)	5.47-7.16
White South African	Chibba and Bidmos (2007)	3.71-5.31

This age-related decrease in stature should be taken into account when estimating stature from skeletal remains, and thus many authors have proposed stature estimation equations that include an age-correction factor (Trotter and Gleser, 1951; Galloway, 1988; Cline *et al.*, 1989; Giles, 1991; Raxter *et al.,* 2006). However, there is no agreement as to the rate of this decrease in stature with age (Trotter and Gleser, 1951; Galloway, 1988; Raxter *et al.,* 2006). There is also no consensus regarding the age at which this decline in stature begins, with researchers suggesting ages of 25 (Borkan and Norris, 1977), 30 (Trotter and Gleser, 1951; Sorkin *et al.,* 1999; Raxter *et al.,* 2006), 40 (Cline *et al.,* 1989; Chandler and Bock, 1991), and 45 (Galloway, 1988). However, Cline *et al.* (1989) suggest that the decrease in stature with age is not significant between the ages of 20 and 60 years. It is also challenging to adjust for age when dealing with forensic cases as age is described as an interval or age range, rather than a point estimate (Priya, 2017).

2.5. Challenges with stature estimation methodology

When developing stature estimation methods, researchers make use of documented statures available in the various skeletal collections. These documented data are not the living stature of individuals, but rather the cadaver length/height which is measured prior to embalming (Bidmos, 2005; Hunt and Albanese, 2005; Dayal *et al.*, 2009; Cardoso *et al.*, 2016). Due to the compression of soft tissues such as intervertebral discs in an upright or standing position, as well as a loss of muscle tone post-mortem, living stature has been shown to be considerably less than cadaver length (Manouvrier, 1892; Trotter and Gleser, 1952; Cardoso *et al.*, 2016). As such, a conversion factor is required to convert cadaver length to living stature (Trotter and Gleser, 1952; de Mendonça, 2000; Bidmos, 2005; Cardoso *et al.*, 2016). Many conversion factors have been proposed, including 0 cm (Dupertius and Hadden, 1951), 1.9 cm (Bidmos, 2005), 2 cm (Manouvrier, 1892; Correa, 1932), 2.5 cm (Trotter and Gleser, 1952), 4.1 cm (Bidmos, 2005) and 4.3 cm (Cardoso *et al.*, 2016), however no consensus has yet been reached regarding which value to use (Cardoso *et al.*, 2016). Furthermore, in a South African context, cadaver lengths, when available, have questionable accuracies (Lundy, 1985; Bidmos, 2005), with differences of 1.89-8.45 cm between living stature estimated using total skeletal height, and living stature estimated using documented cadaver lengths (Bidmos, 2005). In addition, the soft tissue correction factors used to convert TSH to living stature tend to underestimate stature in South Africans (Bidmos, 2005; Bidmos and Manger, 2012; Brits *et al.*, 2017), and the new sex- and population-specific factors proposed by researchers have yet to be validated (Bidmos and Manger, 2012; Brits *et al.*, 2017). Therefore, instead of deriving regression equations to estimate living stature or cadaver length, many researchers regress bone measurements directly against TSH calculated using the anatomical method (Lundy, 1983; Chibba and Bidmos, 2007; Bidmos, 2008a, 2008b; Dayal *et al.*, 2008; Gocha *et al.*, 2013).

As a result of secular change as described above (section 2.4., page 12), populations have either increased or decreased in stature over time (Moore and Ross, 2013; Perkins *et al.,* 2016). Therefore, the statures of individuals from modern populations are often not comparable to those from individuals of the same population that lived in the past (Myburgh *et al.,* 2017). Since many skeletal collections include individuals that lived mainly in the last century or two (Hunt and Albanese, 2005; Dayal *et al.,* 2008), these collections may no longer be representative of the living population (Hunt and Albanese, 2005; Dayal *et al.,* 2008; Dirkmaat *et al.,* 2008; Komar and Grivas, 2008; Brits *et al.,* 2017). It is for this reason that many researchers are now developing stature estimation equations based on bone measurements from living individuals using X-rays (Ibrahim *et al.,* 2017; Milani *et al.,* 2017), computed tomographic (CT) scans (Giurazza *et al.,* 2012; Guirazza *et al.,* 2013) or magnetic resonance imaging (MRI) scans (Bidmos and Manger, 2012; Brits *et al.,* 2017).

Secular change has also resulted in regression equations being time-specific, meaning that equations developed from individuals in the past should not be used to estimate the stature of individuals from modern populations (Trotter and Gleser, 1958; Cardoso *et al.,* 2016). As such, regression equations must continuously be re-evaluated and revised (Cardoso *et al.,* 2016; Brits *et al.,* 2017).

CHAPTER THREE

Materials and Methods

3.1. Materials

Two samples were used in this study. The first sample was for the derivation of regression equations for the estimation of total skeletal height (TSH) and tibial length (TL) from measurements representing tibial fragments. This sample consisted of 200 complete black South African skeletons (100 male and 100 female) obtained from the Raymond A. Dart Collection of Human Skeletons, housed in the School of Anatomical Sciences at the University of the Witwatersrand, Johannesburg, South Africa. Various populations are represented in this skeletal collection, including Zulu, Sotho, Tswana, Xhosa and Ndebele groups. While previous studies have cited no statistically significant differences in cranial elements between these groups (De Villiers, 1968; Lundy, 1983), more recent studies have indeed shown morphological differences (Franklin *et al*., 2005; Franklin *et al.*, 2007). However, due to a lack of methodology distinguishing between these groups in South African forensic anthropology, and due to the fact that forensic anthropologists are generally unaware of the subgroup to which unidentified skeletal remains belong, these various groups were pooled and regarded as a single population (Franklin *et al*., 2008).

The ages of the individuals ranged between 20 and 60 years. This age range is ideal as the decrease in stature that occurs with age as a result of compression of cartilage and intervertebral discs (Trotter and Gleser, 1951; Raxter *et al.*, 2006) is not significant between the ages of 20 and 60 (Cline *et al.*, 1989). In addition, the lower limit of 20 years was selected as it has been shown that at this age, both males and females are assumed to have attained skeletal maturity and growth cessation (Cunningham *et al.*, 2016).

Only complete skeletons, comprising a complete skull, vertebrae (C2-S1), femur, tibia, talus and calcaneus were used. Skeletons with any obvious pathological abnormalities, such as diffuse idiopathic skeletal hyperostosis (DISH), or which had fractures, broken edges, fused vertebrae, or excessive osteophytic lipping were excluded.

The second sample was the validation sample which was used in order to test the accuracy of the regression equations that were derived in this study. This sample was also used to test the reliability of equations specific for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) in estimating stature in black South Africans. This sample consisted of 20 black South African skeletons equally distributed by sex and ranging between the ages of 20 and 60 years. The same exclusion criteria were applied to this sample as the sample used to derive the regression equations.

3.2. Methods

For each skeleton, the TSH using Fully's (1956) anatomical method as revised by Raxter *et al.* (2006) was calculated. This method was used for a number of reasons. Firstly, the recorded cadaver lengths in the Raymond A. Dart Collection, when present, have been shown to be questionable as a result of measurement errors, and therefore cannot be used with confidence in the derivation of regression equations (Lundy, 1983; Bidmos, 2005). Secondly, there is still no consensus as to the conversion factors used to convert cadaver length into living stature (Cardoso *et al.*, 2016), with suggestions ranging between 0 cm (Dupertius and Hadden, 1951) and 4.1 cm (Bidmos, 2005). Lastly, the values calculated for converting TSH into living stature in black South African populations have yet to be tested and validated (Bidmos and Manger, 2012; Brits *et al.,* 2017). Therefore, deriving regression equations from cadaver lengths or estimated living statures may be unreliable and using TSH, which does not require any conversion factors, is considered to be more accurate (Lundy 1988).

3.2.1. Anthropometric measurements

The following measurements, as described by Raxter *et al.* (2006), were measured in millimetres and were taken in order to calculate TSH:

1) Basibregmatic height, defined as the distance between bregma and basion (Figure 1);
2) Maximum height of vertebra C2, measured anteriorly from the highest point of the dens to the lowest point of the body in the midline (Figure 2);
3) Maximum body heights of vertebrae C3 to L5, measured anteriorly in the midline as illustrated in Figure 3;
4) Maximum height of S1, measured anteriorly and in the midline from the most superior to most inferior aspect of the body, where it fuses with S2 (Figure 4);
5) Physiological length of the femur, defined as the distance between the most superior aspect of the head and the inferior margins of the condyles, with both condyles touching the endplate of the osteometric board (Figure 5);
6) Condylomalleolar length of the tibia (hereafter referred to as tibial length or TL), defined as the distance between the most superior aspect of the lateral condyle and the most inferior point of the medial malleolus (Figure 6); and
7) Articulated height of the talus and calcaneus, measured in the physiological position between the trochlea of the talus and the most inferior aspect of the calcaneal tuberosity with both medial and lateral edges of the trochlea touching the endplate of the osteometric board (Figure 7).

Measurements of the skull were taken using a spreading calliper while vertebral measurements were taken using a sliding calliper. Measurements of the long bones and tarsals were taken using an osteometric board. Per convention, the left femur, tibia, talus and calcaneus were measured (Buikstra and Ubelaker, 1994). TSH was then calculated by summing the values of all these measurements. When additional vertebrae were present, such as a 13th thoracic or 6th lumbar vertebra, the maximum midline heights of these vertebrae were also included in the calculation of TSH.

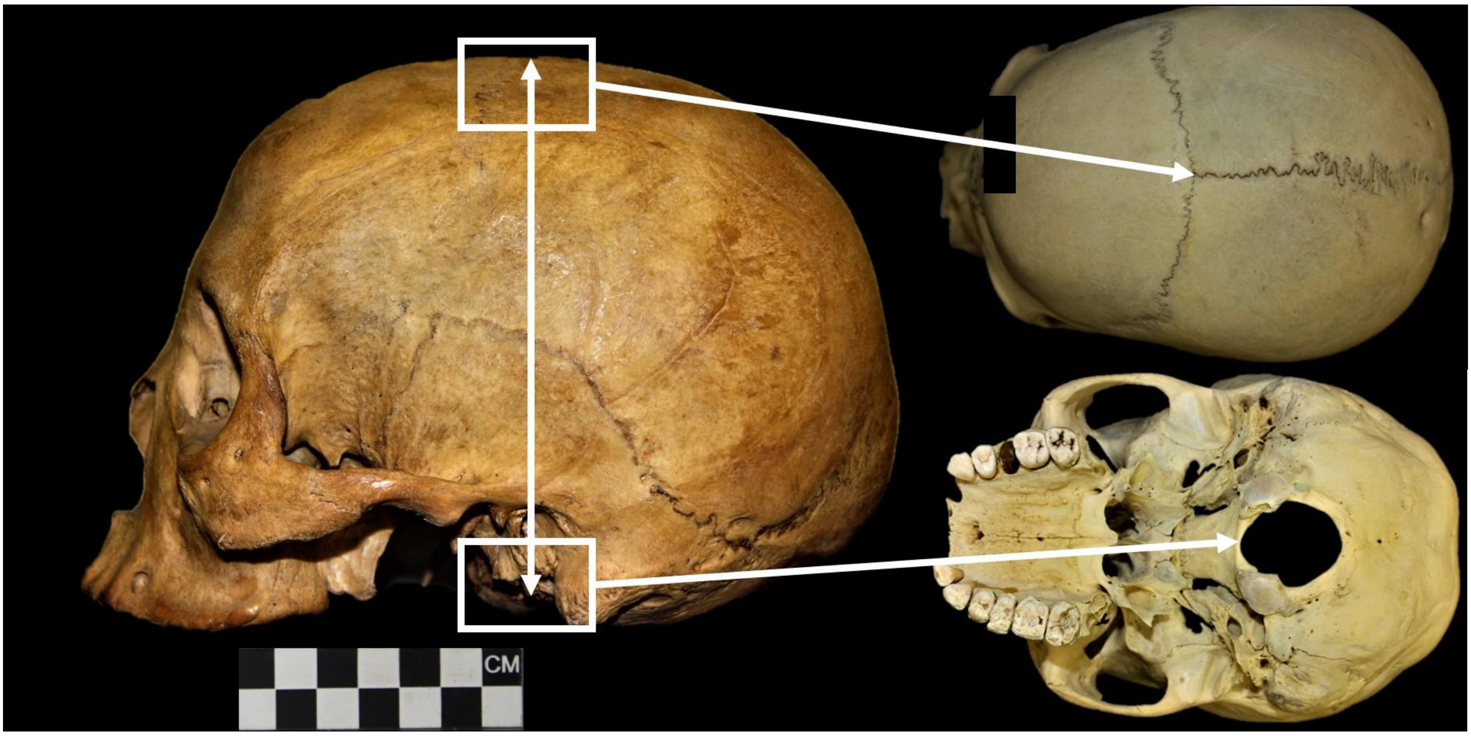


Figure 1. Left lateral (left), superior (top right) and inferior (bottom right) views of the skull showing measurement of basibregmatic height, between bregma (top right) and basion (bottom right).

Figure 2. Anterior view of vertebra C2 (axis) showing measurement of body height.

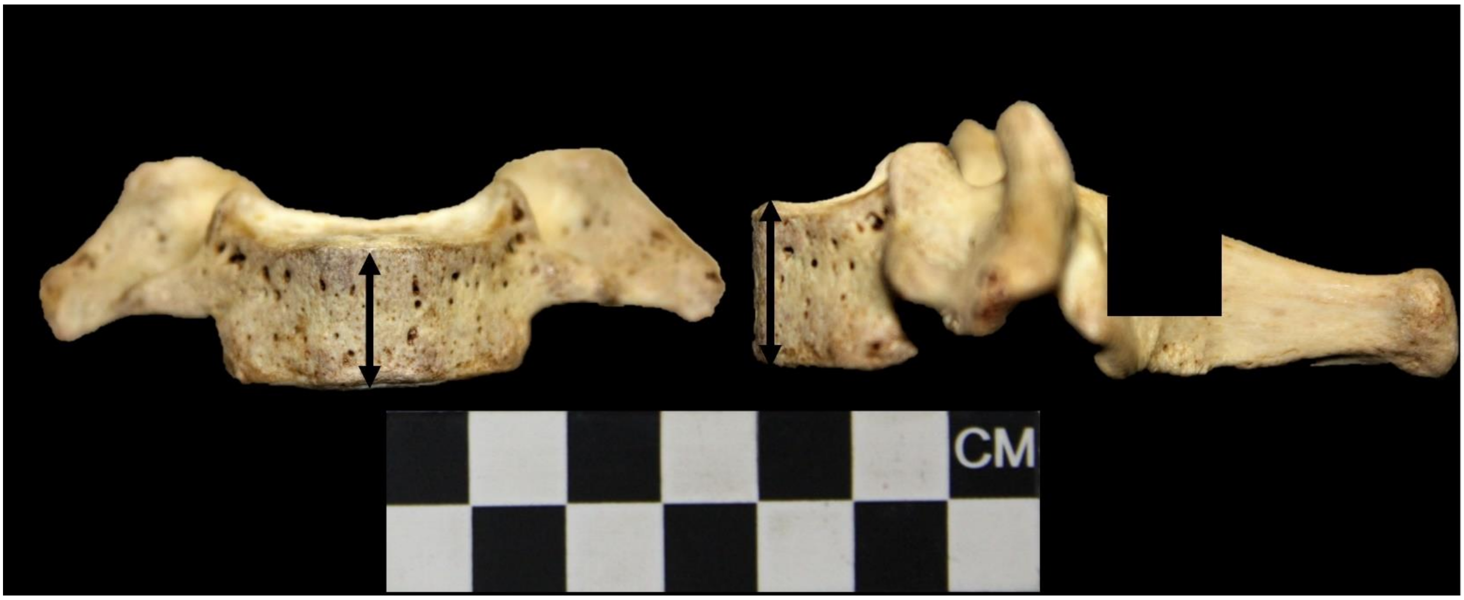


Figure 3. Anterior (left) and lateral (right) views of vertebra C7 showing measurement of body height. This same measurement was taken for vertebrae C3 to L5.

Figure 4. Anterior view of the sacrum showing measurement of body height of S1.

Figure 5. Anterior view of the femur showing measurement of the physiological length.

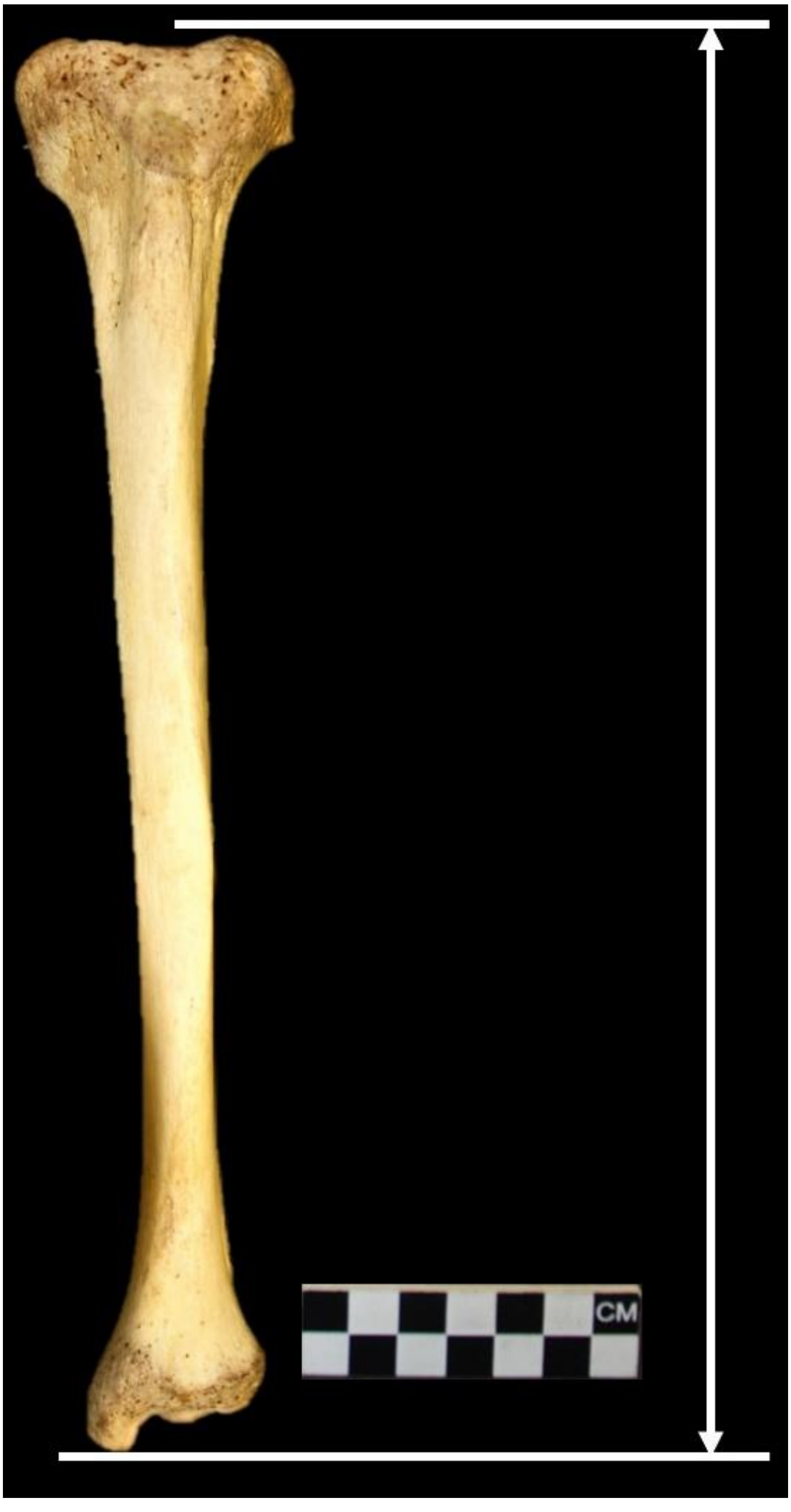


Figure 6. Anterior view of the tibia showing measurement of condylomalleolar/tibial length.

Figure 7. Lateral view of articulated talus and calcaneus showing measurement of talocalcaneal height.

Eleven measurements, as defined in Table 4, were then taken on each tibia to represent various tibial fragments. The first six measurements, i.e. proximal breadth (PXBT) (Figure 8), distal breadth (DSBT) (Figure 9), length of superior lateral articular facet (LTCL) (Figure 10), breadth of superior lateral articular facet (LTCB) (Figure 10), length of superior medial articular facet (MTCL) (Figure 10) and breadth of superior medial articular facet (MTCB) (Figure 10) were taken following stipulations by Chibba and Bidmos (2007). The landmark for distal shaft circumference (DSC) (Figure 9) was first described by Steele and McKern (1969) when estimating maximum tibial length from fragments in a North American population. Proximal shaft circumference (PXC) (Figure 8), soleal circumference (SLC) (Figure 11), proximal length (PXLT) (Figure 11) and nutrient foramen length (NFLT) (Figure 12) were developed in the present study in order to introduce some additional fragmentary measurements.

Table 4. Definition of tibial measurements

Measurement	Abbreviation	Definition
Proximal breadth*	PXBT	The maximum breadth between the medial and lateral condyles including the facet for the fibula. The bone should be rotated to find the absolute maximum
Distal breadth*	DSBT	The maximum breadth between the medial malleolus and fibular notch
Length of superior lateral and medial articular facets**	LTCL and MTCL	The maximum lengths of the lateral and medial articular facets measured along the margins in an anterior-posterior direction
Breadth of superior lateral and medial articular facets**	LTCB and MTCB	The medio-lateral distance of the lateral/medial condyle from the inner surface of the lateral/medial intercondylar tubercle to the outer margin of the articular facet
Proximal shaft circumference†	PXC	The circumference of the shaft at the distal point of the tibial tuberosity where the rugosity terminates
Soleal circumference†	SLC	The circumference of the shaft at the most distal point of the soleal line, where the rugosity terminates. The soleal line may be punctuated with multiple parts. The measurement is taken at the distal point of the very last part
Distal shaft circumference†	DSC	The circumference of the shaft at the point where the anterior crest crosses over to the medial border of the shaft above the medial malleolus.
Proximal length**	PXLT	The distance between the medial margin of the superior medial articular facet and the most distal point of the soleal line as defined above. A spreading calliper may be used to take this measurement if the sliding calliper is not long enough.

Table 4 (continued). Definition of tibial measurements		
Nutrient foramen length**	NFLT	The distance between the most superior point on the intercondylar eminence, usually the medial intercondylar tubercle, and the distal border of the nutrient foramen. A spreading calliper may be used to take this measurement if the sliding calliper is not long enough.

* Measured using an osteometric board

** Measured using a sliding calliper

† Measured using string following the contour of the bone

Figure 8. Anterior view of the proximal tibia showing measurements of proximal breadth (PXBT) and proximal shaft circumference (PXC).

Figure 9. Anterior view of the distal tibia showing measurements of distal breadth (DSBT) and distal shaft circumference (DSC).

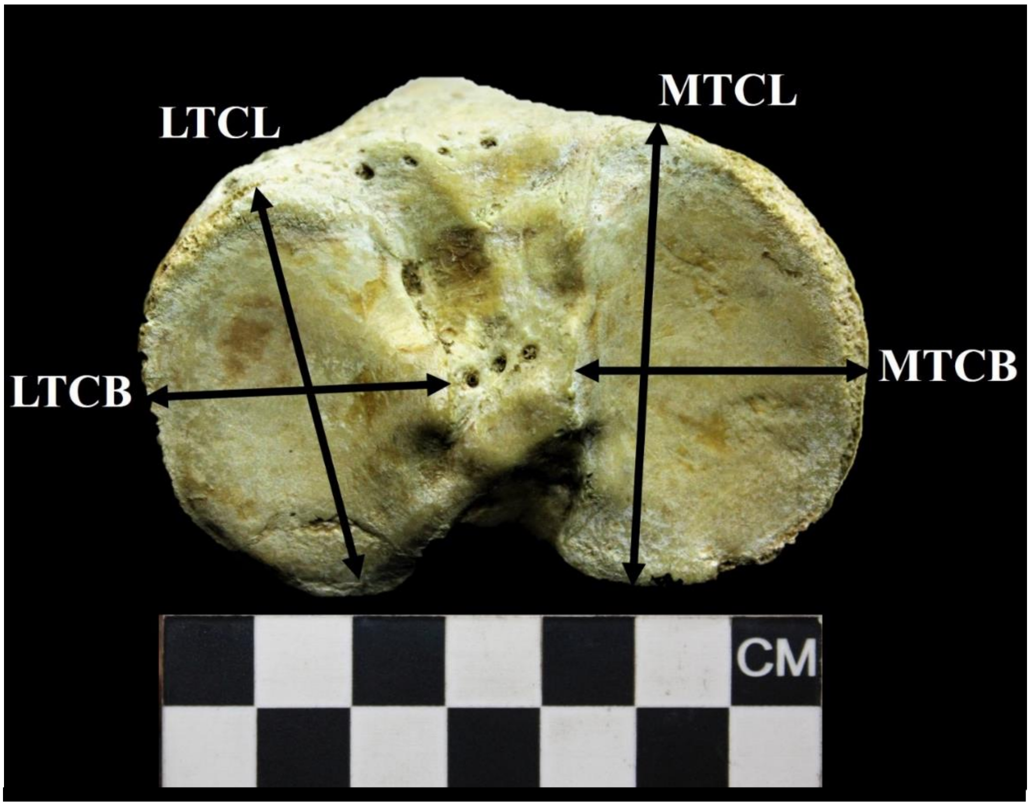


Figure 10. Superior view of the proximal tibia showing measurements of the superior medial and lateral articular facets. LTCL: length of superior lateral articular facet; LTCB: breadth of superior lateral articular facet; MTCL: length of superior medial articular facet; MTCB: breadth of superior medial articular facet.

3.2.2. Data analysis

The repeatability of measurements was assessed by calculating the intra- and inter-observer error rates from measurements taken on twenty randomly selected skeletons using Lin's concordance correlation co-efficient of reproducibility (Lin, 1989). Both TSH and tibial measurements were repeated. However, only two vertebrae representative of the cervical region and one vertebra representative of each of the other vertebral regions were re-measured as suggested by Bidmos and Manger (2012). These included C2, C7, T10 and L5 vertebrae.

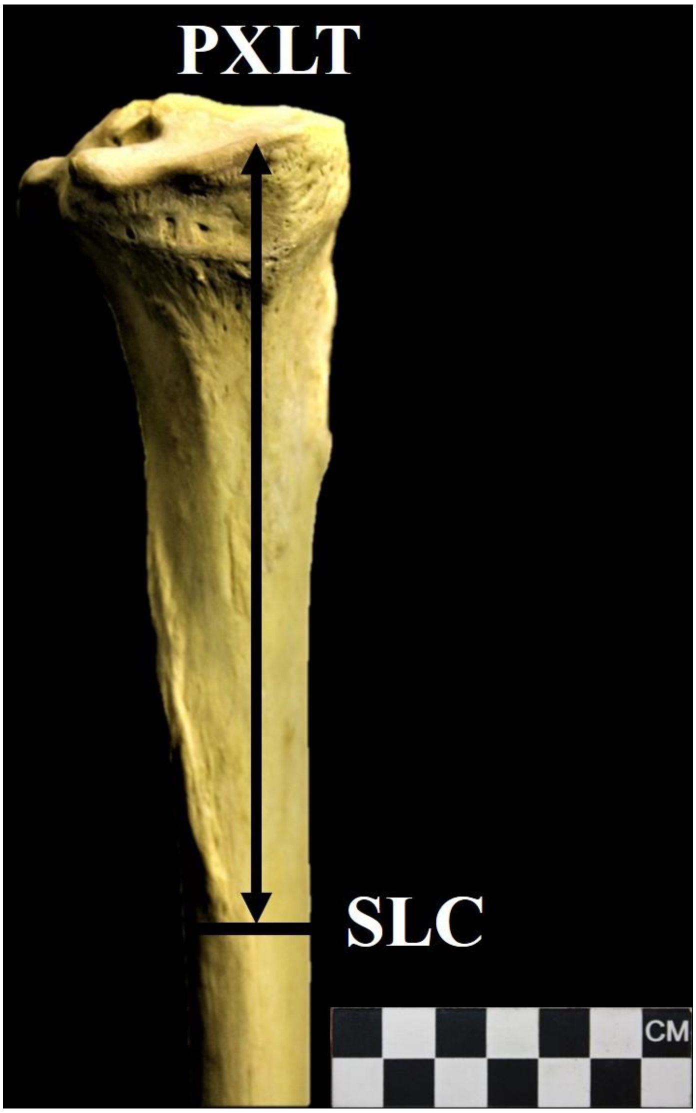


Figure 11. Medial view of the tibia showing measurements of soleal circumference (SLC) and proximal length (PXLT).

Statistical analyses were conducted on each sex separately using the IBM SPSS (version 20) software program for Windows. The sexes were assessed separately since regression equations have been shown to be sex-specific (Trotter and Gleser, 1952; Lundy and Feldesman, 1987; Dayal *et al.*, 2008). The data were tested for normality using the Shapiro-Wilk test (Shapiro and Wilk, 1965) and the outlier labelling rule (Hoaglin *et al.*, 1986; Hoaglin and Iglewicz, 1987) was used to detect outliers.

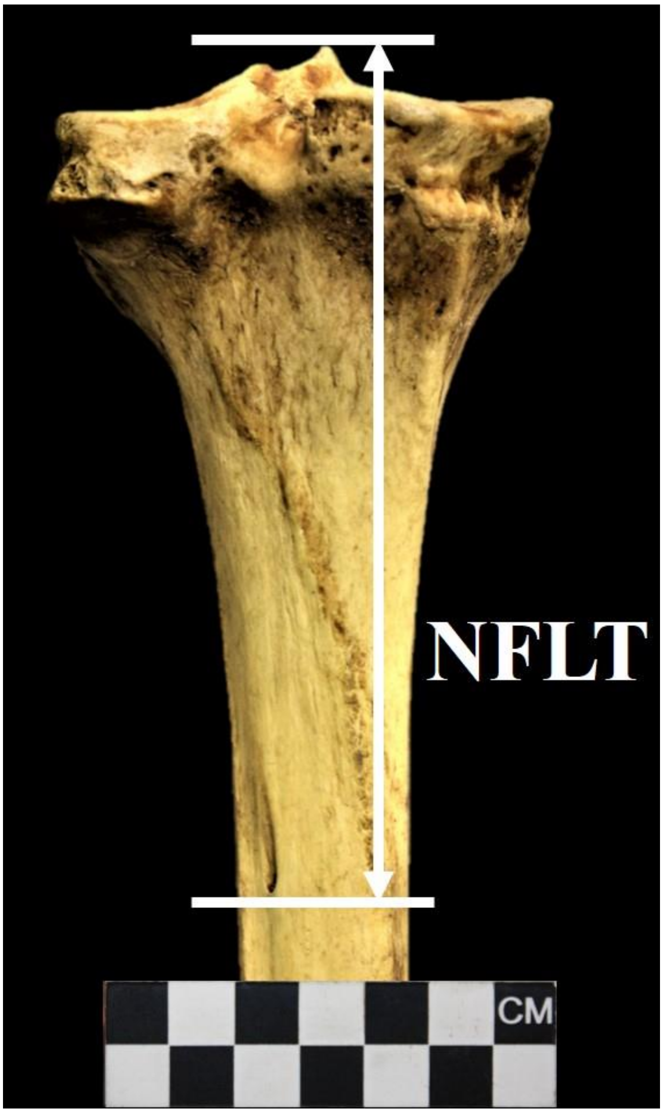


Figure 12. Posterior view of the proximal tibia showing measurement of nutrient foramen length (NFLT).

Descriptive statistics, including minimum, maximum, mean and standard deviation for both TSH and tibial measurements were calculated separately for each sex. Means and standard deviations were then compared between the sexes using T-tests.

For normally distributed variables, Pearson's correlation was used to assess the relationship between each tibial measurement and both TSH and tibial length (TL). For non-normally distributed variables, Spearman's correlation was used to assess these relationships.

Regression equations were then formulated by regressing both TSH and TL on individual measurements and combinations of measurements of the tibia. Univariate equations were derived only for those variables showing significant correlations with TSH and or TL, and multivariate equations were derived using step-wise analyses on all tibial variables. Multiple regressions were also derived on tibial variables associated with specific regions of the tibia including the proximal tibia, tibial shaft, distal tibia and posterior tibia. This is important as step-wise analyses often include variables from various regions of the bone and thus, in order to use these equations, an almost complete bone is required. However, this is generally not the case and only specific regions of bones, such as the epiphyses or the shaft, are available for analysis. Regression equations specific for these regions therefore need to be established. All analyses were conducted using a 95 % confidence interval.

3.3. Accuracy and reliability

3.3.1. Accuracy of equations

The accuracies of the regression equations derived from the present study were tested using the validation sample of 10 female and 10 male black South African skeletons. This was done by estimating TSH and TL from both univariate and multivariate equations and calculating the percentage of individuals whose actual measured TSHs and TLs fell within 1 and 2 standard errors of estimate (SEEs) of these estimated TSHs and TLs. Following guidelines by Bidmos (2008a), 1 and 2 SEEs (± cm) were used to test the accuracy in order to include the majority of the population in the assessment.

To further assess the accuracies of the equations, paired T-tests were conducted in order to determine if there were any significant differences between the TSHs and TLs estimated using these equations and the actual measured TSHs and TLs.

3.3.2. Direct vs indirect methods

An assessment of the accuracies of the direct and indirect methods of estimating TSH was made. In the direct method, TSH is estimated directly from tibial measurements, while in the indirect method, TL is first estimated from tibial measurements and then in a second step, this estimated TL is used to estimate TSH. In order to achieve this, the entire study sample was used to derive regression equations for each sex for estimating TSH from TL (indirect method). The TLs estimated in the validation sample were then used to estimate TSHs using these equations. Paired T-tests were used to compare the TSHs estimated in the indirect method to the actual measured TSHs. Paired T-tests had also already been conducted using TSHs estimated using the direct method (section 3.3.1., page 32) in order to compare them to the actual measured TSHs.

A comparison of the SEEs associated with each method was also made which required the SEEs for the equations in the indirect method to be adjusted. This is necessary since the regression equation used in the initial step of estimating TL from tibial measurements has its own SEE, and the equation used in the second step, estimating TSH from TL, also has its own associated SEE. The overall TSH estimate should then incorporate the SEEs from both steps. The SEEs were adjusted following instructions by Steele (1970), whereby the SEE associated with the estimation of TL was multiplied by the slope in the equation used to estimate TSH from TL. The SEE associated with the estimation of TSH was then added to this product. The SEEs associated with each method were compared using paired T-tests.

3.3.3. Reliability of equations

Regression equations using tibial measurements have been derived for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992). Univariate equations for proximal breadth (PXBT) (for males) and distal breadth (DSBT) (for females) were developed for South African whites, while equations for the length of the superior medial articular facet (MTCL) were developed for both sexes in North American blacks. In order to confirm the population-specificity of these equations, the reliability of those derived for white South Africans and black North Americans in estimating stature in black South Africans was tested. This was done by substituting the values of PXBT, DSBT and MTCL from the validation sample into the various sex-specific equations derived from each population. The resulting stature estimates were then compared in linear graphs to the actual measured statures, as well as to the statures estimated using the equations from the present study. Paired T-tests were then used to determine whether the statures calculated using the various equations were significantly different from the actual measured statures.

Since the equations derived by Holland (1992) were based on estimated living statures (ELSs) and not TSHs, the TSHs calculated using equations from the present study and those from Chibba and Bidmos (2007), as well as the actual measured TSHs, were converted to ELSs using Fully's (1956) soft tissue correction factors.

3.4. Ethics

Ethical clearance for this study was obtained from the Human Research Ethics Committee (Medical) at the University of the Witwatersrand (Clearance Certificate No W-CJ-170301-2).

CHAPTER FOUR

Results

Stature estimation is one of the steps included when constructing the biological profile of unknown skeletal remains (Bidmos and Asala, 2005). Regression equations are most commonly used to estimate stature and can be used with fragmentary remains (Bidmos, 2008a). Regression equations were established to estimate both total skeletal height (TSH) and tibial length (TL) from fragments of the tibia in black South Africans.

4.1. Repeatability

Lin's concordance correlation coefficient of reproducibility (Lin, 1989) was used to determine the intra- and inter-observer error rate for measurements of TSH, including basibregmatic height, heights of C2, C7, T10, L5 and S1 vertebrae, physiological length of the femur, condylomalleolar length of the tibia and talocalcaneal height, as well as the various tibial variables. Most intra- and inter-observer measurements had Pc-values equal to or greater than 0.90 (Tables 2 and 3), and in general, intra-observer repeatability was consistently better (had higher Pc-values) than inter-observer repeatability. The intra- and inter-observer measurements of talocalcaneal height had Pc-values of 0.87 and 0.88 respectively (Table 2). However, the mean difference in measurements was 0.7 mm and 0.9 mm respectively, both well within the 2 mm range of error widely accepted by forensic anthropologists (Stull *et al.*, 2013, 2014). The inter-observer measurements of basibregamtic height and proximal length (PXLT) had Pc-values of 0.81 and 0.83 respectively (Tables 2 and 3), with mean errors of 4 mm and 1.8 mm respectively, with the latter falling within the acceptable error range (Stull *et al.*, 2013, 2014). These results indicate that the measuring technique used is adequate and nearly all measurements are highly repeatable (Lin, 1989).

4.2. Outliers and normality

Only two outlying variables were detected using the outlier labelling rule (Hoaglin *et al.,* 1986; Hoaglin and Iglewicz, 1987); one proximal shaft circumference (PXC) measurement in the male sample and one soleal circumference (SLC) measurement in the female sample. The two individuals associated with these variables were removed from the sample entirely and therefore statistical analyses were run on 99 males and 99 females.

The Shapiro-Wilk test (Shapiro and Wilk, 1965) showed that most variables were normally distributed, except for proximal shaft circumference (PXC) in the male sample, and proximal breadth (PXBT) and soleal circumference (SLC) in the female sample. Therefore, the non-parametric Spearman's correlation coefficient was used to determine the correlation between these variables and both TSH and condylomalleolar length of the tibia (tibial length or TL).

Table 5. Lin's concordance correlation coefficients of reproducibility (Pc-values) for intra- and inter-observer repeatability of total skeletal height (TSH) measurements.

Variable	Pc-value	
	Intra-observer	**Inter-observer**
Basibregmatic height	0.99	0.81
Height of C2	0.99	0.99
Height of C7	0.94	0.97
Height of T10	0.98	0.92
Height of L5	0.99	0.96
Height of S1	0.92	0.92
Physiological length of femur	0.99	0.99
Condylomalleolar length of tibia	0.99	0.99
Talocalcaneal height	0.87	0.88

Table 6. Lin's concordance correlation coefficients of reproducibility (Pc-values) for intra and inter-observer repeatability of tibial measurements.

Variable	**Pc-value**	
	Intra-observer	**Inter-observer**
PXBT	0.99	0.93
DSBT	0.97	0.91
LTCL	0.98	0.91
LTCB	0.99	0.90
MTCL	0.99	0.90
MTCB	0.98	0.90
PXC	0.99	0.90
DSC	0.99	0.95
SLC	0.99	0.96
PXLT	0.99	0.83
NFLT	0.99	0.99

4.3. Descriptive statistics

The descriptive statistics of the measurements, including minimums, maximums, means and standard deviations, are summarized in Table 4. Total skeletal height (TSH) ranged between 135.37 and 168.27 cm for males with a mean TSH of 152.83 cm, while females had a range of 128.29 and 155.52 cm with a mean of 141.73 cm. Condylomalleolar length, or tibial length (TL) ranged between 32.05 and 44.30 cm for males and between 31.30 and 41.65 cm for females, with mean values of 38.83 and 35.69 cm respectively. Males presented with significantly ($p<0.001$) higher mean values for TSH, TL and all other tibial variables compared to females. The ranges of standard deviations for TSH, TL and all other tibial variables were larger for males (2.07-16.84) than for females (1.69-13.26).

Table 7. Descriptive statistics including minimum, maximum, mean and standard deviation (SD) in millimetres for total skeletal height (TSH) and tibial variables.

Variable	**Males**					**Females**					
	No.	**Min**	**Max**	**Mean**	**SD**	**No.**	**Min**	**Max**	**Mean**	**SD**	**P-value**
TSH (cm)	99	135.37	168.27	152.83	6.21	99	128.29	155.52	141.73	5.66	0.000
TL (cm)	99	32.05	44.30	38.83	2.39	99	31.30	41.65	35.69	2.02	0.000
PXBT	99	69.50	85.50	77.01	3.30	99	62.00	81.00	68.34	3.32	0.000
DSBT	99	46.00	58.50	52.49	2.62	99	41.50	54.00	46.83	2.53	0.000
LTCL	99	34.90	48.10	42.17	2.37	99	32.60	43.90	37.49	2.30	0.000
LTCB	99	29.40	39.50	34.47	2.21	99	25.90	37.60	30.76	2.00	0.000
MTCL	99	42.10	56.10	48.65	2.77	99	38.60	51.10	43.11	2.30	0.000
MTCB	99	30.60	41.00	35.00	2.07	99	27.30	36.80	31.18	1.69	0.000
PXC	99	99.00	137.00	114.26	8.37	99	83.00	123.00	102.26	8.18	0.000
DSC	99	79.00	107.00	92.30	5.91	99	69.00	100.00	81.31	5.73	0.000
SLC	99	67.00	92.00	77.57	5.02	99	56.00	85.00	69.97	5.17	0.000
PXLT	99	100.10	186.00	140.71	16.84	99	96.40	168.00	130.93	13.26	0.000
NFLT	99	94.30	153.50	123.76	12.09	99	84.90	140.60	114.55	10.86	0.000

4.4. Total skeletal height (TSH) and tibial variables (direct method)

The first objective of this study was to confirm the need for population-specific standards for estimating TSH, and thereby stature, from tibial fragments. This was done by testing the reliability of equations derived for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland,1992) in a sample of black South Africans. The results (which will be discussed in section 4.6.2.) show that these regression equations are indeed population-specific. New regression equations for estimating both TSH and TL from tibial fragments were therefore derived for black South Africans.

All tibial variables showed a significant correlation ($p<0.01$) with TSH for both males and females. This is illustrated in Figures 13 and 14 which show that all of these correlations were positive and linear. Univariate regression equations were therefore derived for all tibial variables. All tables presenting regression equations are arranged in decreasing order of correlation coefficient and increasing order of standard error of estimate (SEE).

In the male sample, correlations ranged between 0.42 for breadth of superior lateral articular facet (LTCB) and 0.65 for distal breadth (DSBT) (Table 8). For females, distal breadth (DSBT) (0.67) was most highly correlated with TSH, while proximal length (PXLT) displayed the lowest correlation (0.41) (Table 9). All correlations were considered moderate to strong based on the guidelines that were established by Evans (1996).

Regression equations for estimating TSH from individual variables of the tibia in males and females are presented in Tables 8 and 9 respectively. SEEs for these equations ranged between 4.75 cm and 5.66 cm for males, and between 4.23 cm and 5.20 cm for females. R^2, defined as the percentage variation in TSH as a result of tibial variables, ranged between 0.18 and 0.42 for males (Table 8) and between 0.17 and 0.45 for females (Table 9). While correlation coefficients were comparable between the sexes, the values of SEE for males were larger than those for females.

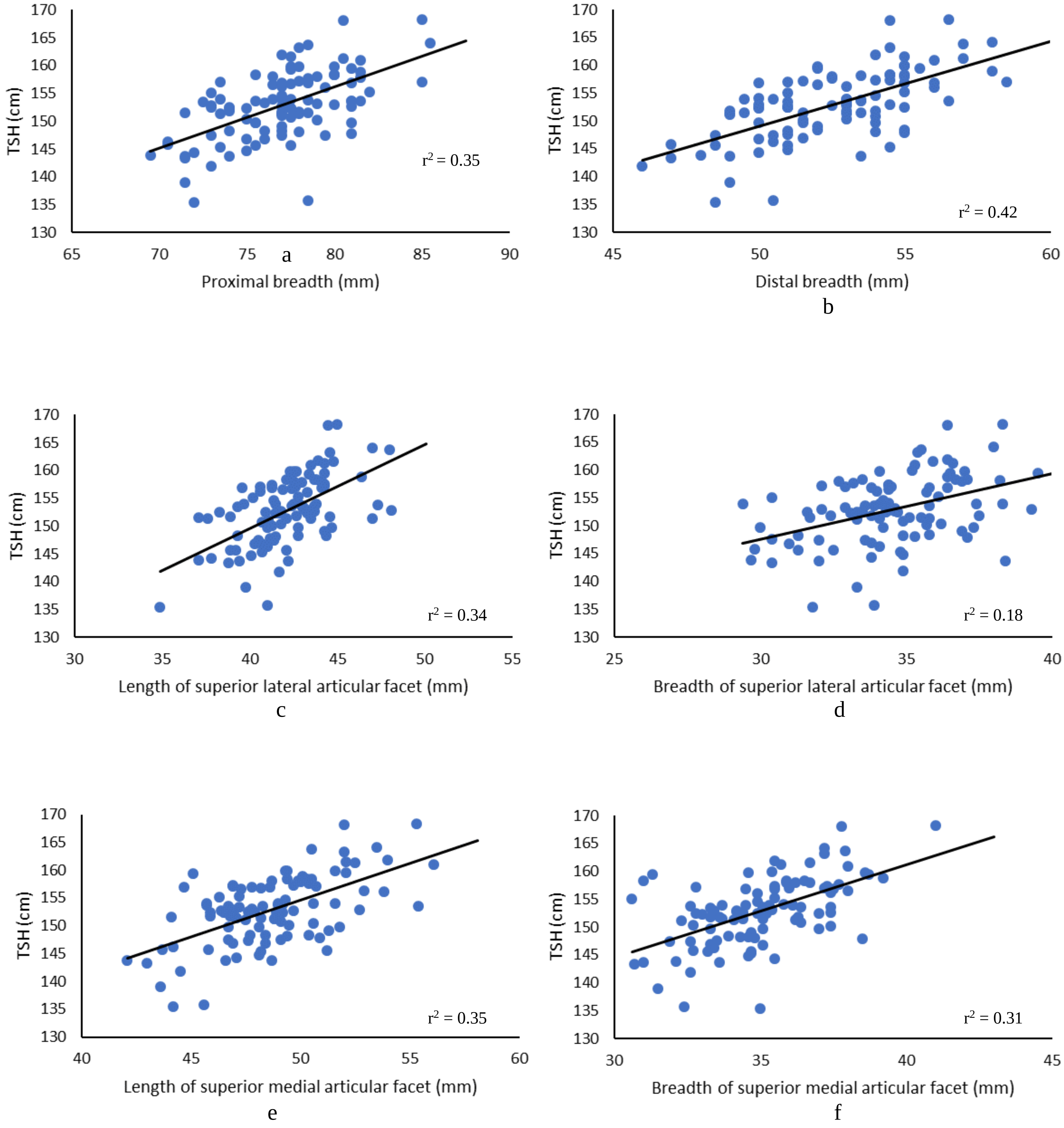


Figure 13. Scatter plots showing the association between total skeletal height (TSH) and PXBT (a), DSBT (b), LTCL (c), LTCB (d), MTCL (e) and MTCB (f) in males.

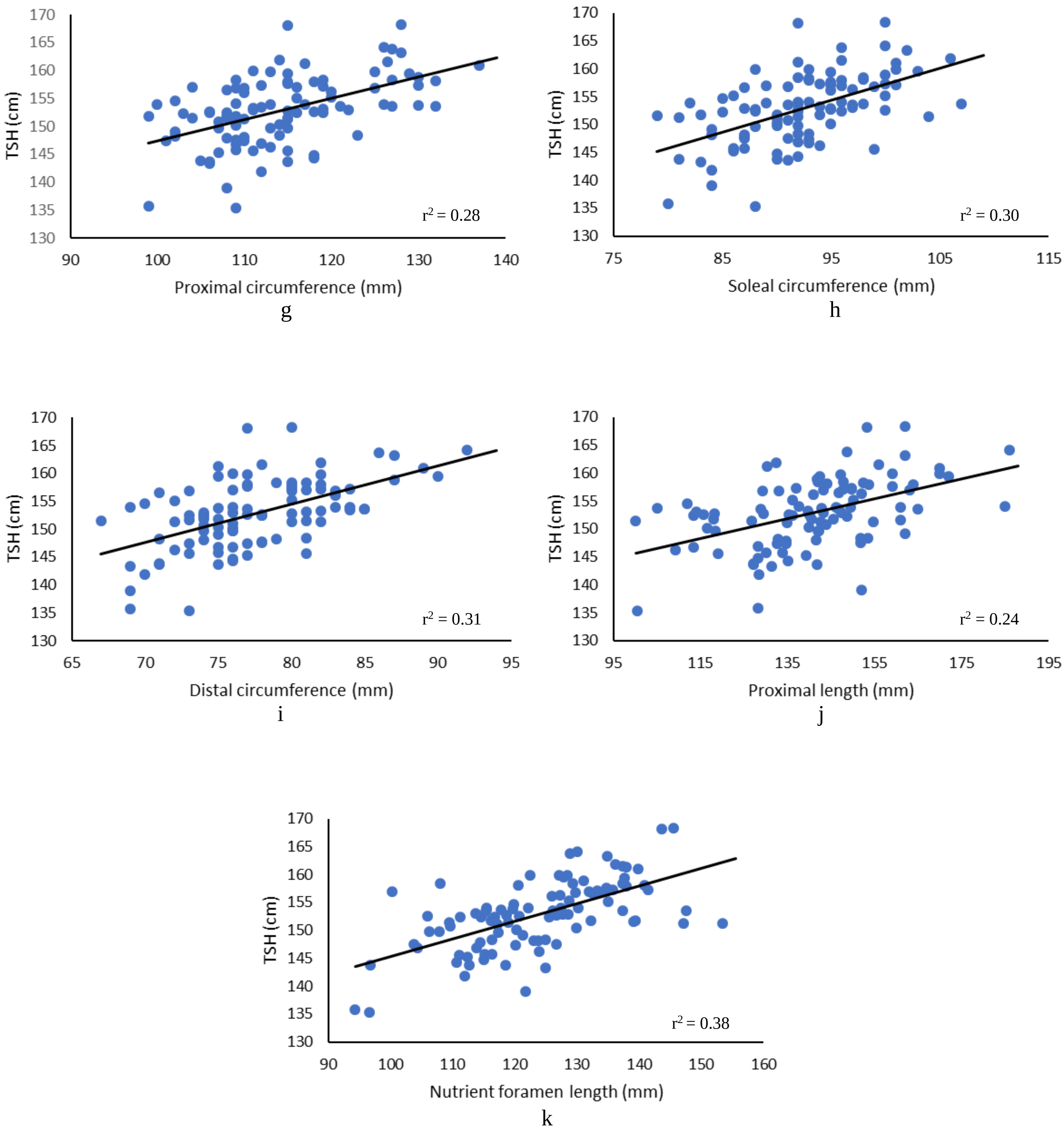


Figure 13 (continued). Scatter plots showing the association between total skeletal height (TSH) and PXC (g), SLC (h), DSC (i), PXLT (j) and NFLT (k) in males.

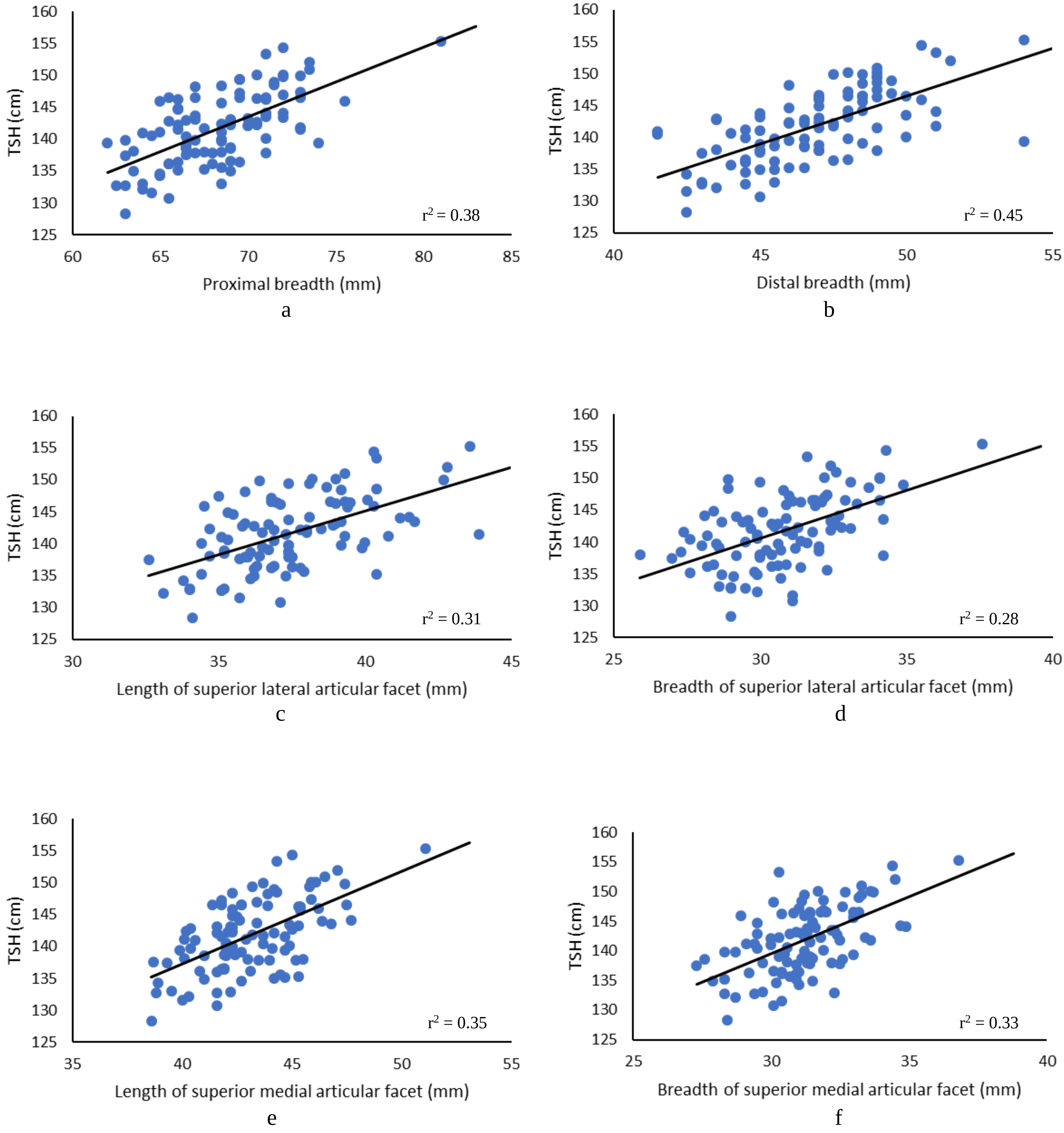


Figure 14. Scatter plots showing the association between total skeletal height (TSH) and PXBT (a), DSBT (b), LTCL (c), LTCB (d), MTCL (e) and MTCB (f) in females.

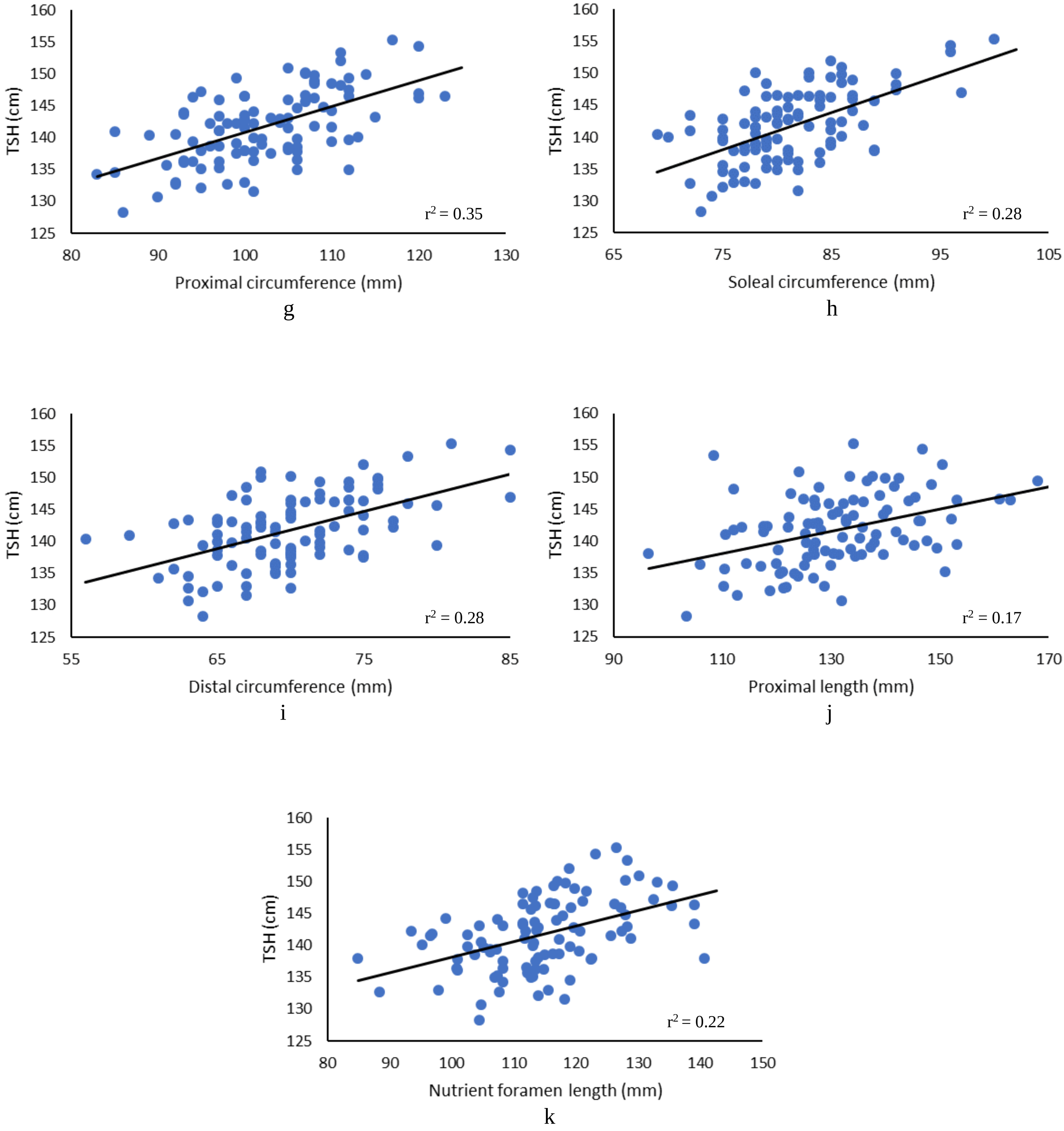


Figure 14 (continued). Scatter plots showing the association between total skeletal height (TSH) and PXC (g), SLC (h), DSC (i), PXLT (j) and NFLT (k) in females.

Table 8. Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from individual variables of the tibia for males. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Variable	**Correlation (r)**	**r^2**	**Slope**	**Intercept**	**SEE (± cm)**	**Accuracy**	
						1 SEE	**2 SEE**
DSBT	0.65	0.42	1.54	72.28	4.75	50 %	100 %
NFLT	0.62	0.38	0.32	113.48	4.90	60 %	90 %
PXBT	0.59	0.35	1.11	67.61	5.05	80 %	100 %
MTCL	0.59	0.35	1.31	88.91	5.05	70 %	100 %
LTCL	0.58	0.34	1.52	88.89	5.09	40 %	90 %
MTCB	0.56	0.31	1.67	94.27	5.18	80 %	100 %
DSC	0.56	0.31	0.69	99.60	5.19	40 %	100 %
SLC	0.55	0.30	0.58	99.66	5.21	80 %	100 %
PXC	0.53	0.28	0.38	109.51	5.36	50 %	100 %
PXLT	0.49	0.24	0.18	127.71	5.46	50 %	90 %
LTCB	0.42	0.18	1.18	112.21	5.66	60 %	100 %

TSH (cm) = variable (mm) x slope + intercept ± SEE (cm)

Table 9. Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from individual variables of the tibia for females. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Variable	Correlation (r)	r^2	Slope	Intercept	SEE (± cm)	Accuracy	
						1 SEE	2 SEE
DSBT	0.67	0.45	1.50	71.61	4.23	90 %	100 %
PXBT	0.62	0.38	1.09	67.16	4.38	80 %	100 %
PXC	0.59	0.35	0.41	99.97	4.59	60 %	100 %
MTCL	0.59	0.35	1.45	79.17	4.60	80 %	90 %
MTCB	0.57	0.33	1.92	81.91	4.66	80 %	100 %
LTCL	0.56	0.31	1.37	90.47	4.73	90 %	100 %
SLC	0.53	0.28	0.58	94.40	4.60	50 %	100 %
DSC	0.53	0.28	0.58	100.98	4.82	70 %	100 %
LTCB	0.53	0.28	1.50	95.63	4.83	80 %	100 %
NFLT	0.47	0.22	0.25	113.68	5.02	80 %	100 %
PXLT	0.41	0.17	0.17	119.01	5.20	90 %	100 %

TSH (cm) = variable (mm) x slope + intercept ± SEE (cm)

Tables 10 and 11 show the regression equations using combinations of tibial variables that best estimate TSH in males and females respectively using step-wise analysis. All equations had significant ($p>0.01$) correlation coefficients and were higher compared to those obtained from univariate equations for both males (0.76-0.81) and females (0.75-0.81). Furthermore, the SEEs (3.69-4.07 cm for males and 3.43-3.76 cm for females) were lower than those obtained using individual variables. Males and females had similar correlation coefficients, but the SEE values were larger for males. R^2 values were similar between the sexes, ranging between 0.58 and 0.66 for males, and between 0.56 and 0.66 for females.

Table 10. Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from combinations of variables of the tibia for males. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Variable	**Function**		
	1	**2**	**3**
DSBT	1.13	0.81	0.69
SLC		0.27	0.31
PXLT			0.08
NFLT	0.22	0.21	0.17
Intercept	65.91	58.34	55.44
SEE (± cm)	4.07	3.86	3.69
Correlation (r)	0.76	0.79	0.81
r^2	0.58	0.62	0.66
Accuracy 1 SEE	50 %	50 %	50 %
Accuracy 2 SEE	100 %	90 %	100 %

TSH (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

Table 12 shows further regression equations for estimating TSH using different combinations of tibial variables in males and females. These equations include variables associated with specific tibial regions including the proximal tibia, tibial shaft, distal tibia and posterior tibia. Correlation coefficients for these equations were significant ($p<0.01$) and comparable between the sexes (0.60-0.73 and 0.57-0.74 for males and females respectively). However, SEEs were larger for males (4.41-5.06 cm) than for females (3.93-4.70 cm).

The equation for the proximal tibia had the highest correlation and smallest SEE for both sexes, while the tibial shaft and posterior tibia equations had the lowest correlations and largest

SEEs in males and females respectively. Males and females had similar r^2 values, which ranged between 0.36 and 0.53 for males, and between 0.33 and 0.55 for females.

Table 11. Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from combinations of variables of the tibia for females. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Variable	**Function**		
	1	**2**	**3**
DSBT	1.35	0.98	0.70
MTCB			0.75
PXC		0.19	0.18
NFLT	0.19	0.18	0.18
Intercept	57.58	55.56	47.10
SEE (± cm)	3.76	3.55	3.43
Correlation (r)	0.75	0.79	0.81
r^2	0.56	0.62	0.66
Accuracy 1 SEE	60 %	70 %	50 %
Accuracy 2 SEE	100 %	100 %	90 %

TSH (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

Table 12. Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from combinations of variables in different regions of the tibia for males and females. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Function	**Slope**	
	Male	**Female**
1. Proximal tibia		
PXBT	0.11	0.18
LTCL	0.78	0.35
LTCB	-0.20	0.25
MTCL	0.55	0.40
MTCB	0.73	0.49
PXC	0.10	0.21
Intercept	54.41	55.29
SEE (± cm)	4.41	3.93
Correlation (r)	0.73	0.74
r^2	0.53	0.55
Accuracy 1 / 2 SEE	60 % / 90 %	70 % / 100 %
2. Tibial shaft		
PXC	0.12	0.25
SLC	0.24	0.37
DSC	0.32	-0.03
Intercept	91.73	88.25
SEE (± cm)	5.06	4.38
Correlation (r)	0.60	0.65
r^2	0.36	0.42

Table 12 (continued). Correlations and regression equations for the estimation of total skeletal height (TSH) (in cm) from combinations of variables in different regions of the tibia for males and females. Accuracy refers to the percentage of actual TSHs falling within 1 and 2 SEEs (± cm) of estimated TSHs.

Accuracy 1 / 2 SEE	70 % / 100 %	40 % / 100 %
3. Distal tibia		
DSBT	1.17	1.27
DSC	0.31	0.17
Intercept	67.41	70.62
SEE (± cm)	4.61	4.20
Correlation (r)	0.68	0.68
r^2	0.46	0.46
Accuracy 1 / 2 SEE	50 % / 100 %	90 % / 100 %
4. Posterior tibia		
PXLT	0.09	0.14
NFLT	0.26	0.21
Intercept	108.47	99.16
SEE (± cm)	4.74	4.70
Correlation (r)	0.65	0.57
r^2	0.42	0.33
Accuracy 1 / 2 SEE	50 % / 90 %	80 % / 100 %

TSH (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

4.5. Tibial length (TL) and tibial variables (indirect method)

All tibial variables showed a significant positive linear correlation ($p<0.01$) with tibial length (TL) for both males and females (Figures 15 and 16). Univariate regression equations for estimating TL were therefore derived for all tibial variables. All tables presenting regression equations are arranged in decreasing order of correlation coefficient and increasing order of SEE.

In the male sample, nutrient foramen length (NFLT) had the highest correlation with TL (0.63) and breadth of the superior lateral articular facet (LTCB) showed the lowest correlation (0.31) (Table 13). For females, correlation coefficients ranged between 0.40 for proximal length (PXLT) and 0.57 for length of superior medial articular facet (MTCL) (Table 14). All correlations were considered moderate to strong, except the correlation between LTCB and TL which was weak (Evans, 1996). Tables 13 and 14 present regression equations for estimating TL from individual variables of the tibia in males and females respectively. SEEs for these equations ranged between 1.86 cm and 2.28 cm for males, and between 1.63 and 1.86 cm for females. All SEE values were much smaller than those obtained for univariate regression equations estimating TSH (ranges of 4.75-5.66 cm for males and 4.23-5.20 cm for females). Both correlation coefficients and SEEs were greater for males than for females. Males also had higher r^2 values (0.10-0.40) compared to females (0.16-0.33).

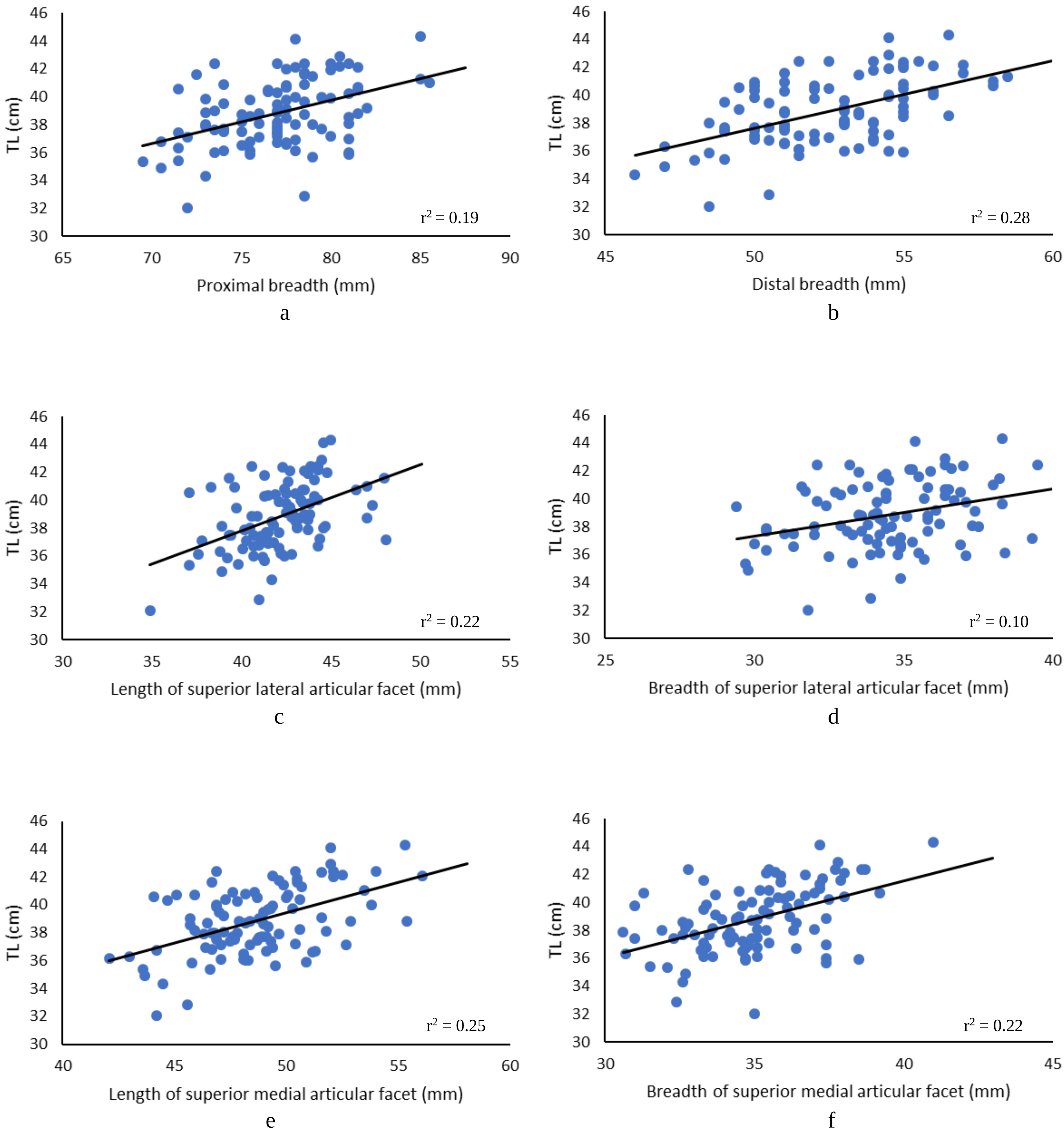
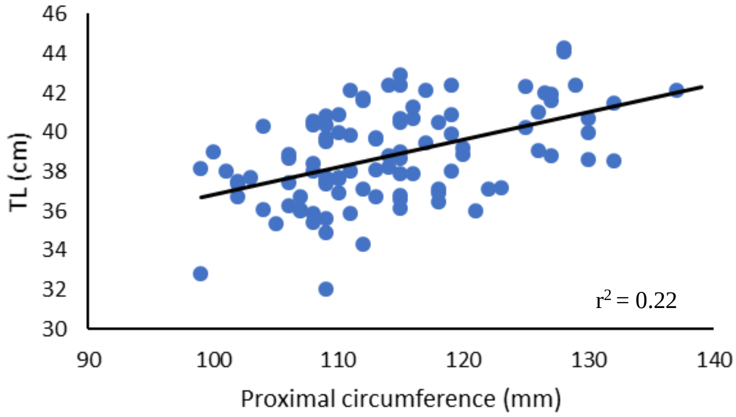


Figure 15. Scatter plots showing the association between tibial length (TL) and PXBT (a), DSBT (b), LTCL (c), LTCB (d), MTCL (e) and MTCB (f) in males.



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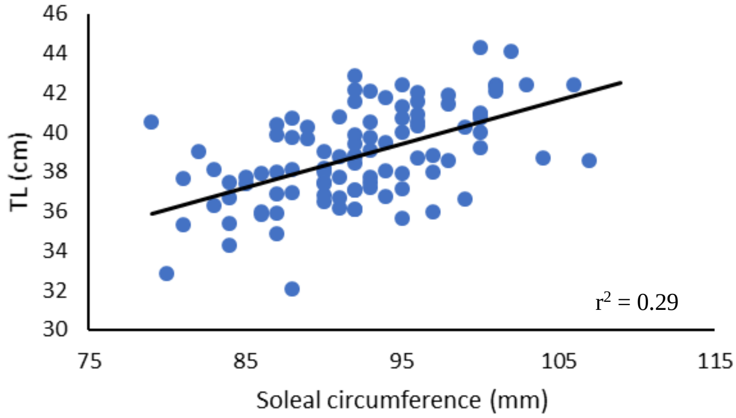

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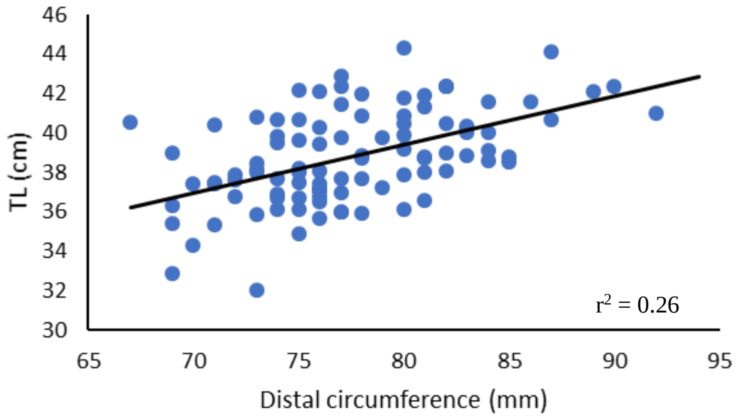
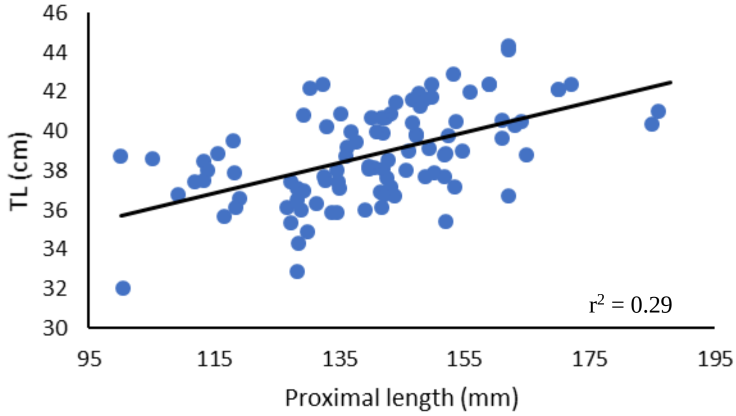


i



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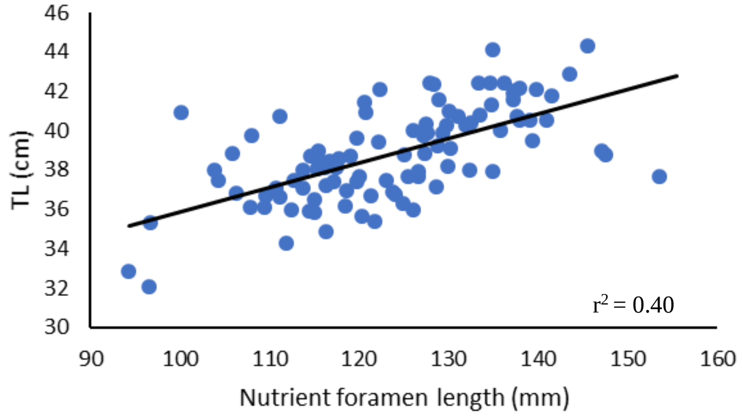


k

Figure 15 (continued). Scatter plots showing the association between tibial length (TL) and PXC (g), SLC (h), DSC (i), PXLT (j) and NFLT (k) in males.

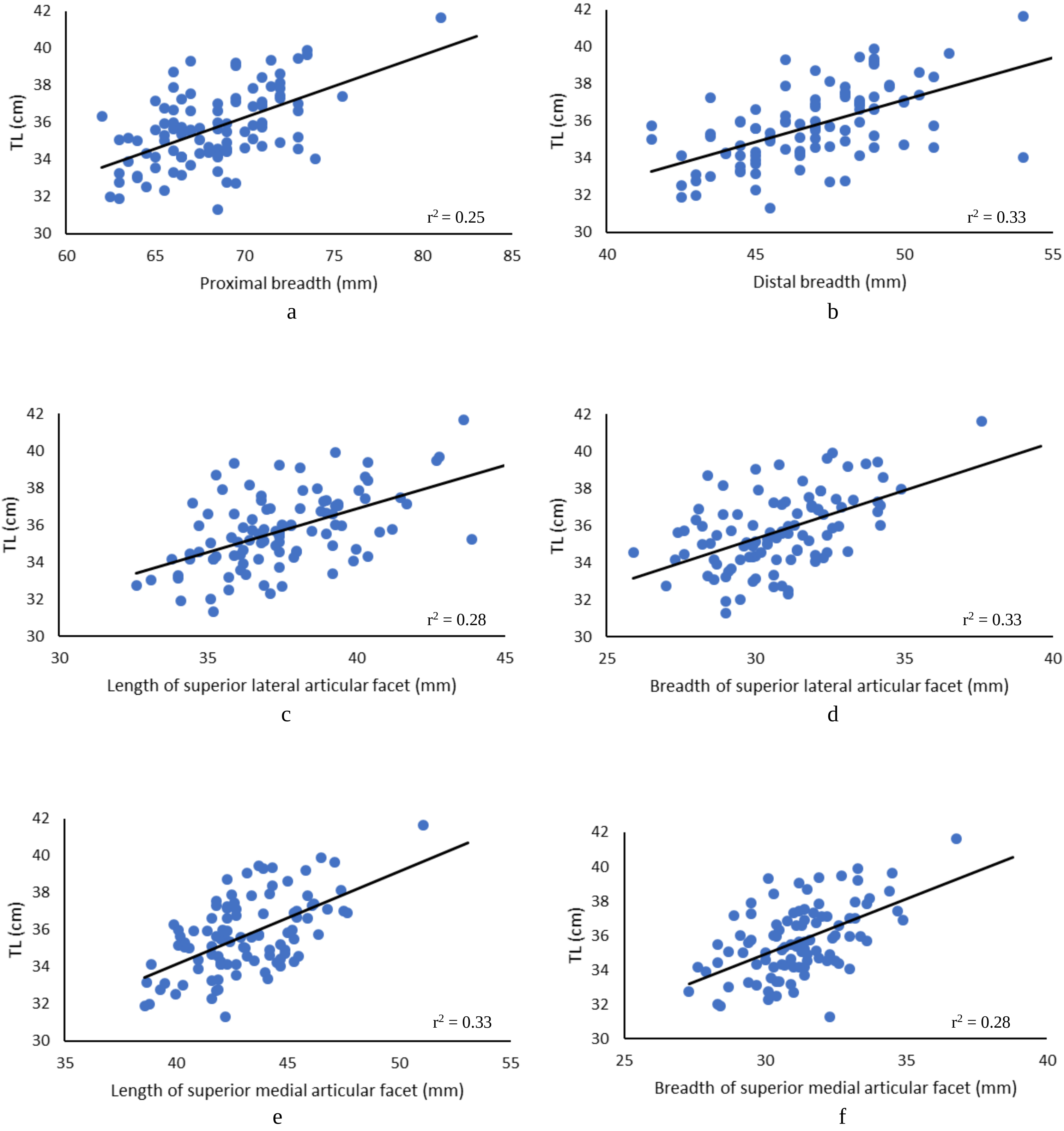


Figure 16. Scatter plots showing the association between tibial length (TL) and PXBT (a), DSBT (b), LTCL (c), LTCB (d), MTCL (e) and MTCB (f) in females.

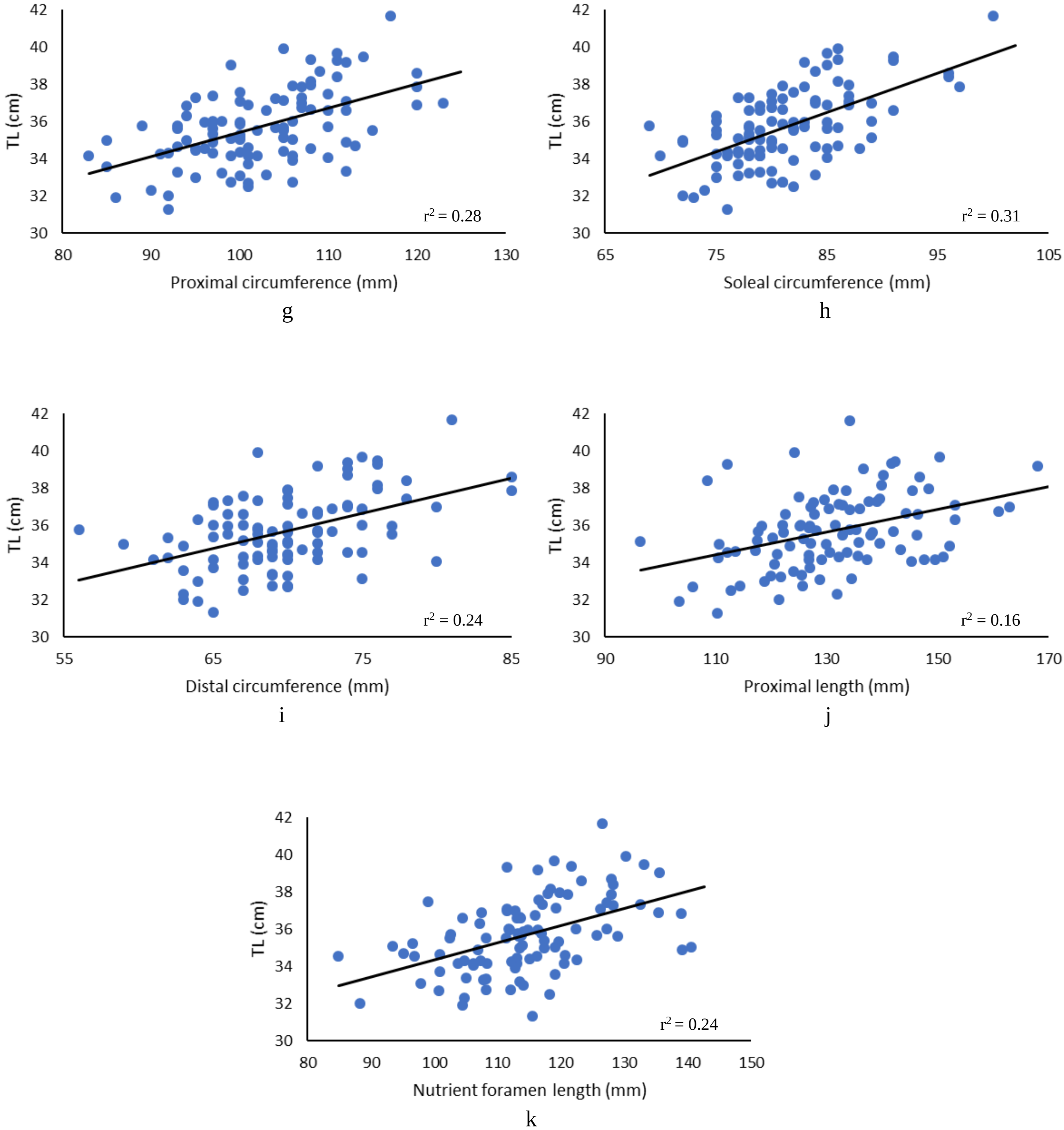


Figure 16 (continued). Scatter plots showing the association between tibial length (TL) and PXC (g), SLC (h), DSC (i), PXLT (j) and NFLT (k) in females.

Table 13. Correlations and regression equations for the estimation of tibial length (TL) (in cm) from individual variables of the tibia for males. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

Variable	Correlation (r)	r^2	Slope	Intercept	SEE (± cm)	Adjusted SEE (± cm)	Accuracy 1 SEE	Accuracy 2 SEE
NFLT	0.63	0.40	0.13	23.31	1.86	7.16	60 %	100 %
SLC	0.54	0.29	0.22	18.50	2.02	7.52	70 %	100 %
PXLT	0.54	0.29	0.08	28.01	2.02	7.53	80 %	100 %
DSBT	0.53	0.28	0.49	13.25	2.03	7.56	80 %	100 %
DSC	0.51	0.26	0.24	19.90	2.07	7.63	60 %	100 %
MTCL	0.50	0.25	0.43	17.77	2.08	7.66	80 %	100 %
MTCB	0.47	0.22	0.55	19.63	2.12	7.75	80 %	100 %
PXC	0.47	0.22	0.14	22.92	2.10	7.71	80 %	100 %
LTCL	0.47	0.22	0.47	18.84	2.12	7.76	50 %	100 %
PXBT	0.43	0.19	0.31	14.83	2.17	7.88	90 %	100 %
LTCB	0.31	0.10	0.34	27.17	2.28	8.13	60 %	100 %

TL (cm) = variable (mm) x slope + intercept ± SEE (cm)

Table 14. Correlations and regression equations for the estimation of tibial length (TL) (in cm) from individual variables of the tibia for females. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

Variable	Correlation (r)	r^2	Slope	Intercept	SEE (± cm)	Adjusted SEE (± cm)	Accuracy 1 SEE	Accuracy 2 SEE
MTCL	0.57	0.33	0.50	14.13	1.67	6.67	80 %	100 %
DSBT	0.57	0.33	0.45	14.42	1.68	6.68	90 %	100 %
SLC	0.56	0.31	0.21	18.49	1.63	6.56	90 %	100 %
MTCB	0.53	0.28	0.64	15.83	1.72	6.79	70 %	100 %
LTCL	0.53	0.28	0.47	18.20	1.72	6.80	90 %	100 %
PXC	0.53	0.28	0.13	22.36	1.73	6.81	70 %	100 %
LTCB	0.51	0.26	0.52	19.74	1.75	6.85	90 %	100 %
PXBT	0.50	0.25	0.34	12.70	1.70	6.67	80 %	100 %
NFLT	0.49	0.24	0.09	25.18	1.77	6.91	100 %	100 %
DSC	0.49	0.24	0.19	22.41	1.78	6.94	100 %	100 %
PXLT	0.40	0.16	0.06	27.70	1.86	7.15	90 %	100 %

TL (cm) = variable (mm) x slope + intercept ± SEE (cm)

Tables 15 and 16 show the step-wise regression equations using combinations of tibial variables for estimating TL in males and females respectively. The correlation coefficients for these equations for both males (0.75-0.82) and females (0.71-0.81) were significant ($p<0.01$) and were higher compared to those obtained using individual variables. The SEEs (1.41-1.60 cm for males and 1.21-1.45 cm for females) were smaller than those obtained using individual variables as well as those obtained from multivariate equations used to estimate TSH (ranges of 3.69-4.07 cm for males and 3.43-3.76 cm for females). Correlation coefficients were comparable between the sexes, but SEE values were slightly larger for males. Both sexes had similar r^2 values (0.56-0.67 for males and 0.50-0.66 for females).

Table 15. Correlations and regression equations for the estimation of tibial length (TL) (in cm) from combinations of variables of the tibia for males. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

Variable	**Function**		
	1	**2**	**3**
SLC	0.17	0.18	0.25
DSC			-0.11
PXLT		0.05	0.06
NFLT	0.11	0.07	0.07
Intercept	10.39	6.87	7.41
SEE (± cm)	1.60	1.44	1.41
Correlation (r)	0.75	0.81	0.82
r^2	0.56	0.66	0.67
Accuracy 1 SEE	80 %	70 %	90 %
Accuracy 2 SEE	100 %	100 %	100 %
Adjusted SEE (± cm)	6.56	6.18	6.13

TL (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

Table 17 shows regression equations using combinations of variables that represent different tibial regions including the proximal tibia, tibial shaft, distal tibia and posterior tibia. All equations had significant ($p<0.01$) correlations which were similar between the sexes (0.57-0.69 for males and 0.58-0.69 for females). R^2 values were also similar between the sexes (0.33-

0.48 for males and 0.34-0.48 for females). However, males had larger SEE values than females (1.76-2.00 cm and 1.50-1.66 cm respectively), and SEE values for both sexes were smaller than those obtained from multivariate equations estimating TSH (4.41-5.06 for males and 3.93-4.70 for females). In males, the posterior tibia equation had the highest correlation and smallest SEE, while the equation for the tibial shaft was the least correlated with TL and had the largest SEE. In females, the proximal tibia was the equation with the highest correlation and smallest SEE, while the equation for the posterior tibia had the lowest correlation and largest SEE.

In order to estimate TSH or TL from these equations (Tables 8-17), the value of the tibial measurement is multiplied by the slope and the intercept is added. The SEE is then added or subtracted from the equation. For example, a male with a PXBT value of 75 mm will have a TSH of:

TSH = 75(1.11) + 67.61 ± 5.05 (Table 8, page 48, PXBT equation)

= 83.25 + 67.61 ± 5.05

= 150.86 cm ± 5.05

For multivariate equations, a female with a DSBT value of 45 mm, a PXC value of 90 mm and a NFLT value of 110 mm will have a TSH of:

TSH = [(45 x 0.98) + (90 x 0.19) + (110 x 0.18)] + 55.56 ± 3.55 (Table 11, page 51, function 2)

= [44.10 + 17.10 + 19.80] + 55.56 ± 3.55

= 81.00 + 55.56 ± 3.55

= 136.56 cm ± 3.55

To this TSH, an appropriate soft tissue correction factor can be added to obtain an estimated living stature (ELS). Soft tissue factors specific for black South Africans have been developed (Bidmos and Manger, 2012; Brits *et al.*, 2017), but have yet to be tested and validated, and therefore the applicability thereof is not yet known. As a result, Fully's (1956) recommended soft tissue values can be added to TSH, or the equation suggested by Raxter *et al.* (2006) can be used to estimate stature. The disadvantage of this is that these factors have been shown to underestimate stature in South African populations (Bidmos and Manger, 2012; Brits *et al.*, 2017).

Table 16. Correlations and regression equations for the estimation of tibial length (TL) (in cm) from combinations of variables of the tibia for females. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

Variable	**Function**			
	1	**2**	**3**	**4**
MTCL				0.21
SLC	0.21	0.18	0.31	0.28
DSC			-0.17	-0.17
PXLT	0.06	0.05	0.06	0.05
NFLT		0.06	0.05	0.05
Intercept	11.53	8.33	7.99	3.58
SEE (± cm)	1.45	1.33	1.27	1.21
Correlation (r)	0.71	0.76	0.79	0.81
r^2	0.50	0.58	0.62	0.66
Accuracy 1 SEE	90 %	90 %	100 %	100 %
Accuracy 2 SEE	100 %	100 %	100 %	100 %
Adjusted SEE (± cm)	6.10	5.81	5.65	5.50

TL (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

Table 17. Correlations and regression equations for the estimation of tibial length (TL) (in cm) from combinations of variables in different regions of the tibia for males and females. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

Function	**Slope**	
	Male	**Female**
1. Proximal tibia		
PXBT	-0.10	-0.09
LTCL	0.26	0.16
LTCB	-0.10	0.16
MTCL	0.22	0.23
MTCB	0.31	0.22
PXC	0.06	0.06
Intercept	9.69	7.27
SEE (± cm)	1.91	1.50
Correlation (r)	0.63	0.69
r^2	0.40	0.48
Accuracy 1 / 2 SEE	80 % / 90 %	80 % / 100 %
Adjusted SEE (± cm)	7.28	6.24
2. Tibial shaft		
PXC	0.04	0.07
SLC	0.13	0.21
DSC	0.08	-0.08
Intercept	16.27	17.37
SEE (± cm)	2.00	1.59
Correlation (r)	0.57	0.63

Tale 17 (continued). Correlations and regression equations for the estimation of tibial length (TL) (in cm) from combinations of variables in different regions of the tibia for males and females. Accuracy refers to the percentage of actual TLs falling within 1 and 2 SEEs (± cm) of estimated TLs.

r^2	0.33	0.40
Accuracy 1 / 2 SEE	70 % / 100 %	70 % / 100 %
Adjusted SEE (± cm)	7.47	6.47
3. Distal tibia		
DSBT	0.32	0.35
DSC	0.14	0.08
Intercept	11.04	13.98
SEE (± cm)	1.97	1.66
Correlation (r)	0.58	0.59
r^2	0.34	0.35
Accuracy 1 / 2 SEE	70 % / 100 %	100 % / 100 %
Adjusted SEE (± cm)	7.40	6.63
4. Posterior tibia		
PXLT	0.04	0.05
NFLT	0.10	0.08
Intercept	20.85	20.17
SEE (± cm)	1.76	1.66
Correlation (r)	0.69	0.58
r^2	0.48	0.34
Accuracy 1 / 2 SEE	70 % / 100 %	90 % / 100 %
Adjusted SEE (± cm)	6.92	6.64

TL (cm) = [(variable a (mm) x slope a) + (variable b (mm) x slope b) … + variable z (mm) x slope z)] + intercept ± SEE (cm)

4.6. Accuracy and reliability

The accuracies of the equations derived in the present study were tested, as well as the reliability of equations derived for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) in estimating stature in a sample of black South Africans.

4.6.1. Accuracy of equations

The skeletons of 20 black South Africans, not used in the calculation of regression equations, were used to assess the accuracies of all univariate and multivariate regression equations. Tables 5-14 show the percentage of actual measured TSHs and TLs that fell within 1 and 2 SEE of the TSHs and TLs estimated using each equation. For univariate equations estimating TSH, the accuracies ranged between 40 and 80 % for 1 SEE and between 90 and 100 % for 2 SEE in the male sample (Table 8). For females, the accuracies ranged between 50 and 90 % for 1 SEE and between 90 and 100 % for 2 SEE (Table 9). For multivariate equations estimating TSH, the male sample had accuracies between 50 and 70 % for 1 SEE and between 90 and 100 % for 2 SEE (Tables 10 and 12), while females had accuracies ranging between 40 and 90 % for 1 SEE and between 90 and 100 % for 2 SEE (Tables 11 and 12).

For univariate equations estimating TL, males had accuracies between 50 and 90 % for 1 SEE and an accuracy of 100 % for 2 SEE (Table 13), and females had accuracies ranging between 70 and 100 % for 1 SEE and an accuracy of 100 % for 2 SEE (Table 14). In the male sample, accuracies for multivariate TL equations ranged between 70 and 90 % for 1 SEE and 90 and 100 % for 2 SEE (Tables 15 and 17). For females, these accuracies ranged between 70 and 100 % for 1 SEE and was 100 % for 2 SEE (Tables 16 and 17).

Paired T-tests conducted between the TSHs estimated using the derived regression equations and the actual measured TSHs revealed that for both males and females, no statistically significant differences ($p>0.05$) existed between these TSHs for any of the equations. For TL, paired T-tests showed that for both sexes, the TLs estimated using the equations were not significantly different ($p>0.05$) from the actual measured TLs for any of the univariate or multivariate equations, except for the proximal length (PXLT) univariate equation in the female sample which significantly underestimated TL ($p<0.05$).

4.6.2. Direct vs indirect methods

In order to assess whether the direct or indirect method was more accurate, the original research sample was used to derive regression equations for each sex for estimating TSH from TL (indirect method). These equations are presented in Table 18. The TLs calculated from the various univariate and multivariate regression equations were converted to TSHs using these equations. Paired T-tests revealed that there were no statistically significant differences ($p<0.05$) between these estimated TSHs (indirect method) and the actual measured TSHs for any of the equations for males. In the female sample, only one univariate equation (soleal circumference or SLC) significantly overestimated TSH ($p<0.05$) by an average of 2.1 cm, while the rest of the estimated TSHs were not significantly different ($p>0.05$) from the actual measured TSHs. As discussed above (section 4.6.1., page 66), no significant differences ($p<0.05$) existed between actual measured and estimated TSHs using the direct method.

Table 18. Regression equations for estimating total skeletal height (TSH) (in cm) from tibia length (TL) (in cm) in males and females.

	Equation	SEE (± cm)
Males	[2.30*(TL)] + 63.49	2.88
Females	[2.53*(TL)] + 51.53	2.44

For further analysis on the accuracy of the indirect method, the SEEs associated with all univariate and multivariate equations estimating TL were adjusted following guidelines by Steele (1970), whereby the SEE of the equation for estimating TL from the tibial fragment was multiplied by the slope in the equation for converting TL to TSH (Table 18). Added to this product was the SEE for the latter equation (Table 18). For example, a TL equation for females with a SEE of 1.63 (Table 14, page 60, SLC equation) will have an adjusted SEE of:

$$1.63(2.53) + 2.44 = 6.56$$

The adjusted SEEs ranged between 7.16 cm and 8.13 cm for males and 6.56 cm and 7.15 cm for females for univariate equations. Adjusted SEE's for multivariate equations ranged between 6.13 cm and 7.47 cm for males and 5.50 cm and 6.64 cm for females. These adjusted SEEs were significantly larger than those associated with equations estimating TSH directly ($p<0.05$).

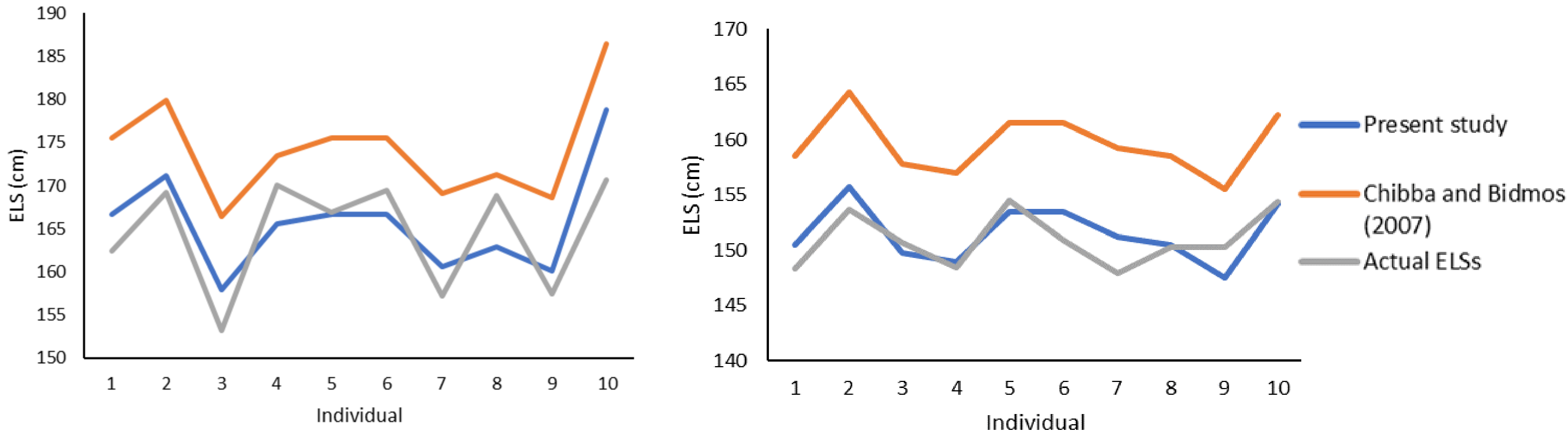
4.6.3. Reliability of equations

The separate sample of black South Africans was cross-tested using regression equations derived for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) in order to confirm the population-specificity of these equations. The equations for proximal breadth (PXBT) and distal breadth (DSBT) specific for white South African males and females respectively were used. The equation for length of superior medial articular facet (MTCL) specific for black North Americans of both sexes was used. The ELSs estimated using the PXBT (males) and DSBT (females) regression equations derived in the present study and by Chibba and Bidmos (2007) for white South Africans, as well as the actual measured ELSs, are presented in Figure 17. Figure 18 shows the actual measured ELSs, the ELSs estimated using the MTCL regression equations derived in the present study, and the ELSs estimated using equations by Holland (1992) for North American blacks.

Since the regression equations from the present study and from Chibba and Bidmos (2007) are used to estimate TSH, the ELSs were calculated by adding the appropriate soft tissue correction factors as suggested by Fully (1956) to the TSHs. This was done to ensure consistency with the results of Holland's (1992) equations which are used to estimate living stature.

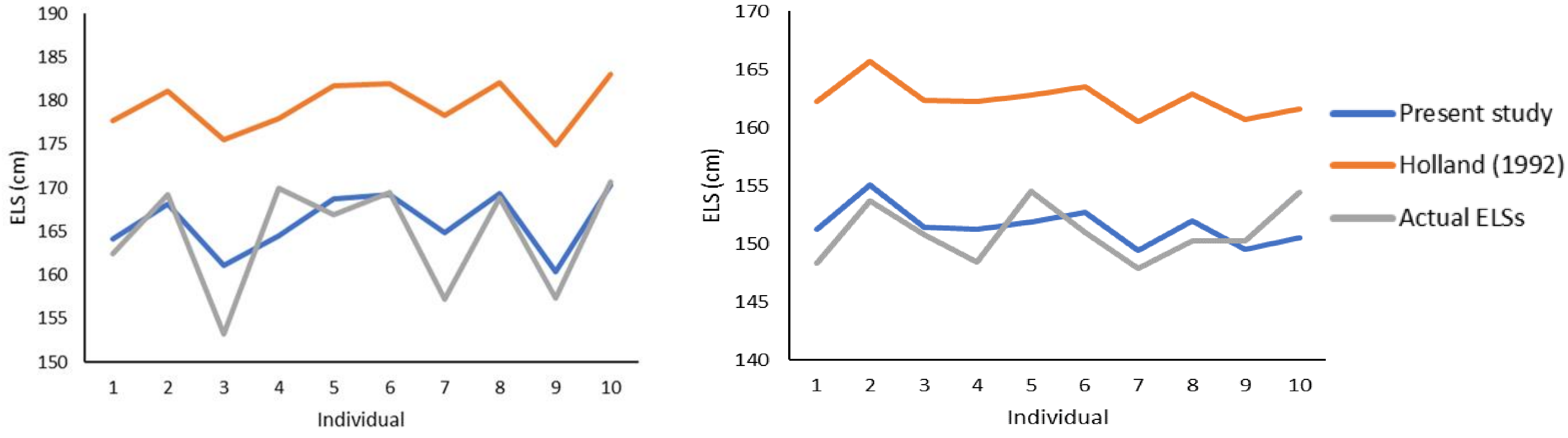
For PXBT in males and DSBT in females, the equations proposed by Chibba and Bidmos (2007) for white South Africans significantly ($p<0.001$) overestimated stature by an average of 9.17 cm (Figure 17). However, there was no significant difference ($p<0.05$) between the ELSs calculated using equations from the present study and the actual measured ELSs in both sexes (Figure 17).

For MTCL in both sexes, Holland's (1992) ELSs significantly ($p<0.001$) overestimated stature by an average of 13.21 cm (Figure 18), but there was a considerable amount of overlap between the actual measured ELSs and the ELSs calculated from the present study, with no significant difference between the two ($p<0.05$) (Figure 18).



Males (PXBT) Females (DSBT)

Figure 17. Comparison of estimated living statures (ELSs) for males (left) and females (right) using the PXBT (for males) and DSBT (for females) regression equations derived in the present study, those derived by Chibba and Bidmos (2007) for South African whites, and the actual measured ELSs.



Males (MTCL)

Females (MTCL)

Figure 18. Comparison of estimated living statures (ELSs) for males (left) and females (right) using the MTCL regression equations derived in the present study, those derived by Holland (1992) in North American blacks, and the actual measured ELSs.

CHAPTER FIVE

Discussion and Conclusion

5.1. Introduction

The estimation of stature is one of the steps included when constructing the demographic profile of unknown or unidentified skeletal remains (Bidmos and Asala, 2005). There are two main methods used to estimate stature. The first is the anatomical method (Fully, 1956) in which each skeletal element contributing to stature is measured and the sum of these elements gives the total skeletal height (TSH). A soft tissue correction factor can then be added to the TSH to give an estimated living stature (ELS). The second method is the mathematical approach (Pearson, 1899) whereby the lengths of individual bones or a combination of bones are used in conjunction with regression formulae to estimate stature. Regression equations have been derived for a number of bones (Pelin *et al.,* 2005; Ryan and Bidmos, 2007; Bidmos, 2008c; Rani *et al.,* 2011; Pininski and Brits, 2014), including the long bones of the lower limb which have the highest correlation with stature (Trotter and Gleser, 1952; Munoz *et al.,* 2001; Dayal e*t al.,* 2008). However, bones are not always recovered intact and are often fragmentary, and therefore regression equations using fragments of bones have been derived (Holland, 1992; Bidmos, 2008a, 2008b; Mandela *et al.,* 2013; Abledu *et al.,* 2016a). These equations are, however, both sex- and population-specific (Bidmos, 2008b) and while formulae for fragments of the tibia have been established for white South Africans (Chibba and Bidmos, 2007), no equations exist for black South Africans. The aim of this study was therefore to establish both univariate and multivariate regression equations for estimating TSH and tibial length (TL) from tibial fragments in black South Africans. This was done by measuring the TSHs and TLs of two hundred skeletons and regressing them on individual variables and a combination of variables of the tibia. Using a separate sample of black South Africans, the accuracies of these equations were tested, as well as the reliability of equations developed for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) in this population. A comparison was made of the accuracies of the direct, whereby TSH is estimated directly from tibial fragments, and indirect methods, in which tibial fragments are first used to estimate tibial length and this length is then used to estimate TSH.

5.2. Repeatability

Lin's concordance correlation coefficient (Lin, 1989) was used to determine the intra- and inter-observer repeatability of measurements of TSH and tibial fragments. Results showed that almost all measurements were highly repeatable with Pc-values equal to or greater than 0.90 (Tables 5 and 6), with intra-observer repeatability being consistently higher than inter-observer repeatability. The intra- and inter-observer measurements of talocalcaneal height had Pc-values of 0.87 and 0.88 respectively, but the discrepancies in means were well within the 2 mm margin of error accepted by anthropologists (Stull e*t al.*, 2013, 2014). The inter-observer measurements of basibregmatic height and proximal length also had lower Pc-values (0.81 and 0.83 respectively). While the mean error was less than 2 mm for proximal length, and within the acceptable error range (Stull *et al.*, 2013, 2014), the mean difference for basibregmatic height was 4 mm and not within this range. This discrepancy may be due to the fact that the skulls had been cut in order to remove brain tissue, and therefore the calottes were separate from the rest of the skull. The calottes therefore had to be rearticulated with the rest of the skull which did not always align very well, thus possibly introducing some measurement error.

5.3. Descriptive statistics

The mean total skeletal height (TSH) for the female sample was 141.73 cm which is comparable to the mean TSH calculated for living South African females (141.10 cm) using Magnetic Resonance Imaging (MRI) scans (Brits *et al.*, 2017). The mean tibial length (TLs) (35.69 cm for the present sample and 36.50 cm for the MRI sample) as well as the mean femoral lengths (43.83 cm for the present sample and 43.30 cm for the MRI sample) were also comparable (Brits, 2016). Females from the current sample can therefore be considered representatives of the living population of black South African females.

The male sample presented with a mean TSH of 152.83 cm, which is statistically significantly taller ($p<0.05$) than the mean TSH reported for living black South African males (144.90 cm) measured from MRI scans (Bidmos and Manger, 2012). However, Ruff *et al.* (2012) noted some errors in the measurement techniques employed by Bidmos and Manger (2012). For example, they reported that Bidmos and Manger (2012) may have mismeasured vertebral heights and underestimated the summed vertebral column height by as much as 8 cm. In addition, talocalcaneal height may also have been mismeasured, resulting in a mean underestimation of 2 cm (Ruff e*t al.*, 2012). If this is the case, the mean TSH for Bidmos and Manger's (2012) sample would be higher and therefore much closer to the TSH reported for males in the present study. This, together with the fact that the mean TLs (38.83 cm for the present sample and 38.20 cm for the MRI sample) and mean femoral lengths (45.67 cm for the present sample and 45.20 cm for the MRI sample) are comparable indicates that the current sample is representative of the living black male South African population.

These findings are important since secular trends in stature have been observed in South African populations (Tobias, 1975; Tobias, 1985; Henneberg and van den Berg, 1990; Myburgh *et al.*, 2017). In addition, secular trends have been shown to particularly affect the distal limbs such as the tibia (Meadows and Jantz, 1995), with negative secular trends affecting tibial length in South African populations (Myburgh, 2016). The fact that the current sample can be considered as representative of the living population, as indicated above, therefore suggests that these secular trends have not influenced the results of the study and indicates that the equations derived in this study are relevant.

Males presented with a significantly ($p<0.001$) higher mean TSH compared to females, suggesting that males are taller than females in the black South African population. This sexual dimorphism in height was also observed by numerous researchers exploring stature in black South Africans (Steyn and Smith, 2007; Pininski and Brits, 2014; Lahner *et al.,* 2016). TL and all other tibial variables were also highly sexually dimorphic, with males presenting with significantly ($p>0.001$) higher mean values than females. Males also had higher standard deviations than females for TSH, TL and all other tibial variables except for proximal breadth (PXBT), which indicates that there is greater variability in the male sample. These results are similar to those of other studies which have demonstrated sexual dimorphism in tibial dimensions for black South African (Kieser *et al.,* 1992), white South African (Steyn and İşcan, 1997), black and white North American (Holland, 1991; Holland, 1992), Colombian (Moore *et al.,* 2016), Guatemalan (Wright and Vásquez, 2003), Croatian (Šlaus *et al.,* 2013), Turkish (Ekizoglu *et al.,* 2016), Indian (Rai *et al.,* 2017) and Japanese populations (Sakaue, 2004).

The TSHs of both males and females in the current sample were significantly shorter ($p<0.05$) than those reported for white South Africans (Chibba and Bidmos, 2007; Bidmos, 2008b), but were slightly taller than those reported for Thai individuals (Gocha e*t al.,* 2013). A comparison of the TSHs with other populations could not be made since most other studies make use of cadaveric height or living stature rather than TSH when developing regression formulae. The present study did not use the cadaveric heights reported in the Raymond A. Dart Collection because the accuracy of these values has previously been questioned (Lundy, 1983; Bidmos, 2005). The present study therefore only used TSH in the derivation of regression equations, which can be used in conjunction with equations developed by Raxter *et al.,* (2006), Bidmos and Manger (2012) and Brits *et al.* (2017) to estimate living stature in black South Africans.

There were also differences in the mean TLs between black South Africans and various other populations, as presented in Table 19. While the mean TLs were comparable to those of white South Africans (Dayal *et al.,* 2008), Indians (Gaur *et al.,* 2016) and Spanish individuals

(Muñoz *et al.*, 2001), they were shorter than or larger than those of various other populations (Table 19).

Table 19. Comparison of mean tibial lengths and standard deviations (SD) between various populations.

Population	Reference	Males		Females	
		Mean (cm)	**SD (cm)**	**Mean (cm)**	**SD (cm)**
Black South African	Present study	38.83	2.39	35.69	2.02
White South African	Dayal *et al.* (2008)	38.25	2.36	35.21	1.99
Indian	Gaur *et al.* (2016)	38.29	1.76	35.43	1.71
Spanish	Muñoz *et al.* (2001)	38.85	2.29	35.05	2.26
Black North American	İşcan and Miller-Shaivitz (1984)	40.45	3.42	36.56	2.13
Nigerian	Didia *et al.* (2009)	46.66	4.50	41.14	3.97
Nepalese	Sah and Shrestha (2014)	37.57	2.16	34.90	1.75
Turkish	Sargin *et al.* (2012)	36.90	2.29	33.22	1.83
Mexican	Garmendia *et al.* (2018)	36.23	2.24	33.14	1.93
Guatemalan	Wright and Vásquez (2003)	34.09	1.80	31.23	1.60
Thai	Gocha *et al.* (2013)	35.57	1.42	33.39	1.85
Korean	Lee *et al.* (2014)	34.98	1.87	32.71	1.42
White North American	İşcan and Miller-Shaivitz (1984)	37.10	2.47	35.02	2.50
Croatian	Petrovečki *et al.* (2007)	37.90	2.00	35.30	2.20

Secular trends may contribute to the differences in TSH and TL between the various populations. Secular changes may cause either an increase or a decline in stature and bone lengths of populations in response to a range of conditions, such as changes in nutrition (Bogin and Rios, 2003; Perkins *et al.*, 2016), health (Hwang *et al.*, 2013), stress (Sheppard *et al.*, 2015), hygiene (Rah *et al.*, 2015), socioeconomic status (Zong *et al.*, 2015) and climate (Bharati *et* *al.*, 2010). Secular trends have been shown to specifically affect the distal limbs, such as the tibia, which explains why TL differs so widely between the populations (Meadows and Jantz, 1995). These differences may also be due to the fact that rates of growth differ between populations, resulting in differences in both height and in body proportions between populations (Eveleth, 1978; Bogin and Rios, 2003; Nyati e*t al.*, 2006; Myburgh *et al.*, 2017). Genetic differences between populations also contribute a large portion of inter-population stature variation (Dauber *et al.*, 2014). These differences in TSH and TL between populations supports the suggestion that equations estimating stature are population-specific and should not be used to determine the stature of individuals from populations different to that which they were derived from.

5.4. Total skeletal height (TSH) and tibial variables (direct method)

5.4.1. Correlation coefficients

Correlation coefficients were similar between the sexes for univariate equations, with a range of 0.42-0.65 for males and 0.41-0.67 for females. Males and females also had similar correlations for multivariate equations. For the stepwise analysis, males had a range of 0.76-0.81, and females had a range of 0.75-0.81. Correlations for region-specific equations ranged between 0.60 and 0.73 for males, and between 0.57 and 0.74 for females. Correlation coefficients for both sexes were higher than those reported for stature estimation using measurements of the tibia in white South Africans (Chibba and Bidmos, 2007) and Thai individuals (Fongkete e*t al.*, 2016), as well as for measurements of the skull (Ryan and Bidmos, 2007; Torimitsu *et al.*, 2016), scapula (Zhang *et al.*, 2016), vertebral column (Jason and Taylor, 1995; Milani *et al.*, 2017), sacrum (Pininski and Brits, 2014), calcaneus (Bidmos and Asala, 2005), metacarpals (Zaher *et al.*, 2011) and phalanges (Habib and Kamal, 2010). However, correlation coefficients were lower than those reported for measurements of the clavicle

(Torimitsu *et al.*, 2017) and femur (Bidmos, 2008a), which is likely due to the fact that the femur is the bone with the highest correlation to stature (Trotter and Gleser, 1952; Lundy and Feldesman, 1987; Dayal *et al.*, 2008). Univariate correlations were lower than, but multivariate correlations higher than those reported for metatarsals (Bidmos, 2008c). Correlation coefficients for multivariate equations were slightly lower than those reported for intact tibiae (Lundy and Feldesman, 1987; Dayal *et al.*, 2008).

The r^2 values for both univariate and multivariate equations were also similar between the sexes. These results indicate that for univariate equations in males and females respectively, between 18 and 42 %, and between 17 and 45 % of the variation in TSH is the result of variation in the tibial variables. For multivariate equations, 36-66 % and 33-66 % of the variation in TSH for males and females respectively can be explained by the variation in the tibial measurements.

5.4.2. Standard error of estimates (SEEs)

The SEE of a regression formula gives an indication of the accuracy of the equation and therefore the stature estimate obtained using that equation (Lundy, 1983). The SEE is defined as a measure of the spread of errors around a straight line (Farrance and Frenkel, 2012), and therefore a larger SEE indicates a lower accuracy and a greater error of the stature estimate, while smaller SEE values indicate greater accuracies.

Males presented with larger SEE values compared to females for univariate equations, which ranged between 4.75 cm and 5.66 cm for males, and 4.23 cm and 5.20 cm for females. Males also had larger SEEs for multivariate equations. Stepwise equations ranged between 3.69 cm and 4.07 cm for males, and between 3.43 cm and 3.76 cm for females. SEEs ranged between 4.41 cm and 5.06 cm for males, and between 3.93 cm and 4.70 cm for females for the region-specific equations. The larger SEE values in the male sample suggests that the equations for males are less accurate and produce estimates of TSH with greater errors or prediction intervals than the female-specific equations. This could be explained by the greater variability in the male sample which was also confirmed by the higher standard deviations for TSH and tibial measurements in males. Holland (1992), Muñoz *et al.* (2001), Bidmos (2008a, 2008b), and Zhang e*t al.* (2016) also reported higher SEE values for males, but Wright and Vásquez (2003), Petrovečki *et al.* (2007), Gocha *et al.* (2013), Lee *et al.* (2014) and Garmendia *et al.* (2018) reported that females had greater SEEs.

The SEEs for both sexes were comparable to those reported for equations estimating TSH from tibial measurements in black and white North Americans (Holland, 1992), but were smaller than those reported for white South Africans (Chibba and Bidmos, 2007) and Thai individuals (Fongkete *et al.*, 2016). SEE values were also smaller than those reported for measurements of the skull (Ryan and Bidmos 2007; Torimitsu *et al.*, 2016), scapula (Zhang e*t al.*, 2016), vertebrae (Jason and Taylor, 1995), sacrum (Pininski and Brits, 2014), femur (Bidmos, 2008a, 2008b), calcaneus (Bidmos and Asala, 2005), metatarsals (Bidmos, 2008c), and phalanges (Habib and Kamal, 2010). The range of SEEs for multivariate equations were only slightly larger than the SEEs reported for intact tibiae in black (2.78-3.06 cm) and white (2.59-3.16 cm) South Africans (Lundy and Feldesman, 1987; Dayal *et al.*, 2008), indicating that these equations can be used to estimate TSH in the absence of complete tibiae.

5.4.3. Accuracy of equations

Distal breadth (DSBT) had the highest correlation with TSH and the smallest SEE value for both sexes and is therefore the most useful individual variable for estimating TSH. This is similar to results for white South African females where distal breadth is the most useful variable (Chibba and Bidmos, 2007), but contrary to results for white South African males where proximal breadth is the variable most useful for estimating TSH (Chibba and Bidmos, 2007).

Breadth of the superior lateral articular facet (LTCB) had the lowest correlation coefficient and largest SEE value in males, while in the female sample, proximal length (PXLT) was the least correlated with TSH and had the largest SEE value. This indicates that these variables are the least useful in estimating TSH and should only be used if other, more highly correlated variables are not available or measurable. Correlation coefficients were not presented for all individual variables of the tibia in white South Africans (Chibba and Bidmos, 2007), and therefore a comparison of the least correlated variables could not be made. A comparison with black North Americans could also not be made since correlation coefficients were not available at all for this sample (Holland, 1992).

All variables were, however, significantly correlated with TSH and all univariate equations estimated TSH fairly accurately for both sexes in the validation sample (40-100 %) (Tables 8 and 9, pages 48 and 49). Additionally, there was no significant difference ($p>0.05$) between these estimated TSHs and the actual measured TSHs. This suggests that in both sexes, all univariate equations can be used with confidence to accurately estimate TSH.

The stepwise analyses yielded multivariate equations with the highest correlations and smallest SEE values in both sexes (Tables 10 and 11, pages 50 and 51). These equations are therefore considered to be the most accurate and will produce stature estimates with the smallest errors. However, these equations make use of variables from different parts or regions of the tibia and therefore to use these equations, an almost complete tibia must be available. Since this is not always the case in either archaeological or forensic contexts (Lundy, 1985; Bidmos, 2006), it is necessary to develop equations that include variables associated with specific or isolated regions of the tibia. For example, carnivorous scavengers tend to first gnaw at the proximal and distal epiphyses of long bones since there is a high fat content in these regions and a much thinner layer of bone protecting this fat (Pokines and Tersigni-Tarrant, 2017). This results in the removal of the epiphyses, leaving behind only the diaphysis or shaft of the long bone available for analysis (Pokines and Tersigni-Tarrant, 2017). Furthermore, in cases of burning, fleshed individuals assume a “pugilistic posture” in which the muscle tissue shrinks, causing the knee to flex and essentially shielding the posterior half of the tibia (Symes *et al.,* 2015). This, together with the greater tissue depth covering the posterior tibia, means that the anterior half of the tibia burns first, while the posterior half burns at a later stage (Symes *et al.,* 2015). In these cases, the posterior half of the tibia may be the only region available or measurable. Therefore, multivariate equations including variables from isolated regions of the tibia were developed, including the proximal tibia, tibial shaft, distal tibia and posterior tibia.

The equations for the proximal tibia yielded the highest correlation coefficients and lowest SEEs in both sexes (Table 12, page 52). This is significant since it shows that the region of the tibia associated with the knee joint is most highly correlated with TSH. It is interesting to note, however, that joint surface dimensions are generally more correlated with sexual dimorphism and robusticity (Holland, 1991; Kieser *et al.,* 1992) rather than TSH.

For males, the tibial shaft equation had the lowest correlation and largest SEE value while for females, the equation for the posterior tibia had the lowest correlation and largest SEE (Table 12, page 52). The results for females are interesting since the equation for the posterior tibia includes length measurements which one expects to be more highly correlated with TSH. However, the equations for the tibial shaft and distal tibia, which include circumference and breadth measurements, usually more associated with sex prediction (İşcan and Miller-Shaivitz, 1984; Garcia, 2012; Brzobohatá *et al.,* 2016), are more highly correlated with TSH.

Although these two equations have larger SEEs compared to the other multivariate equations, the correlations are significant and moderate to strong (0.60 for males and 0.57 for females). These equations may therefore still be useful and the estimated TSHs obtained from them may be accurate. This is further confirmed by the fact that all equations estimated TSH with moderate to high accuracy (50-100 %) (Tables 10-12). Furthermore, no significant difference ($p>0.05$) was found between the actual measured and estimated TSHs. The TSH estimates produced by all multivariate equations can therefore be considered accurate and can confidently be used to estimate the TSH of unknown remains.

Multivariate equations had higher correlation coefficients and smaller SEEs than univariate equations in both sexes, which was also reported by Bidmos and Asala (2005), Bidmos (2008b), Pininski and Brits (2014), and Torimitsu e*t al.* (2016). This is expected since multivariate equations take into account the correlations between multiple independent variables (Alexopoulos, 2010), and therefore using a combination of bones or variables give a more accurate stature estimate than individual bones or variables (Dayal e*t al.* 2008). It is therefore suggested that when multiple variables are available for analysis, multivariate rather than univariate equations should be used since the TSH estimates obtained from these equations will be more accurate and have smaller prediction intervals.

5.5. Tibial length (TL) and tibial variables (indirect method)

5.5.1. Correlation coefficients

Males presented with higher correlation coefficients (0.31-0.63) compared to females (0.40-0.57) for univariate equations estimating tibial length (TL) which was also observed by Mansur *et al.* (2012), Sargin *et al.* (2012), Lee *et al.* (2014), Zhang e*t al.* (2016) and Garmendia *et al.* (2018). However, the opposite was reported in numerous other studies (Muñoz *et al.*, 2001; Bidmos, 2008a, 2008b; Gocha *et al.*, 2013). In contrast, correlation coefficients for multivariate equations estimating TL were similar between the sexes. Stepwise equations had correlations of 0.75-0.82 for males and 0.71-0.81 for females, while region-specific equations had correlations of 0.57-0.69 for males and 0.58-0.69 for females. Values for r^2 were also higher for males in univariate equations but were comparable between the sexes for multivariate equations. In males and females respectively, 10-40 % and 16-33 % of the variation in TL is explained by variation in tibial dimensions for univariate equations, while for multivariate equations, 33-66 % and 34-67 % of this variation is due to variation in tibial measurements.

5.5.2. Standard error of estimates (SEEs)

SEE values were consistently larger in the male sample compared to females. For univariate equations, males had SEE values of 1.86-2.28 cm, while females had SEEs of 1.63-1.86 cm. Stepwise equations had SEEs ranging between 1.41 cm and 1.60 cm for males, and between 1.21 cm and 1.45 cm for females. SEEs were 1.76-2.00 cm for males and 1.50-1.66 cm for females for region specific equations. As with equations estimating TSH, this suggests that equations estimating TL for males are less accurate and will produce stature estimates with greater margins of error than females.

Correlations were higher and SEE values were smaller than those estimating TL from tibial fragments in white South Africans (Chibba and Bidmos, 2007), Kenyans (Mandela *et al.,* 2013), Nigerians (Ugochukwu *et al.,* 2016) and Indians (Sarala Devi and Udhaya, 2014), as well as for fragments of the humerus (Devi e*t al.,* 2014) and ulna (Badkur and Nath, 1990). However, correlations were lower and SEEs were slightly larger than those reported for fragments of the femur (Bidmos, 2008a). This is likely due to the fact that the femur has consistently been shown to be the bone with the highest correlation to stature, including femoral fragments (Trotter and Gleser, 1952; Lundy and Feldesman, 1987; Dayal *et al.,* 2008).

5.5.3. Accuracy of equations

Nutrient foramen length (NFLT) had the highest correlation coefficient and smallest SEE value for estimating TL in the male sample, while in the female sample, length of the superior medial articular facet (MTCL) was the individual variable most highly correlated with

TL (Tables 13 and 14, pages 59 and 60). However, soleal circumference (SLC) had the smallest SEE in the female sample. These variables are therefore considered to be the most accurate for estimating TL. These results differ from those reported for white South Africans, with length of the superior lateral articular facet (LTCL) and proximal breadth (PXBT) having the highest correlation in males, and distal breadth (DSBT) having the highest correlation in females (Chibba and Bidmos, 2007). It is important to note, however, that although a statistical relationship exists between soleal circumference (SLC) and tibial length, this variable has more of a biological association with sex (Garcia, 2012). The biological relationship of this variable with stature therefore needs to be further explored.

In males, breadth of the superior lateral articular facet (LTCB) was the least correlated with TL and had the largest SEE, while proximal length (PXLT) was the variable in the female sample with the lowest correlation and largest SEE value (Tables 13 and 14, pages 59 and 60). These variables should therefore only be used to estimate TL when other, more highly correlated and more accurate variables are not available for analysis. A comparison of the variables least correlated with TL in white South Africans could not be made as these correlation coefficients were not presented (Chibba and Bidmos, 2007). Similarly, a comparison with black North Americans could not be made as no correlation coefficients were available (Holland, 1992).

All variables were, however, significantly correlated with TL and all univariate equations accurately estimated TL (50-100 %) (Tables 13 and 14, pages 59 and 60). Furthermore, all variables yielded estimated TLs with no significant difference ($p>0.05$) from actual measured TLs, except proximal length (PXLT) in the female sample which significantly ($p<0.05$) underestimated TL by an average of 0.73 cm. This suggests that all univariate equations can be used with confidence to accurately estimate TL in both sexes, except PXLT in the female sample which should not be relied upon.

The multivariate equations with the highest correlations and smallest SEE values in both sexes were produced by stepwise analyses and are therefore the equations which will give the most accurate estimates of TL (Tables 15 and 16, pages 61 and 63). However, the variables included in these equations are from various regions of the tibia and an almost complete tibia is therefore required to use these equations. Region-specific multivariate equations were therefore developed. In males, the equation for the posterior tibia had the highest correlation and smallest SEE, while the equation for the tibial shaft yielded the lowest correlation and largest SEE value (Table 17, page 64). These results make sense since the equation for the posterior tibia includes length measurements which are generally more associated with total bone length, while the equation for the shaft includes circumference measurements which are usually more correlated with sex (Garcia, 2012).

In females, the proximal tibia yielded the equation with the highest correlation and smallest SEE, while the equation for the posterior tibia had the lowest correlation coefficient and largest SEE (Table 17, page 64). This is interesting as one would expect length measurements, included in the equation for the posterior tibia, to be more highly correlated with TL than measurements of circumference and breadth (equations for the tibial shaft and distal tibia).

Although the tibial shaft in males and the posterior tibia in females are the least useful for estimating TL, the correlation coefficients of these equations are significant and moderate to strong (0.57 for males and 0.58 for females), and they may therefore still be used to confidently estimate TL. This was confirmed by the fact that there was no significant difference ($p>0.05$) between actual measured TLs and the TLs estimated using all multivariate equations in both sexes. Furthermore, all multivariate equations estimated TL with high accuracy (70-100 %) (Tables 12-14, pages 58-60). These results suggest that all multivariate equations can be used to estimate TL with confidence.

Similar to equations estimating TSH, correlations were higher and SEEs were lower in multivariate equations compared to univariate equations estimating TL. Multivariate rather than univariate equations should therefore be used, when available, to more accurately estimate TL.

Since tibial fragments are much smaller in comparison to TSH than they are in comparison to TL, it is expected that correlations for equations estimating TL would be higher and SEEs would be smaller than those estimating TSH. While SEE values for both univariate and multivariate equations estimating TL were indeed smaller than those for equations estimating TSH, correlation coefficients were also lower, which is unexpected and not clearly understood. Similar findings were also observed by Chibba and Bidmos (2007) for the tibia in white South Africans and by Bidmos (2008a) for the femur in black South Africans.

5.6. Direct vs indirect methods

TSH can be estimated from fragments of bones in one of two ways, namely the direct and indirect methods (Bidmos, 2009). There has been some debate regarding which method yields more accurate TSH estimates. Steele (1970) suggested that the indirect method is more accurate, but both Bidmos (2009) and Fongkete *et al*. (2016) reported that the direct method is both less complicated and more accurate than the indirect method and should be the preferred method to estimate TSH from fragmentary remains.

Both univariate and multivariate equations in the present study were used to estimate TSH directly from tibial measurements, and indirectly by first estimating TL from tibial dimensions and then converting TL to TSH. All TSHs estimated in the direct method did not differ significantly ($p<0.05$) from the actual measured TSHs, and only one TSH estimated using the indirect method (univariate equation for soleal circumference or SLC) was significantly different ($p<0.05$) from the actual measured TSHs. This suggests that both methods yield accurate TSH estimates. However, the adjusted SEEs for TSH estimates obtained using the indirect method (5.50-8.13 cm for both sexes) were significantly ($p<0.05$) larger than the SEEs associated with equations for the direct method (3.43-5.66 cm for both sexes). Since larger SEE values indicate lower accuracies of the equations and thus the TSH estimates, the direct approach appears to be the more accurate method since the SEEs associated with it were smaller than the indirect method.

These results, together with the fact that the direct method is much quicker and less complicated as it only involves one step, indicate that the direct approach should rather be used to estimate TSH from fragmentary tibiae. However, if such equations do not exist, the indirect method can also produce fairly accurate TSH estimates. This is in agreement with the recommendations made by Bidmos (2009) using fragmentary femora.

5.7. Reliability of equations

The reliability of some of the equations derived for estimating stature from tibial fragments in South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) in a sample of black South Africans was tested. This was done in order to confirm the need for population-specific standards. This was achieved by comparing the estimated living statures (ELSs) obtained using each population-specific equation to the actual measured ELSs. Actual measured and estimated TSHs were converted to ELSs using the soft tissue correction factors proposed by Fully (1956).

Equations for South African whites and North American blacks significantly ($p<0.001$) overestimated stature in a black South African sample (Figures 17 and 18, pages 70 and 71), which further confirms the population-specificity of these equations and the recommendation that stature estimation formulae not be used on individuals from populations other than the reference population. These differences in stature between populations may be the result of secular changes in response to a range of conditions such as nutrition (Perkins *et al.*, 2016), socioeconomic status (Zong *et al.*, 2015) and climate (Bharati *et al.*, 2010), or may be the result of differences in growth rates between populations (Bogin and Rios, 2003; Nyati *et al.*, 2006). It is important, therefore, that regression equations be derived for all populations so that stature estimates for individuals from these populations are as accurate as possible.

Results also showed that there was no significant difference ($p>0.05$) between the ELSs derived from equations in the present study and the actual measured ELSs (Figures 17 and 18). This indicates that the equations formulated in this study can be considered reliable and produce accurate stature estimates in black South Africans.

5.8. Study limitations and future research

This study may be limited due to the relatively small sample size used. Constraints in sample size were due to the fact that there were many skeletons that were incomplete, had damaged or broken elements, had fused vertebrae or vertebrae with severe osteophytic lipping. As such, many skeletons had to be excluded. Future studies would therefore benefit from greater sample sizes.

Another limitation was the fact that total skeletal height (TSH) had to be calculated and used to derive the regression analyses rather than cadaveric height or living stature as these were either not available or not reliable.

Future research should also aim to develop regression equations using tibial fragments for the South African coloured population and should also include establishing regression equations using a wider range of tibial variables.

5.9. Conclusion

Measurements of the tibia representing fragments were used to derive regression equations for both total skeletal height (TSH) and tibial length (TL). All tibial variables were significantly correlated with TSH and TL, and both univariate and multivariate equations had correlation coefficients that were higher than and SEEs that were smaller than those reported for tibial fragments in a population of white South Africans (Chibba and Bidmos, 2007). However, correlations were slightly lower than, and SEEs were slightly larger than those reported for fragments of the femur (Bidmos, 2008a) and intact tibiae (Lundy and Feldesman, 1987) in black South Africans.

All equations estimated TSH and TL with relatively high accuracy and most estimated TSHs and TLs did not differ significantly from the actual measured TSHs and TLs.

While both the direct and indirect methods yielded accurate TSH estimates, SEE values associated with the indirect method were much larger than those for the direct method. The direct method should therefore be used to estimate TSH from tibial fragments when such equations exist.

Regression equations for fragments of the tibia derived for South African whites (Chibba and Bidmos, 2007) and North American blacks (Holland, 1992) significantly overestimated stature in a sample of black South Africans by an average of 9.17 cm and 13.21 cm respectively, confirming the need for population-specific regression equations.

In the absence of intact tibiae, the equations derived in the present study can therefore be used to accurately estimate TSH, and thereby stature, from tibial fragments in a population of black South Africans. This is significant since stature is an important component of the biological profile of unidentified skeletal remains and can be very valuable in aiding in the identification of these individuals.

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APPENDIX A

Human Research Ethics Committee (Medical) –

Clearance Certificate No. W-CJ-170301-2

Human Research Ethics Committee (Medical) **50 years 1966 – 2016**

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Website: www.wits.ac.za/research/about-our-research/ethics-and-research-integrity/

Ref: W-CJ-170301-2 01/03/2017

TO WHOM IT MAY CONCERN:

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical).

Investigator: Ms A Spies (student no. 746773).

Project title: Stature estimation from fragments of the tibia in Black South Africans.

Reason: This is a study using complete skeletons of Black South African adult males in the Raymond A. Dart Collection of Human Skeletons housed in the School of Anatomical Sciences. Permission to use the skeletons has been obtained from the Curator of the collection and the Head of the School of Anatomical Sciences. This fulfils the requirements of the waiver given to the School of Anatomical Sciences (W-CJ-140604-1) based on donated tissue for research in the National Health Act No 61 of 2003.

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Professor Peter Cleaton-Jones

Chair: Human Research Ethics Committee (Medical)

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APPENDIX B

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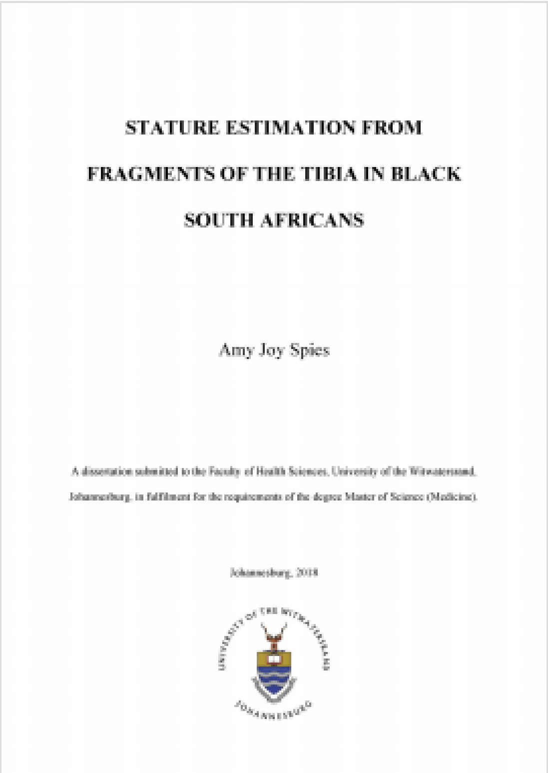

STATURE ESTIMATION FROM FRAGMENTS OF THE TIBIA IN BLACK SOUTH AFRICANS

Amy Joy Spies

A dissertation submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in fulfilment for the requirements of the degree Master of Science (Medicine).

Johannesburg, 2018

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27 July 2018

Ms Thando Mbolekwa
Postgraduate Research Administration
Faculty of Health Sciences
University of the Witwatersrand

Dear Ms Mbolekwa,

Re: Amy Spies (Student number: 746773)

MSc title: Stature estimation from fragments of the tibia in Black South Africans

This letter is to confirm that I have reviewed Ms Amy Spies' Turn-It-In report and am happy to confirm that there is no form of plagiarism. The overwhelming majority of similarities identified by Turn-It-In relates referencing.

Please feel free to contact me should you have any further queries.

Dr. Desiré Brits
Supervisor

Anatomical Sciences