Development of a sport specific anthropometric calibration model to estimate whole body density of professional football players

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Preliminaries

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RESEARCH DEGREE THESIS

AUTHOR'S DECLARATION

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This thesis is dedicated to my little miracle

~ ***Harry*** ~

I would like to take this opportunity to thank several individuals who have continuously supported me throughout my PhD journey.

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كل ما هو ليس معطى خس

There are currently no calibration models that allow whole body density in professional footballers to be estimated. As such, there is a need to develop practical calibration models in order to make sound body composition judgements. The aim of this thesis is threefold. Firstly, to examine the measurement reliability of a range of anthropometric measures, residual lung volume, air displacement plethysmography and hydrostatic weighing (HW). Secondly, to establish reliability and precision of body composition measures used within existing calibration models which estimate whole body density (D_b) from the criterion of HW. Thirdly, to develop and cross-validate new calibration models for professional footballers. Data was gathered from n = 206 male professional footballers ($\bar{x} \pm s$; age = 24.1 ± 5.4 years, body mass = 78.8 ± 8.4 kg and stature = 180.1 ± 7.0 cm) playing in leagues ranging from Barclays Premier to Blue Square Premier. The reliability of all directly measured variables (n = 28) was measured by providing a comparison between inter-tester methods by applying TEM%, and intra-observer test-retest methods by applying the Bland and Altman 95% Limits of Agreement (LoA) method (1986). Following an analysis of TEM%, LoA and the study's *a priori* criteria (± 3.8%), all 28 anthropometric variables were found to be statistically significant (P = < 0.01) and demonstrated reliability. Therefore it is judged to be of practical use with this population. Study 2 assessed the agreement and validity of estimating D_b from 15 existing calibration models by providing a comparison with a criterion method of HW in professional footballers. LoA approaches were used to determine bias and random variation and found that (on average) estimated D_b derived from HW was greater than D_b derived from the 15 models. This analysis suggested that bias ranged from - 0.005 to + 0.015 g ml^{-1} and random errors ranged from 1.012 to 1.090 g ml^{-1}. An *a priori* criteria (± 3.8% P = < 0.05 (g ml^{-1})) was set which found that (on average) in 13 calibration models, the estimated D_b derived from HW was greater than D_b derived from the models. A rank order of LoA identified the best model to use, however, it was not narrow enough for measurements to be of practical use and in most instances, it was concluded that existing models are not appropriate for estimating D_b in professional footballers. Study 3 determined the most reliable measures as potential predictors in the development of two calibration models that were capable of estimating D_b with a sample of n = 140 professional footballers. Additionally, this study aimed to cross-validate the newly developed calibration models on n = 66 participants to determine the validity using LoA. A forced stepwise – backwards regression analysis approach on a sample of n = 140 footballers with nine predictors which met the acceptance criteria (r = 0.950, R^2 = 90%, and β weights) was conducted to develop a 'best fit' and a 'practical' calibration model. Results indicated that the 'best fit' calibration model had the lowest SEM (0.115 g ml^{-1}), the highest R^2 (6.6%) and was statistically significant (P = < 0.005). Results indicated that the 'practical' calibration model had the lowest SEM (0.115 g ml^{-1}), the highest R^2 (4.7%) and was statistically significant (P = < 0.005). The validity of the two new calibration models, wase determined through cross-validation methods on n = 66 professional footballers where both calibration models were normally distributed and findings were within acceptable limits of the study's *a priori* criteria (± 3.8% P < 0.05 (g ml^{-1})). Heteroscedasticity plots illustrated r values = 0.271 and 0.596 and R^2 (%) coefficients = 0.3526 for the 'best fit' and 'practical' calibration models (P = 0.01). Results from LoA were considered narrow enough to be of practical use to estimate D_b of professional footballers. In conclusion, the two calibration models can provide an ecologically and statistically valid contribution to applied sport science knowledge, which ultimately can provide sound judgements about professional footballers' body composition.

Accuracy

General Context

The condition being true, correct, or exact and freedom from error or defect

In the context of this thesis

The extent to which measured values agree with the actual (or expected) values and the extent to which these measured values agree with one another

Agreement

General Context

The unanimity of opinion or coming to a mutual arrangement

In the context of this thesis

The assumption that the mean and standard deviation of the differences are constant

Bias

General Context

A systematic as opposed to a random distortion of a statistic as a result of sampling procedure

In the context of this thesis

How far the average difference lies from the measurement from the parameter it is estimating

Calibration

General Context

To determine, check or rectify the precise use and application of any instrument giving quantitative measurements

In the context of this thesis

The relationship between the values indicated by a measuring instrument/tool and the corresponding values determined by a standard

Concordance

General Context

The degree of similarity or agreement in a pair with respect to the presence or absence of a particular trait

In the context of this thesis

The degree of measurement agreement

Consistency

General Context

A steadfast adherence and agreement to the same principles

In the context of this thesis

An agreement of the values when measured more than once under the same conditions

Heteroscedasticity

General Context
A sequence of random variables

In the context of this thesis
A sequence of random variables if it has constant variance

Error

General Context
A mistake or deviation from accuracy or correctness

In the context of this thesis
The differences between the values associated with repeated measures of a test or instrument/tool made under the same conditions

Sometimes referred to as:
Variability

Objectivity

General Context
The state or quality of being objective

In the context of this thesis
The amount of variability in the values recorded when applying the same test to the same individual(s)

Precision

General Context
The state or quality of being accurate, exact and to arrive at an estimate with precision

In the context of this thesis
The degree to which the same values are obtained following repeated measurements on the same individual(s)

Sometimes referred to as:
Reliability, Repeatability and Reproducibility

Reliability

General Context
Consistent dependability of results with confident certainty

In the context of this thesis
The consistency of values recorded by a single rater in repeated trials under the same conditions on the same participant(s)

Sometimes referred to as:
Precision, Repeatability and Reproducibility

Repeatability

General Context
To reproduce or go through again

In the context of this thesis
The variation in measurements taken by a single person or instrument on the same individual(s) and under the same conditions

Sometimes referred to as:
Reliability, Precision and Reproducibility

Reproducibility

General Context
To make a copy, duplicate or close imitation of

In the context of this thesis
The agreement of test values and test instruments/methods

Sometimes referred to as:
Reliability, Precision and Repeatability

Validity

General Context
The degree to which a study accurately assesses what is it is supposed to assess

In the context of this thesis
The degree of agreement between the values gathered from the measuring tool/instrument being used, and those from a criterion or gold standard test

Air Displacement Plethysmography	ADP
Analysis of Variance	ANOVA
Beta Weight	β
Bod Pod®	BP
Body Fat	BF
Body Volume	BV
British Standards Institute	BSI
Coefficient of Determination	R^2
Gastrointestinal Tract	GIV
Fat Free Mass	FFM
Fat Mass	FM
Forced Vital Capacity	FVC
Hydrostatic Weighing	HW
International Society for the Advancement of Kinanthropometry	ISAK
International Working Group of Kinanthropometry	IWGK
Lean Body Mass	LBM
Limits of Agreement	LoA
Lung Gas Volume	LGV
Mass in Water	M_w
Mass in Air	M_a
Pearson Product-Moment Correlation Coefficient	*r*
Probability	*P*
Residual Volume	RV
Standard Error of the Estimate	SEE
Statistical Package for the Social Sciences	SPSS
Student *t*-Test	*t*
Technical Error of Measurement	TEM
Total Body Fat	TBF
Total Body Mass	TBM
Total Body Water	TBW
Whole Body Density	D_b
Whole Body Density from Air Displacement Plethysmography	$D_{b(ADP)}$
Whole Body Density from Hydrostatic Weighing	$D_{b(HW)}$

Chapter 1
Introduction

1.1 Sports science and football

Football is one of the most popular sports in the world, and with this popularity there are spiralling costs of purchasing players in the transfer market, consequently pressure can be placed on clubs to identify, develop and nurture their existing players (Bunc & Psotta, 2001). As the game of football is ever changing, players and clubs focus now more than ever on developing as top-class athletes. Yet it was not so long ago that most sport coaches would treat the idea of support from a sport scientist with abject cynicism (Gil *et al*., 2005). Clubs can no longer rely on coaching folklore and techniques that have been passed down through the generations, furthermore, gone are the days when a player could get by on talent alone (Reilly & Williams, 2005). Today, it is far more commonplace for clubs to seek an input from sport scientists for a contemporary approach in the quest for that competitive edge (Vestberg *et al*., 2012).

Sports science uses a scientific approach to achieve an optimal performance potential by embracing a whole spectrum of medical advances, such as nutrition, psychology, performance analysis and physiology (Bangsbo *et al.*, 2006). From a practical standpoint, a scientific approach can help equip sport scientists with the skills to identify player profiles that can diagnose players' strengths and weaknesses, provide baseline data for the development of an individual training programme and provide feedback for evaluating the effectiveness of a training programme (Pyke, 2000). These profiles can contribute significantly to examining training adaptation and the efficacy of the training programme utilised throughout the playing season. As such sports science has become an important part of professional football where players are trained to best meet the physical demands of the game (Svensson & Drust, 2005).

1.2 Physiological demands of football

As sports science has become an important part of professional football, training players to perform to the highest level possible is fundamental to success. Typically what makes football so physically demanding is the high-intensity exercise interspersed with periods of lower intensity exercise and to be able to recover rapidly (Casajús, 2001; Stolen *et al.*, 2005; Svensson & Drust, 2005). With evidence suggesting that strategies, tactics and the role of players continue to evolve, players need to acquire a base level of physical conditioning to enable them to perform successfully over a competitive season of around 35 weeks (Bunc & Psotta, 2001; Stolen *et al.*, 2005).

The duration of a match lasts approximately an hour and a half with players working in three major roles. Firstly, players work offensively with or without the ball to maintain possession, secondly, they work offensively in order to score a goal or finally, they work defensively to regain possession or to prevent a goal from being scored (Matkovic *et al.*, 1991; Luhtanen *et al.*, 1999). Although dependent upon the positional role within the team and the team's particular style of play, all players will perform a plethora of performance skills including: kicking; passing; trapping; dribbling; tackling; jumping; turning; heading; changing pace; sprinting and sustaining forceful muscle contractions to maintain balance and control of the ball (Stolen *et al.*, 2005; Svensson & Drust, 2005). A reduction in these skills might limit the performance of a player during matches (Bangsbo & Lindquist, 1992).

Given the seasonal nature of football, it might be expected that players have to perform consistently at a high level for more than 50 matches per season depending upon the success of the team, thereby generating a demand to maintain conditioning levels to sustain performance levels (Riach *et al.*, 2004). It is reasonable then to assume that these varying playing roles impose specific physiological demands on a player (Casajús, 2000). These demands will clearly depend upon playing position, but a player will need to be at an optimum status in several aspects of fitness including energy from the aerobic system and the anaerobic system as well as muscular strength, flexibility and agility (see Figure 1.1) (Casajús, 2001; Svensson & Drust, 2005).

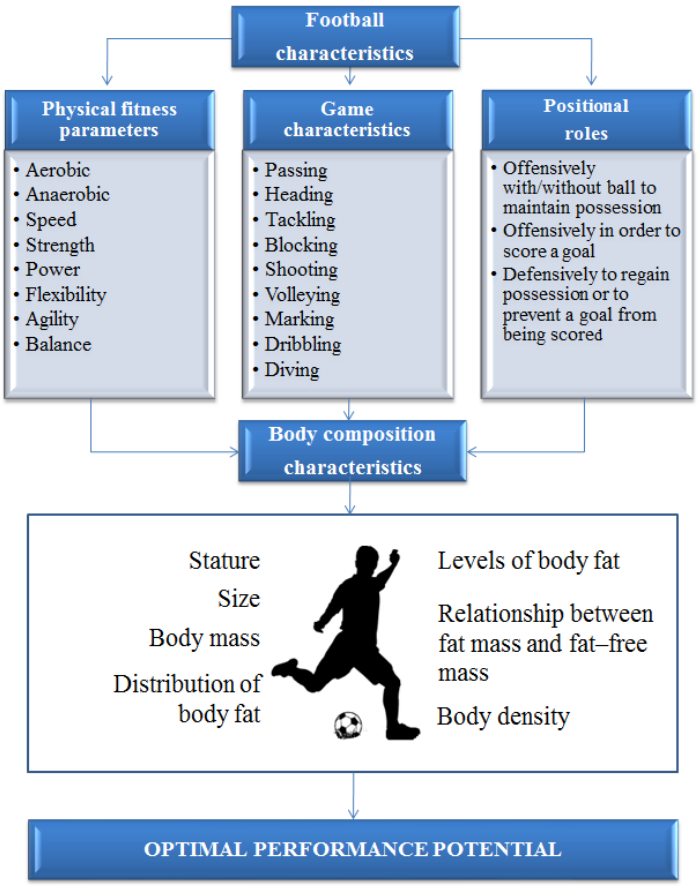

Figure 1.1 Relationships between body composition and optimal performance potential in professional football players (adapted from Herm, 1991; Matkovic *et al.*, 1991; Chin *et al.*, 1992; Tumilty, 1993; Bangsbo, 1994; Di Salvo & Pigozzi, 1998; Luhtanen *et al.*, 1999; Casajús, 2000).

In a game so variable in its physiological demands, players must consequently attain a higher level of conditioning to cope in the modern game which is played at an even faster pace and intensity than in previous decades (Stolen *et al.,* 2005). In order to achieve this higher level, Wells and Reilly (2002) and Gil *et al*., (2005) claim that the relationship between the physiological demands of the game and the composition of the body, is of considerable importance.

1.3 Body composition and football players

Body composition analysis is becoming increasingly widespread in professional football as it helps to further understanding of the relationship between body fat and changes over time with different physical fitness parameters. Although not every body composition characteristic is expected to play a role in optimal performance in football, it has been recognised by researchers such as Reilly *et al*., (2000), Rienzi *et al.,* (2000), Gil *et al*., (2005) and Duthie *et al.,* (2006) that low levels of body fat is desirable for optimal performance as body mass must be moved against gravity. As male athletes generally accumulate body fat in the visceral area around the waist, there is an added metabolic energy requirement needed to displace the excess body fat (Lamb, 1984). In other words, body fat does not contribute to force production, so by achieving optimal levels of body fat and fat-free mass, the player can minimise the negative effects of excess body fat without sacrificing skill (see Figure 1.1) (Wallace *et al*., 2008; Sutton *et al*., 2009).

Professional football players are not considered to be excessively fat, but there is continuous pressure made by managers, coaches and physiotherapists to monitor players' body composition to help players reach optimal performance potential (Stewart, 2006).

Consequently, it is not uncommon for sport scientists to assume responsibility for monitoring and managing their players' body composition over the playing season. As body fat is one of the main factors affecting body composition, the knowledge and understanding of whole body density and how it influences the body could be useful to quantify the effectiveness of a prescribed training programme and/or athletic performance potential.

1.4 Whole body density

Whole body density is the ratio of body mass to body volume and can be used to help estimate the proportion of body fat present in the body (Martin *et al*., 1986). The density of the whole body is however dependent upon the relative size of both fat mass and fat free mass components (Eckel, 2003). Behnke *et al.*, (1942) quantified both the fat mass and fat free components to have densities of 1.100 $g.ml^{-1}$ and 0.900 $g.ml^{-1}$ respectively (Clarys *et al.,* 1984; Clasey *et al*., 1999). However, there are suggestions by many authorities that none of these assumptions can be fully justified (Heyward & Wagner, 2004; Rolland, 2013). For instance, the density of fat remains constant, however, literature confirms that densities vary dependent upon age, sex, ethnicity and physical activity levels (Ellis, 2000; Eckel, 2003; Heyward & Wagner, 2004; Rolland, 2013). This led to the conclusion that fat mass has a lower density than fat free mass, therefore, an estimate of proportion of fat mass to fat free mass can be established (Martin *et al*., 1986; Brodie, 1988).

Direct measures of whole body density can only be made through cadaver analysis, and is understandably fraught with ethical and legal issues. Yet such methods are essential for the validation and comparison of indirect methods of estimation of whole body density

(McArdle *et al*., 2006). It is not therefore surprising that the development of indirect measures of estimating whole body density have increased over the decades. Table 1.1 summarises a range of available laboratory techniques and their relative accuracy with strengths and limitations. Although not all the measures illustrated in Table 1.1 measure whole body density indirectly, it is important to acknowledge that hydrostatic weighing is still considered by many researchers to be the criterion method against which all other indirect methods should be validated mainly attributable to its reliability (Demura *et al.*, 2002; van der Ploeg *et al*., 2003; Eston *et al*., 2005; ISAK, 2012).

Some of these measures have served to promote a renewed interest in the sports science field due to its unique ability to subdivide the body (Bandyopadhyay, 2007; le Gall *et al*., 2010). However, generally speaking, these methods are not accessible to football clubs and sport scientists due to their clinical application and expensive nature. Indeed some clubs do gain access through University laboratories, but in reality sport scientists require a more accessible and convenient method for obtaining data on body composition.

Table 1.1 Summary of laboratory techniques available for the estimation of total body composition characteristics

Method	Measurement	Precision error	Accuracy	Strengths	Limitations
HW	density	± 2%	96-98%	criterion method applicable for large individuals	water immersion requires lung volume impractical
BodPod	density	± 4.5%	>95%	quick, non-invasive immediate results applicable for various populations	claustrophobia requires lung volume stature and mass restrictions
DEXA	FM/FFM	± 1%	97-99%	quick, non-invasive immediate results applicable for various populations	radiation loses accuracy with increased fat mass affected by hydration status
MRI	areas/volumes	<2%	96-98%	generates accurate total and regional body volumes and dimensions	high levels of training required very expensive
CT	areas/volumes	<1%	96-98%	generates accurate total and regional body volumes and dimensions	radiation high levels of training required very expensive
A	density	± 2.5%	>95%	portable inexpensive large database	invasive affected by dehydration and skin thickness technician error
BIA	total body water [converted to FFM]	± 4.5%	<80%	portable fast non-invasive	affected by hydration and temperature status accuracy and precision concerns not recommended for obese or athletic populations

KEY:
HW: hydrostatic weighing; BodPod: air displacement plethysmography; DEXA: dual energy x-ray absorptiometry; MRI: magnetic resonance imaging; CT: computed tomography; A: anthropometry (skinfolds, girths, breadths, widths); BIA: bioelectrical impedance analysis. Percentage accuracy is determined as (100 - % error), where the error is the percentage difference from the true value (adapted from Rolland, 2012)

The most commonly used method within the sports science field is via anthropometry with measures consisting of skinfold thicknesses, girths, breadths, widths and depths (Reilly, 1996). This accessibility relates to the ease with which the various body sites required for measurement can be located, the time taken to carry out the measurements, minimal cost and the relatively low technical expertise required. In turn these measures can often be transferred to calibration models to help estimate whole body density. Thus a number of authorities such as Bird and Davidson (1997), Pyke (2000), Hencken and White (2006) have recommended establishing statistical relationships between anthropometry and aspects of sport performance to assist management, coaches, national governing bodies, sports science teams and players to reach their optimal performance potential. One way of achieving this recommendation is via the use of calibration models to estimate whole body density.

1.5 Estimation of whole body density using calibration models

There are a plethora of calibration models available in the scientific literature for the estimation of whole body density in adult males including those provided by Brožek & Keys (1951), Wilmore and Behnke (1969), Forsyth and Sinning (1973) and Jackson and Pollock (1978). However, many of these models have been derived from measurements taken from a large heterogeneous sample, such as the ubiquitous model presented by Durnin and Womersley (1974). The question remains however, as to whether such models are useful in a sports specific sample and furthermore how they can be transposed into the sports science arena (Egan *et al*., 2006; Wallace *et al*., 2008). Indeed previous studies have indicated that indiscriminate use of calibration models to estimate whole body density on populations that are different to those on which they

were originally derived might lead to significant over or under-estimation of whole body density (Cooper, 1995; Heyward, 2000). Some models have generally been known to report ranges of 1.027 to 1.090 g ml^{-1} with leaner populations, indicating significant underestimation of whole body density (Lohman, 1981; Guo *et al*., 2000; Provyn *et al*., 2012). Thus emphasising researchers concern for the reliability and validity of such models and whether they are fit for purpose. Yet, Mayhew *et al*., (1981) suggested that there has been a dependency upon these generalised calibration models due to the lack of sports specific calibration models. Therefore a degree of caution is required when selecting a model. For instance, if the selection of a model is made by a non-expert, they might be naïve and uneducated in the implications of inaccurately estimating whole body density with their players (Guo *et al.*, 2000; Heyward, 2000). A more effective alternative would be to use a population or sports scientific calibration model.

These population or sports specific approaches have been on the increase in recent years, and have helped to contribute to increasing understanding of body composition in relation to specific sport and physical activity (Lohman, 1984). However, many of these calibration models have been developed using a range of individual anthropometric variables and the emphasis on each variable and the manner in which these variables are used interchangeably differs within models. Additionally small sample sizes and inappropriate analytical methods and more importantly, the omission of a cross validation element to their studies as indices of the model(s) validity are used to develop new calibration models. This cross validation element of the approach is something that very few researchers seem to carry out and ideally it should be

conducted against another sample drawn from the population for which it is intended (Guo *et al*., 2000; Provyn *et al*., 2012). In reality the main reason for not cross validating calibration models is mainly attributable to the lack of sufficient sample size to carry out such a process with statistical rigour (Heyward, 2000).

What remains questionable is that given the popularity of football and the importance of developing and utilising a sports specific calibration model, at present, there are no published calibration models for professional footballers that can be used with confidence. As there is a gap in the literature, the development of reliable football specific calibration models could greatly contribute to the knowledge of the sport and to extend understanding of whole body density in professional football players that could ultimately aid players to reach their optimal performance potential (Hencken, 2004; Svensson & Drust, 2005).

1.6 Summary

To date there are no calibration models that exist in the literature to estimate whole body density on professional football players. From a sports science perspective, there is a significant gap in the literature. As such footballers have been reliant on using more generalised calibration models, many of which have been derived from measurements taken from a heterogeneous sample. These generalised approaches can result in the underestimation of whole body density in male professional football players, which can be detrimental to their health and could impede the effectiveness of a prescribed training programme throughout the playing season. Given the popularity of the game, the development of a football specific calibration model(s) for male professional footballers

therefore could significantly contribute to knowledge of whole body density (Aziz *et al*., 2004; Gil *et al*., 2005; Demura *et al*., 2007). Ultimately these models can provide sport scientists with an essential tool to help monitor and assess whole body density to ensure that a player maintains healthy body fat levels and reach optimal performance potential needed for their football playing position (Hencken, 2004; Svensson & Drust, 2005).

1.7 The aims of this thesis

In view of the assertions and arguments made above and based upon the literature reviewed, the principle aims of this thesis are to:

1. To identify and quantify intra-rater measurement reliability commonly used body composition measures (n = 29) and to establish sources of error through relative and absolute reliability methods. Furthermore to establish the reliability and precision of body composition measures used within calibration models to estimate whole body density when applied to professional football players (n = 206). The aim of this study was to establish reliability in the data collected. Without such confidence in the reliability the comparison of findings is not possible and would not support a sound foundation from which Study 2 and Study 3 in this thesis could be based.

2. To investigate the validity of recognised pre-published calibration models (n = 15) for the estimation of whole body density when compared to whole body density values derived using the criterion method of hydrostatic weighing.

Additionally to investigate the agreement of the estimation of whole body density when applied to professional football players (n = 206). The aim of this study was to investigate whether these generalised calibration models were suitable for professional football players. Data entered into the models were gained from the reliability investigations from Study 1 and the sample size was large to be able to make an informed decision.

3. To determine the most reliable and accurate body composition measures that can be used as potential predictors for the estimation of whole body density on n = 206 professional football players. The potential predictors would be used to develop two sport specific calibration models on n = 140 professional footballers. Firstly to develop a 'best fit' calibration model where there is a high level of understanding and expertise in the area of body composition, and could be used within an academic and research environment. Secondly to develop a 'practical' calibration model that could be used within a football field testing environment. Validity of the two new calibration models, to be determined through cross-validation methods on n = 66 professional footballers to estimate whole body density.

The aim of this study was to develop models that are capable enough to monitor whole body density level of professional football players. Moreover, provide an essential tool for the regular monitoring of players and provide informative insight into the body fat levels needed to determine optimal performance potential. Data entered into the models were gained from the reliability

investigations from Study 1 and the sample size was large (n = 140 participants) and cross-validation processes were used to determine validity of newly developed calibration models on n = 66 participants to be able to make an informed decision.

The main objectives include investigations that examined methodological protocols to:

- Examine the most appropriate assessment method for body mass
- Examine on the most appropriate procedure for maximal exhalation during hydrostatic weighing
- Investigate the number of hydrostatic weighing measurement attempts needed to determine average body mass in water
- Investigate the linearity of the scale for mass and volume within the BodPod
- Investigate the agreement between different methods to estimate residual lung volume

Chapter 2
Review of Literature

2.1 Introduction

Sport coaches have begun to recognise that the most efficacious way of preparing players for the competitive season is one based upon proven scientific methods and not upon trial and error judgements. Indeed, it is not so long ago that most sport coaches would treat the idea of support from a sport scientist with abject cynicism. Today, however, it is far more commonplace for players and teams to seek an input from sport scientists so that players can achieve their full potential.

In recent years, sport scientists have made considerable progressions in identifying footballers optimum anthropometric characteristics required to cope with football at the highest level (Adhikari & Kumar, 1993; Norton & Olds, 2002). A number of authorities, Norton *et al*., (1994), Reilly (1996), Bird and Davidson (1997), Pyke (2000), Hencken and White (2006) recommend establishing relationships between anthropometry and aspects of performance to assist management, coaches, national governing body, sports science team and players to reach their full potential. However, it has been considered by Martin *et al*., (1986), Norton and Olds (1998), Reilly *et al*., (2000) and Hencken and White (2006) that there are many anthropometric predispositions for certain positional roles within football. Not every body composition characteristic is expected to play a role in successful performance, but notably stature and body mass have been considered the most important anthropometric predispositions required (Martin *et al*., 1986; Norton & Olds, 2002; Reilly *et al*., 2000). It is important to recognise that considerable individual differences in low and high levels of body fat occur between players that might play a bigger role in optimal performance potential (Oppliger & Cassady, 1994; Heyward, 2000; Rienzi *et al.*, 2000; Duthie *et al.*, 2006).

Although today's football players are not considered excessively fat, there is continuous pressure by coaches, physiotherapists, managers and sport scientists to reduce players body fat to minimum levels in the knowledge that low levels of body fat will enable them to perform more effectively (Sinning, 1978; Brodie, 1988; McArdle *et al*., 2006; Stewart, 2006). To a certain point, low levels of body fat are beneficial to performance, as the energy cost of physical activity will be lower and the ability to maintain core temperature during prolonged exercise will be enhanced (Reilly & Williams, 2003; Clarkson, 2004). Consequently, those responsible for these players who view fat as detrimental to performance are slow to recognise its importance for health, as body fat plays an essential role in manufacturing hormones and storing vitamins (Stewart, 2006). When body fat is reduced to dangerously low levels, there is a risk of encroachment into essential fat reserves that can cause metabolic dysfunction and at worst affect the health status of the footballer (Katch & Katch, 1980; Lamb, 1984; McArdle *et al*., 1991; Stewart, 2006). Furthermore, it might offset performance benefits of training and compromise fat free mass and energy (McArdle *et al*., 2006). As a result, players must acknowledge that in order to achieve optimal level of performance it is not necessary or desirable that they achieve the lowest level of body fat (Ramadan & Byrd, 1987; Reilly & Williams, 2003; Clarkson, 2004; Stewart, 2006).

In contrast research by Heyward (2000) and Duthie *et al*., (2006) suggested that players possess higher levels of body fat that is optimal for football. High values have been reported many times by Reilly (1990; 1996; 2003; 2005) where suggestions have probably been due to footballers requiring higher metabolic loading imposed by match play and training. Indeed the greater levels of body fat, the greater the detriment to performance, as the fat cells are not contributing toward energy production and the energy costs needed to

move the fat (Casajūs (2001). A notion supported by Withers *et al.*, (1987), Rienzi *et al.*, (2000) and Clarkson (2004) where excess body fat can lead to an earlier onset of fatigue which not only adversely affects the ability to work, but is also associated with skill deterioration, increased injury risk and a decreased adherence to training requirements. Nevertheless, players cannot afford to reduce the muscular mass, as the power component might be compromised. Players should therefore concentrate on reducing the quantity of body fat, but within safe limits (Telford *et al*., 1985; 1988; Rienzi *et al.*, 2000).

As these factors are strongly influenced by age, sex, genetics and training, an argument has been that players levels of body fat levels should be determined when they are healthy and performing at their best (Sloan, 1967; Wilmore, 1983; Hayward, 2000). Heyward and Wagner (2004) suggested that it is wiser to set individual goals than to expect all players to achieve the same level of body fatness. This illustrates the significance of treating each player as an individual, and not as a member of a team (McArdle *et al*., 2006). However, this view challenges Wilmore's (1983) theory, whereby all players are actively encouraged to achieve similar levels of body fat. Arguably, players (if too high in levels of body fat) could feel pressured to engage in unsafe fat loss practices such as prolonged physical exercise, semi-starvation, malnutrition and disordered eating behaviours in an attempt to meet unrealistic fat loss (Roche *et al*., 1981; Heyward & Wagner, 2004; McArdle *et al*., 2006). Research conducted between 1985 to 2004 revealed 19 studies from different countries focusing specifically on football players' age, body mass and stature. A collation of these studies findings can be found in Table 2.1. Results indicated that the n = 809 international football players were very similar in age with mean age of 24.5 ± 2.5 yrs. However, stretched stature and body mass were more variable with mean stretched stature and body mass of 177.6 ± 3.3 cm and 74.2 ± 4.1 kg respectively.

Table 2.1 Overview of anthropometric characteristics of football players from different countries

Ref	Nationality	*n*	Age (yrs)	Stature (cm)	Body mass (kg)
1	America	12	22.5	178.6	76.2
2	Australia	12	23.8	178.6	75.8
3	Canada	16	20.1 ± 1.1	177.3 ± 6.5	72.6 ± 6.2
4	Croatia	44	26.4	179.1 ± 5.9	77.5 ± 7.1
5	Czechoslovakia	15	24.8 ± 3.4	182.6 ± 5.5	78.7 ± 6.2
6	Denmark	65	-	183.0	79.1
7	England	122	23.8 ± 4.4	-	77.1 ± 5.6
8	Finland	31	-	180.4 ± 4.3	76.0 ±7.3
9	Greece	99	25.4 ± 3.3	178.2 ± 5.1	74.5 ± 5.5
10	Holland	78	26.8	179.6	76.6
11	Hong Kong	24	26.3 ± 4.2	173.4 ± 4.6	67.7 ± 5.0`
12	Italy	33	26.3 ± 3.8	178.0 ± 5	75.7 ± 5.
13	Kuwait	15	-	172.7 ± 1.6	67.3 ± 1.9
14	Malaysia	14	19.1 ± 1.0	170.1 ± 5.0	64.8 ± 7.2
15	New Zealand	21	-	178.8 ± 6.8	78.9 ± 6.0
16	Portugal	21	27.6	178.1	73.8
17	Saudi Arabia	23	25.2 ± 2.3	177.2 ± 5.9	73.1 ± 6.8
18	Singapore	147	25.3 ± 4.3	174.0 ± 1.7	70.2 ± 8.7
19	Uruguay	17	-	177.0 ± 0.4	74.5 ± 4.4

References:
1 (Kirkendall, 1985); 2 (Kirkendall, 1985); 3 (Rhodes *et al.*, 1986); 4 (Matkovic *et al.*, 1993); 5 Galanti *et al.*, 1996); 6 (Reilly *et al.*, 2000); 7 (Davis and Brewer, 1991); 8 (Rahkila and Luhtanen, 1991); 9 (Tokmakidis *et al.*, 1991); 10 (Vos, 1980); 11 (Chin *et al.*, 1992); 12 (Caldarone *et al.*, 1990); 13 (Ramadan *et al.*, 1999); 14 (Reeves *et al.*, 1999); 15 (Dowson *et al.*, 1999); 16 (Puga *et al.*, 1993); 17 (Al-Hazza *et al.*, 2001); 18 (Aziz *et al.*, 2004); 19 (Rienzi *et al.*, 1998)

Adapted from Rico-Sanz (1998 p.115)

Findings from Table 2.1 exemplify the argument that footballers, notably goalkeepers, central defence and central attack, tend to be the tallest and heaviest, while the mean stature and body mass of the remaining players are similar (Apor, 1988; Bangsbo, 1994; Reilly, 1996; Todd *et al.*, 1999; Reilly & Gilbourne, 2003; Carvalho *et al.*, 2004; Wallace

et al., 2008). Findings are comparable to other studies, including Raven *et al*., (1976); Rigg and Reilly (1987); Davis and Brewer, (1991); Chin *et al.,* (1992); Puga *et al.,* (1993); Galanti *et al.,* (1996); Jankovic *et al.,* (1997) and Aziz *et al.,* (2004), where they found goalkeepers and defenders were the tallest players compared to the midfield and strikers.

More detailed anthropometric research was conducted during the 1995 Copa America Championships in Uruguay. Data collection of (n = 110) international footballers was conducted as part of the Soccer of Kinanthropometry International Project (SOKIP) (Gomes *et al*., 1999). The SOKIP project provided comprehensive data from six national teams (Argentina, Bolivia, Ecuador, Paraguay and Uruguay) by which elite players anthropometric characteristics could be compared (Rienzi *et al.,* 1998; Gomes *et al*., 1999; Reilly & Gilbourne, 2003). Data revealed the comparison of different playing positions with ANOVAs ($P < 0.05$) indicating the goalkeeper showed systematically higher proportional girths and skinfolds than other players (Gomes *et al*., 1999). In conclusion, body composition analyses indicated no significant differences among the playing positions when the goal keeper was excluded (Gomes *et al*., 1999). These findings might help to quantify the important characteristics required for key positional roles, where body composition rather than playing skills provides an advantage to assist with optimisation in football (Martin *et al*., 1986; Reilly *et al*., 2000; Duthie *et al.,* 2006; Hencken & White, 2006; Slater *et al.,* 2006). Although it is important to note that stature is not in itself a bar to success in football, though it might be a functional advantage in the exploitation for tactical purposes, and therefore could determine the choice or success of playing position (Apor, 1988; Bangsbo, 1994; Reilly, 1996).

All too often, the judgement concerning optimal playing body fat is made on a trial and error basis with reference only to body mass alone, disregarding the players overall body composition characteristics (Mayhew *et al.*, 1981; McArdle, 2006). There is evidence to suggest that optimal body mass could influence the ratio of power to body mass when moved against gravity, hence a low level of body fat is desirable for competitive success (Ekbolm, 1986; Davis & Brewer, 1992; Oppliger & Cassady, 1994; Reilly *et al*., 2000; Gil *et al*., 2005). Clarkson (2004) suggested that it is important to recognise that it is possible to lose fat but increase body mass due to increased muscle mass, especially in the pre-season period. A point already substantiated by Reilly (1996), Rienzi *et al.*, (2000), Egan *et al*., (2004) and Duthie *et al.*, (2006) where findings reported that players accumulated body fat in the off-season, and then reduced fat mass during pre-season.

Possible reasons why these fluctuations occur can be a result of injury, habitual activity of players, energy stores, nutritional status and what stage of the competitive season the body composition assessments were executed (Clarkson, 2004; Egan *et al*., 2004). Therefore players must strive to achieve an optimum sport performance potential with optimal levels of body fat taking into account their playing position (Casajus & Bosco, 2001; Loucks, 2004). By achieving optimal body fat the player can minimise the negative effects of excess body fat on activity without sacrificing power, assuming of course that the desired amount and intensity of training is executed (Bell *et al.*, 1991).

2.1.1 Reasons for measuring body composition

Sport coaches and sport scientists recognise that the most efficacious way of preparing players for competition is based upon complex and challenging blend of many component factors necessary for successful sport performance (Provyn *et al*., 2012; Rolland, 2012).

This places significant professional and academic challenges on the sport scientist. For instance, how the body is made in terms of our individual components has a profound influence over our health and our capacity for exercise (Stewart, 2012). The assessment of body composition is often used as a tool for gauging these various body components therefore this application provides a unique link between the different realms of health and sports performance (Pyke, 2000; Stewart & Sutton, 2012).

Given that most competitive sports typically requires a certain degree of leanness for optimal performance, it is not uncommon for managers, coaches and sport scientists to assume responsibility for monitoring and managing their players body compositions' (Dummer *et al*., 1987; Webster & Barr, 1993). Professional football is no exception. It is a game where the practice of body fat management is an element of a player's preparation, and is of primary concern to both football coaches and their support scientists (Bell *et al*., 1994; Provyn *et al*., 2012). Therefore, the measurement and monitoring of players body composition throughout training and the competitive season should be conducted. As there are many anthropometric predispositions within football, a number of authors such as Norton *et al*., (1994), Reilly (1996), Bird and Davidson (1997), Pyke (2000) and Hencken and White (2006) have recommended establishing relationships between body composition, health and aspects of performance to benefit management, coaches, sports scientists and players, to reach their full potential in the following notable ways:

(a) *Help to determine important characteristics of body composition*

This is probably the major reason for testing a player's body composition. In order to achieve this, the sport scientist would have to be able to identify the major components of physical fitness required for successful performance. It might be relatively easy to

evaluate the players total physical fitness response in a field-test setting. Conversely, it might be difficult to isolate each of the requisite components for evaluation in the field. In a laboratory environment however, sport scientists are often able to isolate given components and assess objectively the players' performance on that particular variable. Ultimately they should be able to suggest which players within particular playing positions may have a functional advantage (Reilly, 1996; Heyward & Wagner, 2004; Hencken & White, 2006).

(b) *Help to customise training for specific positions and roles within the team*

To provide baseline data for the development of a players individual training programme. Measurement results that have been objectively gathered and analysed will form the basis for training prescriptions that are specific to a particular player's position and that are aimed at optimising that player's performance within the team (Norton *et al*., 1994).

(c) *Help to track changes in a player's body composition*

If the sport scientist repeat their body composition measurements at regular intervals, comparisons of a player's results can help the player, manager, coach and sport scientist assess the effectiveness of their prescribed training programme or dietary regimen (Wallace *et al*., 2008). Although, it has to be acknowledged that the sport scientist might well find that training prescribed to one player proves to be effective, but when prescribed to another it might be less effective or not effective at all (Wallace *et al*., 2008; Reilly *et al*., 2009). Additionally, evidence of the Hawthorne Effect has been suggested by Brage and Wareham (2005) and Falk and Heckman (2009) that players are liable to modify their performance if they know that a test variable will be repeated at a later date. Yet this notion is extremely difficult to quantify.

(d) *Help to provide information about the health and wellbeing of players*

Training for high standard competition is a demanding and stressful process that can in certain players, induce a negative health status. Certain tests can be adapted to help screen and monitor players to detect disease and disorders associated with excessively low body fat levels that might not otherwise be identified by a standard medical examination (Heyward & Wagner, 2004). The measurement of body composition is frequently used as a tool for monitoring and gauging levels of body fat. Indeed, there is an ethical expectation that the sport scientist should be aware of the consequences of low levels of body fat that may influence morbidity of a player. In other words, how the health of the player could impede their ability to perform at an optimal level (Wallace *et al*., 2008; Stewart, 2012).

(e) *Help to educate players in the area of body composition*

Sport scientists have an opportunity to provide an educational process where the player learns to better understand their body composition attributes which are required for success in football (Cossio-Bolanos *et al*., 2012). This requires systematic planning of players development programmes, where sport scientists interpret test results directly to the player and, in turn, this process helps the player increase their appreciation of the components of football as well as an awareness of their own strengths and weaknesses.

(f) *Help in the development of a whole body density calibration model*

The generation of anthropometric measures in various body composition variables among elite players might help to provide invaluable data in the future development of calibration models aimed at estimating whole body density (Rolland, 2012).

2.2 Human body composition

The increased attention within the diverse fields of sports medicine and sports science has been mainly due to the demand from athletes, coaches, physiotherapists and managers alike, for quantifying body fatness in relation to health status and sport performance (Hawes & Martin, 2001). While the foundation for much of the theory in body composition was established over the last 100 years, this surge in interest has extended our knowledge in the structural components of the body resulting in the advancement of techniques for assessing body composition (Fields *et al*., 2004; Slater *et al*., 2006; Reilly *et al*., 2009; Peeters & Claessens, 2010).

Body fat appears to be the foremost concern when considering body composition in humans, with the quantification becoming an integral part of the assessment of nutritional, physiological and medical status (Behnke, 1961; Durnin & Womersley, 1974; Vogel & Friedl, 1992). For instance, the fat content might impact on morbidity and mortality with genetics, environment, nutritional habits, age, sex, physical activity and disease all influencing gross composition of the body (Siri, 1956; Durnin & Womersley, 1974; Lohman, 1981; Heyward & Wagner, 2004; Stewart, 2006). Fat accumulates in the form of triglycerides in the cells of adipose tissue and it is estimated that approximately 30% - 50% of total body fat is located subcutaneously (Lohman, 1981; Heyward & Wagner, 2004; Ford, 2008). With the different deposits of fat, the determination of body composition is a complex problem when estimating optimum deposits within the body (Siri, 1956). The inclusion of the total amount of fat in the body exists' as two distinct depots of body fat, essential fat and storage fat.

The most important deposit of body fat is termed essential fat, and is as the name would suggest the amount of fat required for normal physiological functioning (Sinning, 1978; Wilmore, 1983; Clarys *et al*., 1987; Lamb, 1992; Stewart, 2006). Essential fat comprises of fat stored in the muscles, marrow of bones, heart, lungs, spleen, liver, kidneys, intestines and the lipid rich tissues throughout the central nervous system (Lohman, 1981; Clarys *et al*., 1987; Heymsfield *et al*., 2005). It is well documented that essential fat content is highly variable (Siri, 1956; Brožek, 1961; Behnke & Wilmore, 1974; Lohman, 1981; Heyward, 2000; Stewart, 2006). Approximately 2.1 kg of fat in males stored as essential fat represents 3% of the total body mass (Behnke & Wilmore, 1974; McArdle *et al.*, 1991). This 2.1 kg of fat has received considerable attention and there have been attempts to quantify safe or minimal levels of body fat in players, in order to contribute towards health and optimisation of performance (Lohman, 1981; Lamb, 1984; 1992; Heyward, 2000; Duthie *et al.*, 2006; Stewart, 2006).

Storage fat is located in two main areas of the body. Firstly the fatty tissues around the body's vital internal organs, which help to protect them from trauma. Secondly in the subcutaneous adipose tissue that acts as the body's store of energy in the form of a nutritional reserve (McArdle *et al*., 1991; Stewart, 2006). This reserve has an assumed calorific value of approximately 63,500 kcal of possible energy and is most subject to change with diet and exercise (Hayward, 2000; Gately *et al*., 2003; McArdle, 2006). Indeed, storage fat demonstrates the most striking variation in nutritional status that varies considerably along the emaciation – obesity continuum (Brožek & Keys, 1951; Heyward, 2000; Gately *et al*., 2003).

2.2.1 Direct measurements of human body composition

Direct measurements of human body composition can only be made through cadaver dissection analysis (Clarys *et al*., 1984; Brodie, 1988; Withers *et al*., 1996). This type of analysis is essential for comparison and validation of indirect methods of assessing body composition (Rolland, 2013). Although dissection analyses on human cadavers are labour intensive, requires specialist laboratory equipment and personnel, and raises numerous ethical questions and legality issues (Behnke & Wilmore, 1974; McArdle *et al*., 2006). Quantification of body fat through cadaver analysis has two basic assumptions concerning the human body (Behnke *et al*., 1942; Martin *et al*., 1986). Firstly, body mass can be divided into two components which consist of fat mass (FM) and fat-free mass (FFM) (Going, 1996; Clasey *et al*., 1999; Heyward & Wagner, 2004). Secondly, these two compartments have densities that are assumed to be constant for all individuals: fat mass = 0.900 $g.ml^{-1}$ and fat free mass = 1.100 $g.ml^{-1}$ (Withers *et al.*, 1987; Clasey *et al*., 1999).

It is important to note that these values are irrespective of age, sex, ethnicity, genetic endowment and training status of the participants (Heymsfield *et al*., 1996; Withers *et al.*, 1996; Heyward & Wagner, 2004). Fat mass is the absolute amount of body fat within the body, with at least half stored in the subcutaneous tissues (Keys & Brožek, 1953). However, an oversight is that fat mass also represents the small quantity of organ-related essential fat that is equivalent to approximately 3% of body mass (Fox & Corbin, 1986; Withers *et al.*, 1996). Behnke (1942) considered fat mass an *in vivo* entity relatively constant in water, organic matter and mineral content, throughout the active adult's life span (Behnke & Wilmore, 1974; McArdle, 2006). Whereas fat free mass represents the body mass devoid of all extractable fat that includes the body's non-fat tissue comprising of bone, muscle, organs and connective tissue (Womersley *et al.*, 1976; McArdle, 2006).

Literature from 1945 to 1984 revealed that cadaver analyses have only been completed on six adult cadavers for body composition purposes (Clarys *et al.,* 1984; Brodie, 1988). Cadaver analyses were performed on five males and one female, ranging in age from 35 – 90 years with cause of death including heart disease, skull fracture, carcinoma and natural causes. However, none of these previously reported dissections by Mitchell *et al*., (1945), Forbes *et al*., (1953), Dempster (1955) and Moore *et al*., (1968) included any skinfold measurement or extensive anthropometry (Brodie, 1988; Clarys *et al*., 1984). Given the emphasis that is placed upon cadaver analysis for the comparison and validation of indirect methods of assessing body composition, research until 1984 was somewhat limited (Clarys *et al.,* 1984; Drinkwater *et al*., 1986; Stewart, 2006).

The Brussels Cadaver Study conducted by Martin *et al.,* (1984) is considered a pioneering large scale project and has added significantly to the literature on direct measurement of body composition (Beunen & Borms, 1990; Stewart, 2006; Marfell-Jones *et al*., 2008). Before dissection, 25 human cadavers (12 men and 13 female) all over 50 years of age were subjected to numerous anthropometric measures. Each cadaver was dissected and weighed for the components of skin, skeletal muscle, adipose tissue, bones and viscera (Clarys *et al*., 1987; Martin *et al*., 1989). The study was unique in the sense that it generated more than 2,500 individual sets of data per cadaver that included anthropometry, densitometry, radiography and osteometry (Clarys *et al*., 1987; Martin *et al*., 1989). Furthermore, results from the Brussels Cadaver Study suggested that the variation of density of the two compartments of fat mass and fat-free mass is greater than previously believed (Martin *et al*., 1986; Going, 1996). These findings were further tested by Martin *et al*., (1986) using data from the dissections of the Brussels Cadaver Study where the composition of the fat free mass varied considerably with a range of 41.9% - 59.4% for

muscle and 16.3% - 25.7% for bone. In light of the evidence provided from the Brussels Cadaver Study, literature has reported that it was unwise to assume therefore that fat free mass has a constant density due to obvious changes in total body mass from physical activity or age (Withers *et al.*, 1996; Visser *et al*., 1997; Clasey *et al*., 1999).

The data that has been obtained from cadavers raises concerns about applying the relationship found in such a sample to the resent study population (Behnke & Wilmore, 1974; Clarys *et al*., 1987). For instance, athletes present a problem, as there are no published cadaver reports on dissected tissue masses of athletes, although it is clear that their body composition differs from those of non-athletic cadavers (Stewart, 2006). Based on these assumptions, until more cadaver information is available to establish values for the various compartments of fat content in the human body, the solution might be to convert fat values to percentage body fat (%BF) (Siri, 1956; 1961). This possible solution should however be used sparingly, as recommendations by Behnke (1961), Damon and Goldman (1964) Sloan and Weir (1970), Clarys *et al*., (1984) and ISAK (2005) suggest that body density measures are better placed for body composition comparisons. Furthermore, due to the inherent problems that are associated with the dissection of human body, science has been forced to turn to indirect measurements' of body composition assessments (Behnke & Wilmore, 1974). Whilst highly accurate, cadaver analyses are not realistic given the population sample, therefore within the context of the present study it is also more practical to use indirect methods of measuring body composition parameters.

2.2.2 Indirect measurements of human body composition

Researchers have devoted considerable time and effort to ensuring that most indirect assessments are validated for precision, reliability and ease of administration (Behnke & Wilmore, 1974; Sheng, 1988). These methods are considered as being relatively simple, non-invasive and inexpensive (Sinning & Wilson, 1984; Russo *et al.,* 1992). However, due to the complexity of the anatomical levels of the body, the serious issue regarding some measurement methods being more valid than others is a continuing one. Therefore, knowledge of the organisational and fundamental structures of the body is a necessity.

One of the earliest and most prominent pieces of research on body composition was undertaken by Matiegka (1921) where a method for the anthropometric fractionation of body mass into four main components of bone, skin, subcutaneous fat, muscle and visceral were proposed (Drinkwater & Ross, 1980; Withers *et al*., 1991). However, it was not until Wang *et al.,* (1992) further delineated Matiegka's work into five distinct levels upon which a full understanding of human body composition could be conducted and organised to help comprise total body mass (TBM). Due to the increased complexities at each level, multiple compartments are distinct, with physiological and biochemical connections (Wang *et al.,* 1991; 1992). Furthermore, the interrelationships between the five different levels of organisation are important to provide a useful framework to help explore the different approaches to body composition assessment (Wang *et al.,* 1992; Hawes & Martin, 2001). The levels are defined as: I - atomic, II - molecular, III - cellular, IV - tissue system and, V - whole body (Figure 2.1).

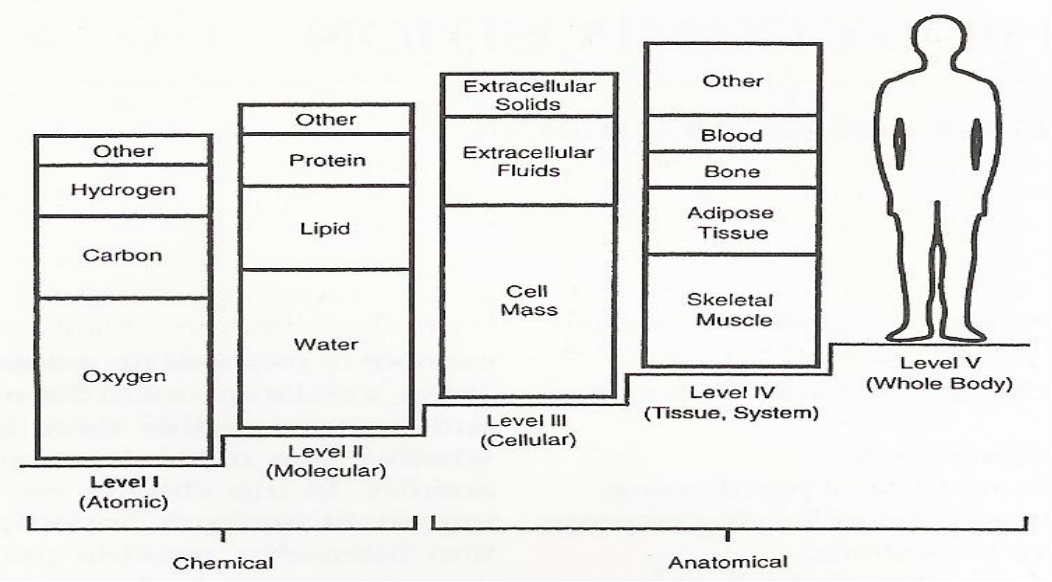

Figure 2.1 The five levels of human body composition (Taken from Wang *et al*., 2000)

The atomic level (I) consists of 50 elements that are distributed in various tissues and organs. Six elements, oxygen (O_2), carbon (C), hydrogen (H), nitrogen (N), calcium (Ca) and phosphorus (P) account for more than 98% of total body mass in the reference man (Behnke, 1942; Keys & Brozek, 1953; Wang *et al.,* 1992). Body composition analysis at the atomic level has traditionally only been possible through cadaver and biopsy procedures, and more recently, by using whole body potassium-40 (K^{40}) and γ neutron activation techniques (Gately *et al.,* 2003; Shen *et al*., 2005; McArdle *et al*., 2006). The importance of this technique is that it allows estimation of total body protein stores from its nitrogen content. Unfortunately there is limited instrumentation available, making this almost inaccessible to all but a few researchers (Hawes & Martin, 2001).

The molecular level (II) is made up of more than 100,000 chemical compounds, that range in complexity and weight with five closely related components of water (H_2O), lipid (L), protein (Pro), mineral (M) and glycogen (G) (Hawes & Martin, 2001). Water is the most abundant compound in the body and comprises 60% of the total body mass in the reference

man (Behnke, 1942; Wang *et al.,* 1992). Methods used to estimate body composition at this level are essentially based upon assessments of body water and body minerals. Total body water (TBW) has been measured in adults using well-established isotope-dilution techniques involving tritrated water ($^{3}H_2O$) and the 18-oxygen isotope ($^{2}H_2{}^{18}O$), bone mineral content quantified by dual-energy x-ray absorptiometry (DEXA) and total body protein (TBP) by neutron activation analysis of nitrogen. However, these methods tend to be in the clinical domain due to the expertise required and expensive nature (Forbes, 1987; Preuss & Bolin, 1988; Prentice, 1994; Hawes & Martin, 2001).

The cellular level (III) is divided into three components, the cell mass, extra-cellular fluid and extra-cellular solids. Extra-cellular fluid contains ≈ 94% H_2O by volume and the extra-cellular solids represent ≈ 65% of the dry bone matrix in the reference man (Behnke, 1942). Although the volume of extra-cellular fluid can be measured by isotope-dilution techniques, there are no techniques available to measure both whole body cell mass or extra-cellular solids, suggesting why this level is the least researched level in the five level model (Wang *et al.,* 1991; Prentice, 1994; McArdle *et al*., 2006).

The tissue system level (IV) combines with the cellular level into groups depending upon the cellular makeup of the tissues, organs and systems. Tissues comprise ≈ 75% of total body mass in the reference man and when combined with the viscera and blood they constitute ≈ 85% of total body mass (Behnke, 1942; Wang *et al.,* 1991). Most of the information regarding body fatness that exists at this level has come from cadaver and biopsy analysis (Clarys *et al.,* 1987; Martin *et al.,* 1990; Cattrysee *et al.,* 2002). More recently, computed tomography (CT) has been shown to be able to accurately and reliably estimate areas and volumes of subcutaneous, visceral and total body adiposity in adults

(Kvist *et al.,* 1983; Tokunaga *et al.,* 1983; Seidell *et al.,* 1990). Magnetic resonance imaging (MRI) and ultrasound procedures have also been shown to be non-invasive, harmless techniques that produce similar results to CT when assessing adipose tissue (Seidell *et al.,* 1990). These methods are very similar to those used to assess the molecular Level (II) with expertise and expense limiting access.

The whole body level (V) focuses on whole body levels of body composition assessment and deals with the relationship between the body's overall size, shape, proportion, maturation and physical form with $\geq$ 10 suggested dimensions at this level (Ross *et al*., 1980). Its purpose according to Ross *et al*., (1980) is to help understand human movement in the context of growth, exercise, performance and nutrition. These common anthropometric procedures are the most readily measured and include measures such as, stature; body mass; segment lengths; body breadths; body girths; body depths; circumferences; skinfold thicknesses; body surface area; body mass index (BMI); body volume and whole body density (Beunen & Borms, 1990). Measurements are typically easier to execute at this level, due to the availability, expense and setting and in many ways better suited to larger scale research studies (Wang *et al.,* 1999; Hawes & Martin, 2001).

The five level model provides the basic context for human body composition assessment and creates a framework for explaining the relationships between them (Shen *et al*., 2005). However, to date, studies of body composition are somewhat limited in scope, by focusing on only a few components at one or two levels and thereby failing to appreciate the connections between levels (Wang *et al.,* 1991). Unfortunately as there is not one practical direct method for quantifying total body fat (TBF) *in vivo*, it can be seen that these constraints have led to most of the indirect measurement techniques being validated against

direct methods at the tissue system and whole-body levels. There is a strong suggestion that knowledge and expertise of these levels allows promising developments for future research where the newer technologies such as DEXA, CT and MRI offer considerable potential (Shen *et al*., 2005; Stewart, 2006). These technologies will undoubtedly transform the understanding of optimum body compositions within sporting contexts (Olds, 2004; Stewart, 2006). Although, it has been suggested by Stewart (2006) that more sophisticated methods such as CT and MRI are likely to remain in the clinical domain due to their time consuming and excessive expense. Hence the need for simpler and more rapidly use methods of acceptable accuracy (Rolland, 2013).

2.3 Whole body density

Body fat is one of the main factors affecting body composition in humans, thus knowledge of its density is a critical piece of data when optimising performance potential (Norton & Olds, 2002; Demura *et al*., 2007). Whole body density is the proportion of body fat present in a human body, compared to its overall mass and volume. By definition, density is the mass of an object divided by its volume, where:

Whole body density = mass / volume

(Hawes, 1996)

With the relationship between density, mass and volume, whole body density can be determined by the application of Archimedes' principle of water displacement. Mass is determined by weighing the body in air and volume is determined by the amount of water displaced when the body is fully submerged (Hawes, 1996; Rolland, 2013). Archimedes' the Greek mathematician, discovered that the volume of water displaced, is the difference

between the weight of the body in air and the weight of the body when immersed in water is buoyed up by a counterforce that equals the weight of the volume of water it displaces. This buoyant force helps to support an immersed subject against the downward pull of gravity and is equivalent to the mass of water it displaces (Norton & Olds, 2002). At this point, several adjustments to the volume are required to estimate of whole body density. Firstly the measurement of gas volumes which remain in the body after maximal expiration as these gases may increase buoyancy and have been considered the largest potential source of error in the measurement of whole body density. These gases consist of residual volume (RV) within the lungs and volume of gas in the gastrointestinal tract (GIV) (see section 2.5.1 and 2.5.2) (Fields *et al*., 2002; Pesola *et al*., 2004; Demura *et al*., 2007). Secondly, adjustment for the density of water at different temperatures with barometric pressure (BTPS) is required. Errors inherent in the interpretation of whole body density can also be caused by variation in the water by as much as 2.7% (Siri, 1961). However, Jüurimäe *et al.,* (1992) found that water temperature would have little effect on measurement errors. After determination of body volume, the following relationship is used to determine whole body density:

$$\text{Whole body density } (D_b)\ (\text{g ml}^{-1}) = M_a/(((M_a - M_W)/D_W) - (RV + GIV))$$

(Norton & Olds, 2002)

Where: M_a = mass in air (kg); M_w = mass in water (kg) (M_w), D_w = density of water ($g.ml^{-1}$), RV = residual lung volume (l) and GIV = Gastrointestinal tract volume (l). Archimedes discovery allows researchers to apply the principle of water displacement and the relationship between density, mass and volume.

Since the 1940s, researchers made attempts to use body density as a means of predicting gross composition of humans. Behnke *et al.,* (1942) was the first to suggest that measuring whole body density could quantitatively assess human body composition by estimating body fatness. The research based on n = 99 healthy naval men aged between 20 – 40 yrs has been referred to as a benchmark, as it provided a simple yet practical method for the research population to measure fat mass and fat free mass in humans (Shen *et al*., 2005). This method was based on the assumptions that the proportions of fat mass and fat free mass can be calculated from the known densities of both components (Brožek & Keys, 1951; Brodie, 1988). Behnke *et al.,* (1942) quantified fat fee mass to have a density of 1.100 $g.ml^{-1}$, whereas the density of fat mass to be 0.900 $g.ml^{-1}$.

The density of the whole body will obviously be dependent upon the relative size of fat mass and fat free mass components (Eckel, 2003). Regrettably, none of these assumptions can be fully justified, as it is assumed that the density of fat remains constant. However, there is suggestions that there may be variations of fat density is relatively unstable in relation to age, sex and diseased populations (Heymsfield *et al*., 1990; Ellis, 2000; Eckel, 2003; Rolland, 2013). Although some fat free density variations are recognised when compared to those of race differences and athletic populations (Visser *et al*., 1997; Clasey *et al*., 1999; Heyward & Wagner, 2004).

Dissections from 25 cadavers conducted by Clarys *et al*., (1984) reported the variation among the population with respect to the proportions of bone, muscle and the residual components that comprise of the fat free mass. Proportions of fat free mass composed of muscle were between 41.9 and 59.4% whilst that for bone was between 16.3 and 25.7%. The coefficient of variation of the muscle density was about 1%, but the density of the

bone varied considerably among cadavers (Clarys *et al*., 1984; Ross *et al*., 1984; Norton & Olds, 2002). This led to the conclusion that the density of the fat free mass probably varies with a standard deviation of 0.02 $g.ml^{-1}$ (Martin *et al*., 1986). In other words, fat mass has a lower density than fat free mass, therefore, an estimate of proportion of fat mass to fat free mass can be established (Katch *et al.*, 1967; Wilmore, 1969; Sinning, 1974; Brodie, 1988).

With these assumptions in mind, these findings may make generalisations to younger healthier populations inappropriate. Unfortunately the densities determined from such cadaver studies were applied uniformly to the entire population, without regards to the densities with age (Martin *et al*., 1986; Brodie & Eston, 1992; Norton & Olds, 2002; Eckel, 2003). In light of evidence provided by these cadaver investigations, and in particular the Brussels Cadaver Study, stringent requirements of the fat free density requires constituent tissues of the fat free mass to be (i) of constant density (1.100 $g.ml^{-1}$) and (ii) present in fixed proportions in all participants at all times (Clarys *et al*., 1984; Martin *et al*., 1986; Lohman, 1989). Literature has reported negative body density estimations that could arise if violations exist of the previously mentioned two requirements (Behnke *et al.*, 1942; Ross *et al*., 1984; Martin *et al*., 1986).

Our quest for knowledge and understanding regarding body density and how it can affect performance potential has indeed intensified in recent years. This quest has been driven in large part by the desire to gain an advantage within the sports science arena. Yet for the non-expert, such as the football coach, understanding why body density measures are important and useful, can often be confusing. With the primary goal of assessing body density to determine the proportion of fat mass relative to fat free mass, understanding

these proportions can influence the whole body density in such a way that could impede the effectiveness of a prescribed training programme and/or athletic performance potential. In general, the assumed density of fat fee mass and fat mass is 1.100 $g.ml^{-1}$ and 0.900 $g.ml^{-1}$ respectively, although research has continuously proven that athletes have higher body density levels than the general population, raising questions over its validity. Regardless of the method of body composition assessment used, regular assessment is essential to ensure that a player firstly maintains overall health and secondly reaches optimal physical requirements needed for football and their playing position.

2.4 Indirect measurement tools of human body composition

The concept involving the estimation of body density from body composition measures is relatively straight forward, although the actual measuring of body density can be extremely difficult due to the body's irregular shape (Ellis, 2000). Despite major recent technological advancements and understanding of the complexities of the human body, the only way to directly measure the human body is via cadaver dissection analysis. Clearly sports scientists are, for obvious legal and ethical reasons inadequately qualified to anatomically dissect. It must also be recognised that successful prediction of optimum performance potential will never be fully realised until such time that sport scientists are able to identify an individual's genetic limits of sport performance. Until such time, the method of estimating body density or measuring body fat may be estimated from methods such as dual energy x-ray absorptiometry (DEXA), air displacement plethysmography (BodPod), hydrostatic weighing and anthropometry (Ellis, 2000; Wallace *et al*., 2008). All practical techniques for measuring body composition in live participants are indirect and each with their own advantages and limitations (Jüurimäe *et al*., 1992; Hawes & Martin, 2001).

2.4.1 Dual energy x-ray absorptiometry (DEXA)

Dual energy x-ray absorptiometry (DEXA) has been utilised for the past three decades in a variety of clinical and research applications such as weight-loss clinics, eating disorder clinics, bariatric surgery clinics and elderly related health clinics and to assess the effect of diet, exercise and chronic disease (Hawes & Martin, 2001; Wallace *et al*., 2008). Due to its unique ability to subdivide the body into segments of bone, mineral mass and fat tissue mass, the development of such as body composition tool has promoted a renewed interest in the field of anthropometry (Hawes & Martin, 2001; Wallace *et al*., 2008).

The precision of DEXA in measuring body composition variables has been considered to be in good agreement with hydrostatic weighing (van der Ploeg *et al*., 2003; Shypailo *et al*., 2008; LaForgia *et al*., 2009). In addition it overcomes the population-specific nature of calibration models for predicting body density from anthropometric measures, and the assumptions of constant fat-free tissue density associated with hydrostatic weighing. As such, DEXA is increasingly gaining recognition as a criterion method for body composition research (van der Ploeg *et al*., 2003; Shypailo *et al*., 2008; Wallace *et al*., 2008).

DEXA is an attractive alternative to hydrostatic weighing due to its rapid, safe, minimal participant cooperation (Pateyjohns *et al*., 2006; Shypailo *et al*., 2008). Furthermore, DEXA estimates of body composition appear to be less affected by fluctuations in total body water compared to hydrostatic weighing. In addition it overcomes the assumptions of constant fat-free tissue density associated with hydrostatic weighing (LaForgia *et al*., 2009). In the future, it is likely that additional body composition methods and calibration models will be developed and validated using DEXA as a reference method, especially for

population subgroups for whom hydrostatic weighing is not feasible (e.g., spinal cord injured and elderly) (Ball *et al*., 2004; Pateyjohns e*t al*., 2006; LaForgia *et al*., 2009). Although DEXA is fast, easy and accurate, it does have a range of limitations. For instance, DEXA does not replace hydrostatic weighing as it does not estimate whole body density. Thus it is somewhat difficult to establish the validity of DEXA in comparison to hydrostatic weighing.

Still, researchers are beginning to use DEXA to develop and cross-validate body composition field methods and calibration models, with promising research by Shypailo *et al*., (2008). Yet DEXA has not been verified by human cadaver analyses, therefore more work is needed in this area to establish its validity (Ellis, 2000; Santos *et al*., 2010). It is also important to add that DEXA is not a suitable measurement for field testing as previously mentioned and is still not a popular tool amongst sport science support staff (Eston *et al*., 2004; Santos *et al*., 2010). Therefore in view of these signficant limitations the application of DEXA as a measurement tool was not pragmatic in respect of the present study.

2.4.2 Air displacement plethysmography (BodPod)

There is only one commercial system available for air displacement plethysmograph, which is known by the trade name BodPod® (BodPod model 2000A, Life Measurement Instruments, Concord, CA, USA) (Dempster & Aitkens, 1995; Miyatake *et al.*, 1999; McArdle *et al*., 2006). The BodPod system uses the inverse relationship between pressure (P) and volume (V) to derive body volume of a participant from a 750 L fibreglass shell that comprises of two chambers (Plate 5) (Dempster & Aitkens, 1995).

The volume of a participant is measured indirectly through the application of relevant physical laws (Boyle's Law) by subtracting the volume of air it displaces inside an enclosed chamber when the participant is inside, from the volume of air in the chamber when it is empty (Fields *et al.,* 2004; Vescovi *et al*., 2002; Heymsfield, 2005; Hull & Fields, 2005). With the procedural difficulties associated with under weighing the introduction of air displacement plethysmography in 1995 gained popularity among body composition researchers (Maddalozzo *et al.,* 2002; Buchholz *et al.,* 2004; Hull & Fields, 2005). This is mainly attributable to air displacement plethysmograph offering several viable operating alternatives to hydrostatic weighing (Millard-Stafford *et al*., 2000; Fields *et al.,* 2002). For instance, by replacing the intimidating inconvenience of water immersion (≈ 30 minutes) with the comfort of air (≈ 5 minutes), can place fewer demands on the participant (Fields & Goran, 2000; Yee *et al.,* 2001; Maddalozzo *et al.*, 2002). As a result, there is potentially a wider clinical application (i.e. athletes, children, obese, older adults and people with disabilities) (Hoffman *et al.*, 2001; Wells & Fuller, 2001; Hull & Fields, 2005).

Since its development, current literature has indicated varying degrees of reliability and validity issues (Wagner *et al*., 2004). Several researchers have reported significant differences in whole body density by the BodPod and hydrostatic weighing (Collins *et al*., 1999; Lockner *et al*., 2001; Millard-Stafford *et al*., 2001). Collins *et al*., (1999) reported reliability values of 0.994 and a technical error of measurement of 0.448 % and discovered that BodPod whole body density measurements (1.064 ± 0.002 g.ml^{-1}) were significantly greater ($P < 0.05$) than hydrostatic weighing whole body density (1.060 ± 0.002 g.ml^{-1}), concluding that that the BodPod was over predicting body density (Collins *et al*., 1999). Interestingly, Lockner *et al.,* (2001) found there was a significant difference between

average BodPod whole body density (1.0466 ± 0.0187 $g.ml^{-1}$) and average hydrostatic weighing whole body density (1.0403 ± 0.0187 $g.ml^{-1}$) ($P < 0.0005$). From a measurement point of view, there have been reports that obese participants and large athletes on occasion may struggle to sit inside and close the BodPod. With respect of these findings and as the present author had access to BodPod, it was considered advantageous to use the BodPod as one of several measurement tools in the present study.

2.4.3 Hydrostatic weighing

Historically, researchers sought a means of establishing the oil content of fish. A two compartment model was established that identified oil with a low specific gravity and a second component consisting of the remaining tissue which had higher specific gravity (Eckel, 2003). By 1942, Behnke *et al*., had refined this technique and devised an underwater weighing system to estimate whole body density of humans with a method called densitometry or hydrostatic weighing with simultaneous measurement of underwater weight (Siri, 1956; Gnaedinger *et al.*, 1963). Fundamentally, the nature of the measurement procedure involved a participant being weighed by means of a suspended autopsy scale, whilst fully submerged and at maximal expiration in a densitometer or hydrostatic weighing tank. This method was able to quantify both fat mass and fat free masses (see section 2.2.1) and with the assumption that these two known and constant densities have served as the reference technique which other methods are compared (Siri, 1961; Eckel, 2003).

For the past seven decades hydrostatic weighing has been regarded as the criterion method for laboratory investigations, against which other methods should be validated. This regard is mainly attributable to its validity and reliability that have been based on

pioneering cadaver and body composition analysis research (Martin *et al*., 1986; Brodie & Eston, 1992; Demura *et al.,* 2002). Due to its traditional method, it has been suggested by some researchers such as Fields *et al.,* (2002), Gately *et al*., (2003) and Hull and Fields (2005) that many technological advances have resulted in the criterion method, possibly being replaced by dual-energy X-ray absorptiometry (DEXA), 4C analysis and Air Displacement Plethysmography.

Given the status of this criterion method to estimate body density, it is unfortunate that many limitations exist, although, many methodological protocols are currently in place in an attempt to minimise these issues. Firstly the issue of consecutive measures of underwater weighing that are needed to estimate body mass in water (Withers *et al.,* 1987; Brodie, 1988; Demura *et al.,* 2002; Slater *et al.,* 2006). This issue relates to the procedural difficulties of hydrostatic weighing, such as body position and breathing manoeuvres (see Chapter 3.8.2) (Demura *et al.,* 2002; Slater *et al.,* 2006). Furthermore the issue regarding the number of measurement attempts to perform when determining the average hydrostatic water value (see Chapter 3.8.3) (Demura *et al.,* 2002; Slater *et al.,* 2006).

Such limitations can be reduced by using the post-submersion technique which is associated with less apprehension, greater comfort and reduced water disturbance and using the fourth, fifth and sixth measurement attempts to determine a mean underwater weight value. Secondly, density corrections need to be made to account for the water temperature within the hydrostatic weighing tank. Siri (1961) estimated that 2.7% error was due to water variation, although Jüurimäe *et al.,* (1992) claimed that water temperature would have little effect on measurement errors. Such errors can be reduced by setting the temperature of the water that approximates the mean body temperature of the participant of between 35 – 36 ^{o}C and minimise further corrections (Brodie, 1988; Lohman, 1992).

Regardless of these limitations, hydrostatic weighing is considered and used as the criterion for the present study and used to estimate whole body density with the population sample**.**

2.4.4 Age related considerations of hydrostatic weighing

Due to the human growth and development process, body fat stores and body densities change throughout life which involves an increase in body size and compositional changes of tissues and organs and chemical maturation of tissues and organs (Zafon, 2007; Gomez-Cabello *et al*., 2012). From a population point of view, this is quite predictable with notable increases up until 8 years of age, during adulthood a peak is reached, then subsequently falls with age due to the decline in external fatness (Martin *et al*., (1985; Pierson *et al*., 1991; Norton & Olds, 2002). From this point, Pierson *et al*., (1991) compared density values from other body composition methods, such as body water, body potassium, dual-photon absorptiometry, bioimpedance analysis and total body electrical conductivity with participants ranging from young adults to the elderly in 389 healthy Caucasians. This paper failed to report changes in fat free mass with age across the inter-methods comparisons and yet they are highly dependent on age (Pierson *et al*., 1991; Lohman, 1992). In contrast Eston *et al*., (2009) found that unlike the prepubescent children, the changes in fat free mass in an elderly sample had very little effect on body density. Suggestions of a decrease in mineral content and an increase in protein content of fat free mass provided slightly lower overall body density values in the elderly. Hence the role of changes in body density with ageing is more dubious and fortunately, does not cause a problem with the present study population sample.

2.4.5 Sex related considerations of hydrostatic weighing

Body fat and body density differ between males and females with body density significantly higher in men than in women. This is mainly attributable because of higher bone density, greater muscularity and the women's tendency to have more subcutaneous body fat due to the sex specific reproductive requirements to carry a foetus to full term (Vogel & Friedl, 1992; Eston *et al*., 2009). Generally speaking, this population related issue does not factor within the present study as the entire sample are all men.

2.4.5 Ethnicity related considerations of hydrostatic weighing

Previous studies have reported that non-Caucasian populations have greater muscularity, body density and bone mineral compared with Caucasians (Schutte *et al*., 1984; Utter *et al*., 2003). Research by Schutte *et al*., (1984), Demura *et al*., (2001) and Collins *et al*., (2004) suggested that non Caucasian have 10-20% more bone mineral than Caucasians of the same stature. Theoretically this should indicate that the fat free mass of non-Caucasians is denser than that of Caucasians (Schutte *et al*., 1984; Demura *et al*., 2001; Collins *et al*., 2004). Indeed, body density values of non-Caucasians are assumed at 1.113 $g.ml^{-1}$ compared to 1.100 $g.ml^{-1}$ in Caucasians (Schutte *et al*., 1984; Collins *et al*., 2004). Fields *et al*., (2000) reviewed twelve published studies and concluded the need for more research to estimate body density among ethnic populations, as current calibration models are significantly underestimating in non-Caucasian populations (Collins *et al*., 2004). Thus suggesting separate calibration models should be used for estimating body density (Donnelly *et al*., 1991; (Fields *et al*., 2000; Demura *et al*., 2001; Utter *et al*., 2003; Collins *et al*., 2004). Ethnicity has been taken into consideration within study 3 and the development of new calibration models to estimate whole body density.

2.4.6 Measurement considerations of hydrostatic weighing

It is vital that the establishment of validity, reliability and application of body density estimation measurements is performed (Fields *et al.*, 2002). Recent research by Collins *et al.*, (2004), Fields *et al.*, (2005), Hull and Fields, (2005) have found significant results that influence the validity and application of some measurements and warranted measurement considerations when dealing with influences such as measurement sequence considerations. To avoid erroneous data Levenhagen *et al.*, (1999), Lockner *et al*., (2000) and Fields *et al*., (2004) recommend that anthropometric measurements be conducted prior to hydrostatic weighing or exercise and that the participant be dry and lotion free (Fields *et al.*, 2004). This is due to elevated body temperature and body moisture resulting from hydrostatic weighing or exercise, on other measurements (Fields *et al.*, 2000; Fields *et al.*, 2004). Collins *et al.*, (1999) and Lockner *et al*., (2000) reported significant differences when the BodPod preceded hydrostatic weighing. Findings suggested that participants recovering from elevated metabolism from either exercise or presence in a tank of warm water for ≈ 15 mins as part of the hydrostatic weighing procedure, their breathing patterns were likely to change over time (Fields *et al*., 2002). More importantly, the key assumption is that the exact lung volume value is not a concern, but the breathing patterns and subsequent lung volume procedure should be an analogous measurement process (Fields *et al*., 2002). Conversely, studies including Levenhagen *et al.*, (1999), Lockner *et al*., (2000) and Fields *et al.*, (2004) investigated the effects of BodPod and hydrostatic weighing testing under non-dry and non-resting conditions.

These methods were randomised, with some BodPod measurements made first and in other cases hydrostatic weighing were first. Participants that were recovering from elevated metabolism as a result of the hydrostatic weighing procedure caused their breathing pattern

to change, which resulted in a regression that significantly deviated from the line of identity (Fields *et al*., 2002). A similar type of research by Collins *et al*., (2004) reported the mean of body density from the BodPod was significantly greater than body density from hydrostatic weighing ($P < 0.05$). Therefore within the context of the present study, all measures should precede hydrostatic weighing when the participants are completely dry and in a rested state (Lockner *et al*., 2000; Fields *et al*., 2004).

2.5 Gas volumes

According to Fields *et al*., (2002), Pesola *et al*., (2004) and Demura *et al*., (2007) accurate estimation of body density is only possible with measurements of gas volumes which remain in the body after maximal expiration. The emphasis should be that any gas remaining in the body after maximal expiration may increase buoyancy and might cause inaccuracies with the estimation of whole body density (McCrory *et al*., 1998; Demura *et al*., 2006). It is generally considered that such inaccuracies associated with the determination of these gas volumes are the largest potential sources of error in the measurement of body density (Mathur *et al.*, 1990; Donnelly *et al.*, 1991; Van Der Ploeg, 2000). These gas volumes consist of the volume of gas in the gastrointestinal tract (GIV) and residual volume (RV) within the lungs (McCrory *et al*., 1998; Pesola *et al*., 2004).

2.5.1 Gastrointestinal tract volume

Many researchers have made an assumption to the volume of gastrointestinal tract to be approximately 0.1 – 0.15 l (Figure 2.2) (Buskirk, 1963; Fields *et al*., 2002; Demura *et al*., 2006). Since this volume is a relatively small, Keys and Brožek (1953), Going (1996) and Demura *et al.*, (2006) claim that it has little influence on the determination of body density due to its volume size. Furthermore, it is not possible to directly or indirectly measure in a

standard manner (Durnin & Satwanti, 1982; Brodie, 1988; Fields *et al*., 2002). This could perhaps explain the reason why the gastrointestinal tract volume has been largely ignored in a majority of studies (Crapo *et al.*, 1982; Mathur *et al.*, 1990; Withers *et al*., 1991; Going, 1996; Fields *et al*., 2002; Demura *et al*., 2006).

2.5.2 Residual lung volume

Residual lung volume is defined as the volume of gas in the lungs after maximum voluntary expiration and is important due to several factors (Dewitt *et al*., 2000; Fields *et al*., 2002; Clausen & Wagner, 2003). Firstly, it prevents the inside surfaces of the lungs touching and sticking together, thus reducing friction and secondly, it prevents the lungs from collapsing, as the gaseous exchange is continuously occurring (Fields *et al*., 2002; Clausen & Wagner, 2003). In most healthy young adults residual lung volume is set by a static balance between the compressive forces from expiratory muscles and the force from the elastic recoil of the chest wall (Clausen & Wagner, 2003). When considering air in the lungs, residual lung volume forms part of four subdivisions of volumes and four capacities, as illustrated in Figure 2.2.

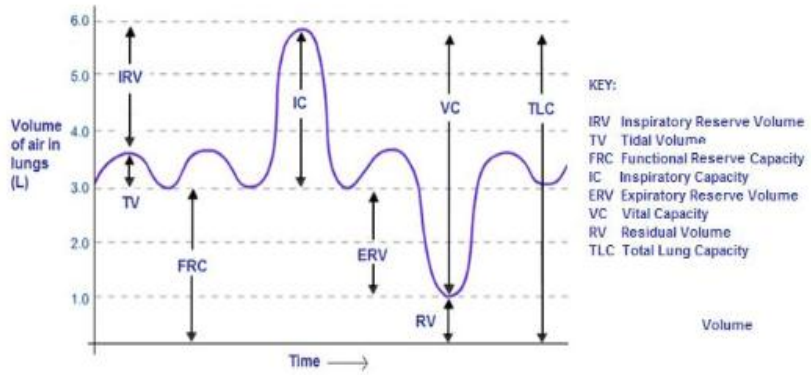

Figure 2.2 Respiratory volumes for a typical adult male as displayed by a Spirogram (Adapted from McArdle *et al*., 1991)

Where, lung volumes consist of tidal volume (TV), inspiratory reserve volume (IRV), expiratory reserve volume (ERV) and finally residual volume (RV). Lung capacities consist of inspiratory capacity (TV + IRV), functional reserve capacity (ERV + RV), vital capacity (TV + IRV + ERV) and total lung capacity (RV + VC). The spirometer trace in Figure 2.2 identifies the external and internal respiration where inhalation and exhalation causes the scan to move in an upward and downward deflection from a horizontal baseline (Dewitt *et al*., 2000; Fields *et al*., 2002; Wanger *et al*., 2005). Ever since Hutchinson (1846, cited Hepper *et al*., 1960) reported their study of the capacity of the lungs and respiratory functions in men, many attempts have been made to define the correlations between lung volumes and various physical measurements in the hope that it would be possible to estimate lung volumes (Mathur *et al.,* 1990; Nunez *et al*, 1999; Dewitt *et al*., 2000). There are several potential influences that determine the size and function of the normal lung (Quanjer *et al*., 1993). These influences could include environmental issues such as physical activity, socio-economic status, altitude and smoking history and more controversial issues such as physical characteristics including stature, age and ethnic group (Hepper *et al*., 1960; Quanjer *et al*., 1993).

2.5.3 Stature influencing residual lung volume

Hutchinson (1846, cited Hepper *et al*., 1960) investigated the influence of stature with lung volumes, along with other variables and combinations such as, body mass, surface area, circumference and volume of the thorax. Hepper *et al*., (1960) extended Hutchinson's (1846) research on n = 39 healthy men, with a mean age of 31.0 y (21.0 – 44.0 y) and mean stature of 180.4 cm (164.0 – 198.0 cm). Results concurred with Hutchinson (1846) findings where lung volumes were closely related to stature but correlations were not satisfactory when stature is extended beyond 183 cm (Hepper *et al*., 1960). Quanjer *et al*.,

(1993) found that stature contributed to 20% of the influences in the size and function of the normal lung. Therefore, it seems improbable given the nature of the current population, and the literature informing the present study, that residual volume estimated from stature provides no real concern (Quanjer *et al*., 1993; Stocks & Quanjer, 1995; Pesola *et al*., 2004; Wanger *et al*., 2005).

2.5.4 Age influencing residual lung volume

The size of the lungs is relative to body size which varies with age, particularly in young men during the latter part of adolescence (Brožek, 1960; Roberts *et al*., 1991; Quanjer *et al*., 1993). As the aging process is associated with degenerative changes, a decline in the elasticity of lung tissue components produces a decrease in breathing reserve and an associated increase in residual lung volume (Crapo *et al*., 1982; Clausen & Wagner, 2003). Conversely, changes in lung function may not entirely be associated with age, as regular aerobic training can influence the age related decline in static and dynamic lung functions (Brožek, 1960; Crapo *et al*., 1982; Roberts *et al*., 1991; Quanjer *et al*., 1993; Roca *et al*., 1998). However, research by Crapo *et al*., (1982), Roberts *et al*., (1991) and Roca *et al*., (1998) have generally suggested that spirometric lung functions do not begin to decline until the age of 25 y. Generally speaking, residual lung volume can vary throughout the adult age span, and could lower the body density of older participants (Brožek, 1960; Crapo *et al*., 1982; Quanjer *et al*., 1993; Roca *et al*., 1998). There is an assumption that change of lung volume changes with age, but based on these factors presented and given the participants for this study, this should not be considered as problematic.

2.5.5 Ethnic group influencing residual lung volume

There is a considerable amount of research concerning the effects of race and ethnicity, but little is known about the precise underlying physiological mechanisms that may determine the differences in lung volumes (Oschenitz *et al*., 1972; Mathur *et al*., 1990; Donnelly *et al*., 1991; Quanjer, 1993; Stocks & Quanjer, 1995; Pesola *et al*., 2004; Demura *et al.*, 2006). Evidence indicates that the shape of the chest appears to be the most important determining factor (Stocks & Quanjer, 1995; Pesola *et al*., 2004). Anthropometric research by Stocks and Quanjer (1995) and Pesola *et al*., (2004) has suggested that individuals of European descent have approximately 10 – 22% larger chest volume at full inspiration than of black African descent. Perhaps suggesting the differences in chest length was relative to differences in chest dimensions and the power of respiratory muscles (Quanjer, 1993; Stocks & Quanjer, 1995). It therefore seems likely that the differences in total lung capacity and forced vital capacity are probably due to the differences in chest lengths (Donnelly *et al*., 1991; Stocks & Quanjer, 1995; Pesola *et al*., 2004).

As the racial differences in lung volumes are of such a magnitude that a possible approach to overcome this problem could be to correct the assessment of lung volumes based on race specific norms (Pesola *et al*., 2004; Demura *et al.*, 2006). Pesola *et al*., (2004) has recommended this correction to be approximately 12%, thus reducing predicted lung volume error to less than 5% for this population. Indeed, there are varying equations that could be used to predict lung volume to correct for this type of error and they are widely used and seem useful in practice, however, the procedure is far from ideal (Roberts *et al*., 1991; Roca *et al*., 1998; Fields *et al*., 2002). Given that the current population consisted of a number of Non-Caucasians, these factors were taken into account and corrected for by inputting the appropriate formulae for ethnicity into the spirometer before measurement.

2.6 Estimation of residual lung volume

The determination of residual lung volume is technically challenging and involves rather elaborate techniques that vary from: (i) helium dilution, where a closed-circuit spirometer apparatus is filled with a mixture of gas in the lung with a known volume of gas containing helium and oxygen; (ii) nitrogen (N_2) washout, where the technique is based on the participant inhales 100% O_2 and exhales through a one-way value measuring N_2 content and volume; (iii) body plethysmography, where changes in lung volumes that accompany compression or decompression of the gas in the lungs during respiratory manoeuvres, and (iv) using imaging techniques such as conventional radiographs, computerised tomography, magnetic resonance imaging, where images at the time of lung inflation can provide estimates of lung volumes (Pesola *et al*., 2004; Wanger *et al*., 2005; Demura *et al.*, 2006).

In healthy male adults, absolute lung volumes generally do not differ significantly when measured by different techniques even though results represent fundamentally different volumes (Clausen & Wagner, 2003; Wanger *et al*., 2005; Demura *et al.,* 2006). Due to the complex nature of measurement protocols, a number of studies have attempted to estimate body density without measuring residual volume directly (Brožek & Keys, 1953; Buskirk, 1961; Gnaedinger *et al.,* 1968). Practically, many studies have used alternative estimation techniques, including application of regression equations following spirometry measurement (spirometry method) and panting manoeuvres (panting method) and general predictive equations based on stature, age and ethnicity (prediction method) (Mathur *et al*., 1990; Quanjer *et al*., 1993; Pesola *et al*., 2004).

2.6.1 Spirometry method

Residual lung volume cannot be directly measured with spirometry, but there is an assumed value of 0.9 – 1.6 l in a normal healthy adult male (see Figure 2.1) (Lockner *et al*., 2000; Fields *et al*., 2002). Any assumptions in the determination of residual lung volume may lead to errors in body volume as large as ± 0.5 l for a given individual, thus leading to an underestimation of body density (Demura *et al*., 2007). Residual lung volume can however be estimated via spirometry, as it is considered the most common pulmonary function technique to measure lung function, specifically the volume and flow of air that can be inhaled and exhaled (Quanjer *et al*., 1993; Pesola *et al*., 2004). Typical measures with spirometry include: (i) vital capacity (VC) and its two subdivisions (a) slow vital capacity (SVC) which is the maximal amount of air exhaled steadily from full inspiration to maximal expiration and is not time dependent and (b) forced vital capacity, which involves the volume of lungs from full inspiration to forced maximal expiration. (ii) forced expiratory volume in one second (FEV^1) where the volume of air is expelled in the first second of a forced expiration (iii) forced expiratory ratio (FER %) is the percentage of FVC expelled in the first second of a forced expiration ((FEV^1/FVC) x100) (iv) forced expiratory flow between 25-75% (FEF 25-75%) (also known as the maximum mid-expiratory flow (MMEF)) this is the expiratory flow rate in the middle part of a forced expiration.

Lung volumes derived from conventional direct measures such as radiographs and computed tomography scans are usually based on the volumes within the outlines of the thoracic cage and the volume of tissues, as well as the lung gas volume (Dewitt *et al*., 2000; Wanger *et al*., 2005; Demura *et al.*, 2006). With such extensive measures, evidence suggests that it is difficult to reach a consensus where all lung volume measures are in

agreement (Van Der Ploeg, 2000; Pesola *et al*., 2004). For instance, a study by Wanger *et al*., (2005) compared various direct and indirect methods and results indicated that body plethysmography yielded higher results than helium dilution, nitrogen (N_2) washout and spirometry, thus reinforcing the previous point. However, few studies have compared spirometry based estimations with direct measurements. Those that have suggest similar findings, for instance, Glady *et al*., (2003) designed a spirometry-based algorithm to predict lung impairment in an attempt to reduce the number of patients undergoing unnecessary and costly direct lung volume testing. Results indicated that the application of the algorithm on n = 265 hospital patients would eliminate the need for direct lung volume testing by 49% and reduced costs by 33% (Glady *et al*., 2003). Similarly Ueda *et al*., (2005) enrolled n = 62 cancer patients who were scheduled to undergo major lung resection, with similar results for patients with spirometry and computerised tomography variables (Ueda *et al*., 2005). Future studies are mindful that measuring residual lung volume via spirometry provides a reliable alternative to direct methods, given the cost, equipment and expertise needed to execute direct measures (Wanger *et al*., 2005; Demura *et al.,* 2006).

One of the volumes of particular interest is forced vital capacity. Forced vital capacity denotes the volume of gas which is exhaled during a forced expiration starting from a position of full inspiration and ending at complete expiration (Quanjer *et al*., 1993; Miller *et al*., 2005). It is distinguished from the inspiratory reserve volume and expiratory reserve volume (see Figure 2.1). As the measurement is performed during forceful exhalation, the manoeuvre is highly dependent on participant cooperation and effort. Since results are dependent on these factors, forced vital capacity can be underestimated if not enough time is allowed for lung emptying, where the emptying rate is determined by airflow limitation

(Stocks & Quanjer, 1995; Demura *et al.*, 2006). Fortunately there are a plethora of regression equations available in the literature that uses forced vital capacity to estimate residual lung volume (Crapo *et al*., 1981; Knudson *et al*., 1983). Many require varying indices to complete the estimation, such as age, sex and ethnicity, but all have limitations. Given that these equations are used as estimation, selection of the most appropriate equation is important. Within the present study the equation developed by Sinning (1975) was considered the most appropriate for the professional football population sample, where:

$$RLV_{spir} = FEV\ (BTPS)\ (l) \times 0.24\ (males)$$

(Sinning, 1975)

Where: RLV = Residual lung volume; FEV = forced expired volume; BTPS = body temperature and pressure saturated (Sinning, 1975; Knudson *et al*., 1983). Pertinent authors such as Weltman and Katch, (1981), Viljanen *et al.,* (1982) and Roberts *et al.*, (1991) have recommended that to ensure reliability and reproducibility, to repeat the measure at least three times and report the largest value rather than the mean. This measurement protocol is vigorously utilised within sport sciences, the medical profession and assumed within the present study (Miller *et al*., 2005). Other reliability issues that could have an impact on forced vital capacity, include obstructive lung disease defects such as asthma, emphysema or may be as a consequence of airway closure resulting in gas trapping, rather than as a result of disease (Quanjer *et al*., 1993; Miller *et al*., 2005). Clearly something to consider when undertaking a study such as this, however, these obstructive lung disease defects did not factor with the population sample as they would have been eliminated through the health screening process.

2.6.2 Panting Method

Estimation of body density by the air displacement method also requires determination of the quantity of air in the lungs (known as thoracic gas volume). The residual lung volume can be estimated by the BodPod to account for isothermal conditions in the lungs via a procedure known as the panting method (Crapo *et al*., 1982; Fields *et al*., 2002; Heyward & Wagner, 2004). The panting manoeuvre requires participants to breathe through a disposable tube and filter that are connected to the reference chamber of the BodPod. Tidal breathing is detected by small pressure fluctuations in the airway during mid-exhalation (Wagner *et al*., 1999; Buchholz *et al*., 2004; Ishiguro *et al*., 2005). These fluctuations produce pressure transducers in the breathing circuit during airway occlusion.

The increase of compressibility exists as a consequence of isothermal behaviour which is referred to as the surface area artefact (SAA). Each participants surface area artefact is automatically computed and accounted for based on the Dubois (1916) formula (Life Measurement Inc., 2006). Tidal breathing is calculated on the basis of these changes in pressure in the lungs (Crapo *et al*., 1982; Fields *et al*., 2004; Life Measurement Inc., 2006). During tidal breathing, this state represents average thoracic gas volume, and is equal to functional residual capacity plus half of tidal volume (Life Measurement Inc., 2006). Research by McCrory *et al*., (1998) and Fields *et al*., (2002) suggested that the BodPod method for prediction of residual lung volume may not be valid for athletic populations. These findings are also in agreement with Collins *et al*., (1999), where results found that predicted residual lung volume were significantly higher than measured residual lung volumes in collegiate football players. There have been numerous reports that participants could not adequately perform the panting manoeuvre to obtain measured thoracic gas volume (Nunez *et al*, 1999; Dewitt *et al*., 2000; Lockner *et al*., 2000). Indeed these

findings were comparable with the present study findings when determining various methodological protocols (section 3.8.5) consequently the panting method was eliminated as a method of choice.

2.6.3 Prediction Method

Given the practicability of obtaining lung volume measurements, prediction methods derived from healthy participants, allow assumptions regarding whether their measured volumes fall within a range expected for a healthy person (Grimby & Sölderholm, 1963; Roberts *et al*., 1991; Crapo *et al*., 1992). As previously mentioned, stature, and age have been proposed to determine residual lung volumes, and have been shown to be the best factor for narrowing the range of predicted values for individual participants (Viljanen *et al*., 1982; Donnelly *et al*., 1991; Roberts *et al*., 1991; Demura *et al*., 2007). Further research has involved using other variables such as fat free mass, thoracic diameter, trunk length and body surface area to predict residual lung volume in the assumption that both anatomical and mechanical factors may account for differences (Donnelly *et al*., 1991; Crapo *et al*., 1992; McCrory *et al*., 1998; Roca *et al*., 1998). However, the use of predicted residual lung volumes compared to direct residual lung volumes measures has been reported to cause significant differences of ± 1.8 3.4 l against helium dilution methods from Cliff *et al*., (1999) and 0.56 $P < 0.001$ against plethysmography from Blaney (2008).

Prediction equations were derived over a period of thirty years that may not necessarily reflect the current population characteristics (Roberts *et al*., 1991; Roca *et al*., 1998; Levenhagen *et al*., 1999; Pesola *et al*., 2004; Demura *et al*., 2007). Furthermore, using participants that were smokers and non-smokers is likely to produce a lower mean value than that obtained from non-smokers alone (Roca *et al*., 1998; Fields *et al*., 2002; Pesola *et*

al., 2004). Although these errors generally have only small effect on body density, the interpretation of results should be made with reservation (Roberts *et al*., 1991). The prediction method was therefore not used within the present study.

2.7 Anthropometry

In most circumstances, DEXA, BodPod and hydrostatic weighing are the preferred method for estimating body composition, but they are impractical for professional football players. Although more lucrative clubs, such as Manchester United and Tottenham Hotspur have purchased their own BodPod (Cranleigh, 2012) these methods are not suitable for mass measurements or for field testing because of the laboratory-based nature, the expense of the equipment needed, the expertise involved and the time it takes to make each assessment (Lohman, 1992). Moreover, some football clubs gain access to body composition equipment and expertise through Universities laboratories. In reality though, whilst these laboratory techniques are a football clubs solution for determining body composition, it is far more practical, simpler, and less expensive to use anthropometry (Reilly, 1996; Pyke, 2000; Hencken & White, 2006; Wallace *et al*., 2008). Additionally, using a set of skinfold calipers or measuring tape requires far less time which is advantageous when regularly monitoring a player, team and/or squads progress throughout the playing season.

2.7.1 Anthropometric skinfold thickness

Since the early 1900s there is significant empirical logic in the notion that the greatest depot of subcutaneous body, quantified by skinfold thicknesses, provides an accurate and direct estimate of total body fat and they have significant face validity (Wang *et al*., 2000; Norton, 2002; Bellisari & Roche, 2005; Stewart, 2006). A vast number of studies have

reported that skinfolds provide us with an indication of the level of subcutaneous fat located around the body and its accessibility at each site (Clarys *et al*., 1987; Norton *et al*., 2000; Heyward & Wagner, 2004; Stewart, 2006). Although it was Clarys *et al*., (1987) and Wang *et al.,* (2000), that were able to approximately quantify that 40 – 60% of total body fat is located in the subcutaneous region of the body. The accessibility of the subcutaneous fat has been reported to vary from individual to individual, as well as from site to site, dependent upon age, sex, genetics, level of physical activity and measurement technique employed (Hawes, 1996; Stewart 2006). With this accessibility in mind, anthropometric skinfold measures can provide a relatively accurate and direct measure of the amount of subcutaneous fat and therefore is an invaluable tool when tracking changes in fat stores (Hawes & Martin, 2001; Norton, 2002). Although, it is worth noting that since major health risks, such as cardiovascular disease, diabetes and obesity are known to be associated with these body fat depots, the challenge has been to quantify total body fat using simple, time and cost effective methods (Nordhamn *et al*., 2000; Norton & Olds, 2002; Mueller & Malina, 2005).

2.7.2 Harpenden skinfold caliper

The harpenden skinfold caliper was an adaptation of a device used in industry for measuring the thickness of pieces of wood, metal and leather with the design enabling two springs to apply an opening and closing force to the caliper jaws, just enough to counteract the increase in tension in the springs (Clarys *et al*., 1987, Gore *et al*., 2000). Each jaw has a surface area of 90 mm^2 which is generally considered large enough to place a fold of subcutaneous fat, although in case of the obese population, calipers cannot open wide enough (Tanner & Whitehouse, 1955; Olds, 2004).

Early research conducted in 1955 by Tanner and Whitehouse claimed that the use of skinfold calipers was the best method to measure subcutaneous adipose tissue mainly due to its simplicity and that they can give readings to the nearest 0.1 mm (Norton *et al*., 2000; Wang *et al.*, 2000). A study conducted by Schmidt and Carter (1990) found a mean of 8.25 $g.mm^{-2}$ for ten new Harpenden skinfold calipers and that the jaw pressure was no greater than 8.67 $g.mm^{-2}$, suggesting that even new calipers should be calibrated (Carlyon *et al*., 1996). However, Gore *et al*., (2000) explored Carlyon *et al*., (1996) claim and found that 500,000 cycles of opening and closing new Harpenden springs (equivalent to 10 years heavy use) does not alter the spring coefficient. The second outcome was that a 5% change in jaw pressure would correspond to an approximate 5% change in skinfold thickness. Providing the calipers do not deteriorate in condition, they can achieve consistent jaw pressure. Consequently, a concerned rater may attempt to counteract this problem by firstly checking the jaw pressure of the recommended 10.0 $g.mm^{-2}$ is carried out regularly to maintain the quality and life span of the caliper and secondly to use a single pair of calipers throughout the research investigation (Carlyon *et al.,* 1996; Gore *et al.*, 2000). Both these factors were enforced within the present study. Fundamentally as the harpenden skinfold caliper has been an extensively used instrument in past research and regarded as the criterion instrument by International Society for the Advancement of Kinanthropometry (ISAK), the harpenden was the preferred caliper of choice within the present study (Carlyon *et al.*, 2004; Olds, 2004).

2.7.3 Skinfold compressibility and caliper reading time

According to Himes *et al*., (1979) and Martin *et al*., (1991) the variability in both the skin thickness and skinfold compressibility can affect the relationship between the caliper reading at a particular site on the body, and the actual thickness at that site. Even though

the skinfold caliper exerts an ideal pressure of 10 $g.mm^{-2}$, the pressure exerted by the jaw face either side of the fold can displace some extra cellular fluid and may force some adipose tissue globules to slide into areas of lesser pressure (see Figure 2.3) (Cameron, 1984; Bellisari & Roche, 2005). The sliding will be influenced by the skinfold caliper jaw springs. For instance, the jaws of the caliper are controlled by a spring therefore the reading can depend on the strength of that spring (Bellisari & Roche, 2005).

Figure 2.3 Schematic section of a skinfold thickness measurement site (Taken from Krider, 2006)

Cadaver studies by Becque *et al*., (1986), Martin *et al*., (1985, 1991) and Clarys *et al*., (1987) have shown significant differences in inter-participant and inter-site skinfold-compressibility. Investigations by Martin *et al*., (1991) involved the measurement of thirteen skinfold sites in six male and seven females unembalmed cadavers aged 55 to 94 yrs. All skin was removed and its thickness measured at the exact sites of skinfold measurement (Martin *et al*., (1991). Results indicated that mean skinfold-compressibility over all sites was 53.5% in men (Martin *et al*., (1991). Such marked variability in

skinfold-compressibility could be attributed to sex, age and site location (Martin *et al*., 1985, 1991). Clarys *et al*., (1987) research also investigated skinfold application in two separate cadaver dissection studies and indicated that skinfold compressibility is by no means constant. Findings revealed that depending upon anthropometric location males had thick skin, especially at the biceps, chest, supraspinale and abdominal sites (Clarys *et al*., 1987). Whereas, Himes *et al*., (1979) measured the compressibility of subcutaneous fat thickness on 65 white American youths and found that the medial calf was the least compressible among the seven sites used. Thus suggesting a range of compressions at different sites needs to be taken into account in order to minimise error.

One recommendation by Lohman *et al*., (1984), Becque *et al*., (1986) and MacDougall *et al*., (1991) is to minimise error due to the variation of skinfold-compressibility by considering the length of measurement reading time after the application of skinfold calipers. The change in the thickness of the skinfold from the application of the caliper until the end of the measurement period, can range between 0.3mm and 4.5mm (Becque *et al*., 1986). While not a dramatic absolute change *per se*, this can result in large differences when estimating total body fat (Becque *et al*., 1986). Therefore review of the literature, found many vague and contrasting recommendations. For instance, Krider (2006) suggested waiting until the caliper needle has stabilised and stopped moving, whilst Beta Technology (2005) albeit referring to the Lange skinfold caliper, stated that the reading should be taken immediately after the first rapid fall. The skinfold compression made by the caliper, independent of the measured thickness, becomes an important issue when reducing error in the estimation of the actual uncompressed skin plus fat thickness (Martin *et al*., 1991). To further confound the issue, what is clear is that there is no uniform procedure between releasing the caliper handle and reading the value. In most cases, no

exact details are reported in the literature (Rao *et al*., 1974; Krämer & Ulmer, 1981; Martin *et al*., 1991). Nevertheless, this unresolved concern of skinfold compressibility and reading time has been addressed notably by Krämer and Ulmer (1981). Results indicated that readings vary considerably and as the rater has no control of the movement of the needle and reading, this may have an influence on the value of the skinfold thickness (Krämer & Ulmer, 1981). Although analyses were not provided in their paper, evidence recommended two seconds after the full pressure of the calipers are applied (Krämer & Ulmer, 1981). This notion was also sanctioned by Jackson and Pollock (1985), MacDougall *et al*., (1991) and Ross and Marfell-Jones (1991), although Becque *et al*., (1986), Ross & Marfell-Jones (1983) and Lohman *et al*., (1988) recommend the measurement is made about four seconds after the pressure is released.

As there are limited studies on the application of skinfold calipers and skinfold compressibility, it therefore remains to be identified what the most appropriate measurement reading time is recommended. A solution for the present study was to follow ISAK recommendations with a measurement reading scale of two seconds after the application of the calipers, as they have considered this method to be twofold. Firstly, this time had a limited bearing on the discomfort of the participant and secondly was found to be the most reliable reported protocol available in relevant literature research (Jackson & Pollock, 1985; Ross & Marfell-Jones, 1991; ISAK, 2011).

2.7.4 Dehydration considerations

There is acknowledgment by researchers that dehydration is associated with changes in body temperature, blood flow and skin turgidity (Norton *et al*., 1998; Shen *et al*., 2005). Since subcutaneous fat contains varying amounts of water, it is possible that some of the

fluid that is lost due to sweating whilst exercising may have an impact on the tissue area (Lohman, 1986; Martin *et al*., 1985). The amount of fluid loss can be up to 3.0 $l.h^{-1}$ of water in an athlete (McArdle *et al*., 1986). Research by Katch *et al*., (1994) claimed that fluid losses equivalent to approximately 1% of body mass can cause significant increases in body temperature and redistribution of blood to the periphery. This redistribution causes the arterioles to dilate to increase blood flow and causes the skin to swell (Withers, 1983; Jackson & Pollock, 1985; Norton *et al*., 1998). The effects of dehydration may theoretically lead to an overestimation of subcutaneous skinfold thickness compared to that of a typical hydrated state (Norton *et al*., 1998).

It has been suggested by Consolazio *et al.,* (1963) that dehydration can cause the skinfold thickness to increase due to changes in skin turgidity or tenseness by up to 15%. These findings were in contrast to a study reported by Norton *et al.,* (1998) who investigated eight participants being involved in hyper-hydration and hypo-hydration states. Hyper-hydration involved the participants ingesting 25 ml.kg body $weight^{-1}$ during a 20 minute interval, whereas hypo-hydration involved participants to actively dehydrate by about 2-2.5% of their body mass in an environmental chamber at a temperature of 40-44 ^{o}C and between 75-85% humidity. Seven skinfolds were taken before and after the experiment with results indicating no significant changes in skinfold measures taken before and after moderate dehydration induced by heat and/or exercise ($P < 0.001$).

Research evidence is conflicting, but it is possible that differing hydration levels may alter skinfold thickness and could play a significant role in the day to day fluctuations (Utter *et al*., 2003; Heyward & Wagner, 2004). Furthermore, there are no specific guidelines on normal hydration status prior to engaging in any body composition assessments, but should

be an important area for consideration given the conflicting findings (Shen *et al*., 2005). What could be considered from a practical point of view is that the skinfold land-marking procedure and grasping of the skinfold can be more exact if the participants' skin is dry and not taken immediately after physical activity or showering (Utter *et al*., 2003; Heyward & Wagner, 2004). Consequently to reduce such issues, all participants in the present study followed and adhered to strict pre-testing procedures (see section 3.3) which included refraining from consuming food or fluid for at least four hours before measurement and from exercising for a twelve hour period before measurement.

2.7.5 Body fat distribution considerations in relation to skinfold thicknesses

There is evidence to suggest that body fat distribution is related to an individual's hormone levels and genetics (Lamb, 1984; Telford *et al.*, 1985; Norton & Olds, 2002). Inherited genetic factors greatly influence body fat distribution and certainly impact long-term programming of body size and shape (Telford *et al.*, 1985). For instance excess fat, centralised in the visceral area, has been shown to be associated with metabolic complications and an increase in the risk of cardiovascular disease and certain cancers that may complicate the relationship of optimal physical performance with health (Telford *et al.*, 1985; Norton & Olds, 2002). Evidence based on cadaver analyses research has indicated that males tend to have largest and thickest deposit of subcutaneous body fat centralised in the visceral area of the waist, but can have a tendency to change to some extent with increasing body fatness (Clarys *et al*., 1987; Martin *et al*., 1989). Yet the skinfold sites of the upper trunk seem to be employed more frequently than others within calibration models, with the triceps skinfold being one of the most popular (see Table 5.0) (Wang *et al.*, 2000; Ball *et al*., 2004). To date, ten different skinfold sites are frequently used within pre-published calibration models for adult males (see Figure 2.4 and Table 5.7)

(Wang *et al*., 2000; Heyward & Wagner, 2004). This compounds the issue and raises the question of which anthropometric skinfold sites to use to estimate total body fat (Eston & Reilly, 1996; Stewart, 2006). A combination of usually two or more skinfold sites are generally used in order to estimate total body fat (Bellisari & Roche, 2005; Ishiguro *et al*., 2005).

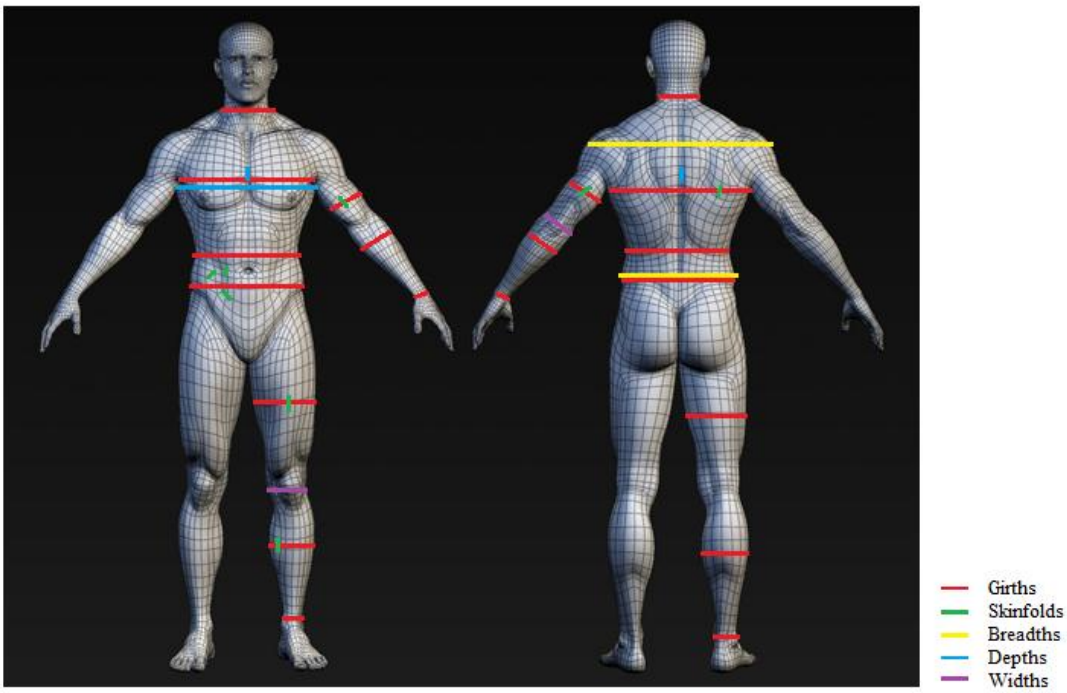

Figure 2.4 Schematic of anthropometric measurement locations (Image taken from Anon1, 2013)

There is additional evidence to support the premise that the summation of four or more skinfold measurements for the estimation of total body fat is more reliable (Bellisari & Roche, 2005; Ishiguro *et al*., 2005). These findings support the use of several sites such as biceps, triceps, subscapular and suprailiac to determine total body fat (Pollock & Jackson, 1984). Although Jackson *et al.*, (1980) found that the sum of seven skinfolds demonstrated a high correlation to the mean body density values in an athletic population. What is evident is that the literature is conflicting to the number of sites to use when estimating total body fatness. Research conducted by Seltzer and Mayer (1967) were the first to use

the triceps skinfold as the criterion for diagnosis of obesity, as they indicated that the triceps was representative of total body fatness. This finding was regardless of disproportionate distributions of adipose tissue in various parts of the body.

Sardinha *et al*., (1999) also reported the use of the triceps skinfold along with upper arm girth and body mass index (BMI) as a health-related definition of obesity in n = 330 children. Results indicated that triceps skinfold gave the best results for obesity screening in children aged 10 – 15 yrs (Sardinha *et al*., 1999). Furthermore, Pawson *et al*., (1991) examined triceps skinfold thickness with subscapular skinfold and body mass index, to establish the prevalence of overweight and obesity in US Hispanic populations (n = 7052 Mexican Americans, n = 1307 Cubans and n = 2690 Puerto Ricans). What challenges Seltzer and Mayer (1967) criterion for obesity is that other measures, such as upper body skinfolds, girths and BMI are being used (Pawson *et al*., 1991; Sardinha *et al*., 1999). In reference to other skinfold measures, research by Nordhamn *et al*., (2000) investigated anthropometric measurements in overweight and lean participants and found ICC values ranged from 0.84 to 0.93 and were lower for overweight than for lean participants for biceps, subscapular and abdominal skinfolds (P = 0.031, P < 0.001 and P = 0.048, respectively).

Generally speaking, it is evident from research that the triceps are the most commonly used skinfold due to its location, accessibility and reliability factor (Sardinha *et al*., 1999; Stewart, 2006). What is important is for athletes who are considered to have less total body fat and more muscle, their distribution of fat generally favours the limb sites, especially that of the thigh (Heyward & Wagner, 2004; Stewart, 2006). Literature suggests the importance of using a variation of upper, lower and trunk skinfold sites, provide an

excellent method for monitoring and measuring total subcutaneous fat levels (Lohman, 1981; Martin *et al*., 1985; Norton, 1996; Bellisari & Roche, 2005; Stewart, 2006). Therefore, when establishing which skinfold sites to use, researchers need to be mindful of these constraints when designing their own calibration models and furthermore to use a range of measures and of course appropriate statistical analyses that determine the most valid model to suit. Once again, these issues were considered when developing new calibration models for professional footballers in Chapter 6 (study 3).

2.7.6 Estimation of total body fat from anthropometric girths, depths and widths

Researchers such as Lohman (1981), Pollock and Jackson (1984), Clarys *et al*., (1987) and Mueller and Malina (1987) consider measurement of anthropometric skinfolds to be the most practical in the sport science field. Although, contrasting research has indicated that anthropometric measurements such as girths, breadths and widths can be used to estimate relative adiposity of athletes and adipose tissue distribution in a more reliable manner (Mueller & Malina, 1987; Nordhamn *et al*., 2000; Reilly & Williams, 2003). For instance, a study conducted by Mueller and Malina (1987) found the reliability of six anthropometric girths (0.96) were significantly higher ($P < 0.01$) than that of skinfold thicknesses at five sites (0.91), suggesting girths are more reliable.

Nordhamn *et al*., (2000) estimated the correlation of anthropometric girths in overweight and lean participants. They found the intra-class correlation coefficients (ICC) for waist girths were lower for overweight than for lean participants (0.85 vs. 0.95, $P < 0.01$). Although ICC avoids the issue of linear relationships, therefore, low ICC value implies that correlations can be underestimated in overweight groups. Investigations into past studies that have developed calibration models to estimate whole body density and have found that anthropometric girths, breadths and width measures are used within the

development of calibration models, but sparingly. For instance, evidence from Table 5.7 shows that ten studies used a wide range of girths, breadths and width measures, but only Forsyth and Sinning (1973b) included the biliocristal breadth and Wickkiser and Kelly (1975) included the waist girth within their calibration model(s). Thereby highlighting the point that these measures are used, but as one of many other variables within their calibration models.

Further scrutiny of studies indicates that anthropometric girths, breadths and width measures are omitted completely from their calibration model(s) development. Given that anthropometry can provide valuable data on adipose tissue distribution, this questions why there are relatively few within these generalised calibration models. Therefore more studies are needed that directly focus on girths, breadths and widths and as such girths, breadths and width measures will be considered within chapter 6 (study 3) of the present study (Norton *et al*., 2000; Reilly & Williams, 2003; Stewart, 2006).

2.8 Calibration models to estimate whole body density from anthropometry

Given the accessibility of subcutaneous fat around the body, may be a reason which has led to the proliferation of formulae and equations to estimate whole body density from various components of body composition (Clark *et al*., 1992; Provyn *et al*., 2012). The formulae are normally subdivided into regression equations generally developed on anthropometric based formulae that predicts the dependent variable (whole body density) from a series of independent variables such as body mass, stretched stature, skinfolds, girths, breadths, depths and widths (Atkinson & Nevill, 2001; Provyn *et al*., 2012). Within scientific literature these regression equations are correctly termed calibration models and the development of generalised calibration models provides a wealth of body composition

information relating to different ages, sex and ethnicity (Vincent, 1999; Atkinson & Nevill, 2001). A pertinent example of such a calibration model would be the early model proposed by Durnin and Womersley (1974). They used a sample of n = 481 participants over an age range of 16 – 72 years, demonstrating one of the largest anthropometric data sets of its time. They were also one of the first to consider not only different populations and ages, but to use a variety of body composition measurement combinations to estimate whole body density (Cooper, 1995).

Four years later, the work of Jackson and Pollock (1978) provided another large scale data set on a sample of n = 403 participants ranging in age from 18 – 61 years, which was used to develop a new model. As more and more calibration models were being developed, many questions were being raised about the 'generalised model' approach (Katch & Katch, 1980; Vincent, 1995). The model presented by Durnin and Womersley (1974) was derived from a large heterogeneous sample of males which might be deemed as problematic. For instance, a number of studies purport to have investigated the validity of previously published calibration models and found that validity is disappointing poor when applied to a specific population (Cooper, 1995; Vincent, 1995; Heyward, 2000). As such, further research led to the development of 'population-specific' models for varying populations, ages and levels of activity (Guo *et al*., 2000; Provyn *et al*., 2012). The important difference between population specific models and those of a more general nature is the extent to which they can be applied (Pollock & Jackson, 1984). Although it is questionable is whether a population specific model can be developed on sample as large as the ones reported by Durnin and Womersley (1974) and Jackson and Pollock (1978) (Kelley & Maxwell, 2003; Provyn *et al*., 2012).

2.8.1 Limitations of calibration models to estimate whole body density

Authors such as De Lorenzo *et al*., (2000), Demerath *et al*., (2002), Ball *et al*., (2004), Ishiguro *et al*., (2005) and Peeters *et al*., (2013) investigated how effective calibration models are in terms of accuracy and consistency of measurement values. When further scrutinising the methodological approaches to the design and development of some of the most popular calibration models, various limitations quickly become apparent. These limitations are no means exhaustive and could be replicated in other limitations, never-the-less they account for several areas of concern:

2.8.2 Limitation 1 - The number of anthropometric variables used as individual components within a calibration model

Questions have risen relating to the restrictive range of anthropometric measures used within a calibration model and in particular, the anthropometric site location (Heyward, 2000; Atkinson & Nevill, 2001). What is evident is that of the vast number of measures available, four skinfold sites of the biceps, triceps, suprailiac and subscapular are all or partly used within calibration models for young adult men. For instance, Durnin and Rahaman (1967) and Durnin and Womersley (1974) used all biceps, triceps, subscapular and suprailiac skinfolds, and Lohman (1981) and Thorland *et al*., (1984) used three skinfolds, demonstrating the commonly used approach for these skinfolds when developing calibration models. The reason why these specific measures were used in their models is likely to be because of their impact on the estimation of whole body density. Another possible reason could be the recommendations from previous research indicating that the site location provides an accessibility advantage, although this is unclear. Unfortunately many authors have self-perpetuated without any justification why or why not these variables are included within their model(s).

Evidence from other empirical studies and recommendations in the literature have shown that skinfolds from the lower limb account for a significantly greater proportion of variance in body fat (Clarys *et al*., 1987; Eston, 2003; Bellisari & Roche, 2005). Yet closer inspection of the components of numerous calibration models discovered that many failed to take into account any lower limb measures. Indeed, in recognition of the potential importance of skinfolds from the lower limb as a predictor of body composition, the steering group of the British Olympic Association (BOA) recommended that the anterior thigh skinfold should be summed together with the four skinfolds used in the Durnin and Womersley (1974) model to provide an index of whole body density (Reilly *et al*., 1996). There is little evidence however, that the sum of five skinfolds recommended by the BOA is, in fact, the optimal combination to assess whole body density in males. This may arguably predict different whole body densities on the same participant, and place significant challenges if the sport scientist is to obtain reliable and valid results from calibration models (Sheng, 1988; Pyke, 2000; Atkinson & Nevill, 2001).

On another note, when comparing studies that have developed calibration models, there are a wide ranging number of anthropometric variables gathered. For instance, Wilmore and Behnke (1969), gathered over 54 body composition variables around the body which was the largest compared to Sloan and Weir who gathered 2 variables. The average number of variables for the existing calibration studies was 15, indicating possible constraints such as time, resources and expertise. Furthermore, questioning whether indeed all these potential variables are even used in the development of the calibration model. There is no evidence to suggest that the greater number of variables that are gathered will result in a 'better' calibration model. What it does provide is an opportunity to use a number of different site locations around the body and variables such as skinfolds, circumferences, girths and body

mass. Although evidence from Katch & McArdle (1973) and Thorland *et al*., (1984) have demonstrated that variables typically consist of skinfolds and circumferences, which potentially offer a cheaper and quicker measurement process which could aid a sports scientist whom is working in the field. However this suggestion might cause a potential problem in that the sport scientist may not necessarily have the expertise or specialist equipment to carry out such measures, and/or the time to facilitate a large squad of players over a playing season.

2.8.3 Limitation 2 - The emphasis of how anthropometric variables are used interchangeably within a calibration model

In some instances, the manner in which the body composition variables are used interchangeably within the calibration model regression equation can provide an outcome with a different bias, which can result in significant errors in whole body density (g ml^{-1}) (Ball *et al*., 2004; Ishiguro *et al*., 2005; Peeters *et al*., 2013). Interrogation of various calibration models found that some variables were provided as stand-alone outcomes, some as a combination of summed variables, some squared or even logged. Research by Oppliger and Cassady (1994) and Rolland (2013) found that the use of both logarithmic and non-logarithmic transformations have been applied in order to formulate estimates and correlations of whole body density from skinfold measurements. For instance, Durnin and Womersley (1974), developed models from single skinfolds measurements and from the Σ of two or more skinfolds, and they also carried out logarithm of each skinfold thickness rather than use the actual measurement. The logarithmic transformation was desirable because Durnin and Womersley (1974) showed this with statistical analysis that the frequency distribution of the general population skinfold measurements is skewed. They illustrated this curvilinear relationship between anthropometric measures and whole body

density in a scatter plot. In order to straighten up the line of skinfold measurements and the relationship, they used the $\log_{10}$ Σ skinfolds (triceps + biceps + subscapular + iliac crest skinfolds). This comes about as a result of the large amount of body fat that is stored subcutaneously. Therefore, the subtraction of the skinfold thickness would provide a better correlation with whole body density (Durnin & Womersley (1974). It is evident that they attempted various methods to design their model, but given they had sample sizes as small as n = 24, once the division of the overall sample was split into sex and age groups (see Section 5.1) and with only nine potential variables to use, it is plausible that Durnin and Womersley (1974) were left with no option but to log transform, rather than use stand-alone outcomes.

In another pertinent example, Jackson and Pollock (1978) developed nine separate calibration models using the summation of skinfolds and log transformations. In their paper they commented that there were collinearity issues and as their aim was to provide a more stable estimate of subcutaneous fat. It would appear that Jackson and Pollock (1978) followed a trend similar to the research of Durnin and Womersley (1974), in the development of such calibration models. They too had wide ranging sample of male participants (n = 308 men) that was split into sex and age groups, with nine potential variables to use. Even though Jackson and Pollock (1978) used a variety of different approaches when developing their calibration models, their final outcome resulted in the summation of the three skinfolds (triceps, abdominal and subscapular). Results indicated that these independent variables provided them with a high correlation with whole body density and it was thought that this model would provide a more feasible field test (Jackson & Pollock, 1978).

What is often not discussed in calibration studies, is whether there has been any collinearity issues. Collinearity refers to two or more non-independent predictor variables that are highly correlated and is a common feature in regression analysis and can potentially be a problem because it can lead to the wrong identification of predictors in a calibration model (Mukherjee & Roche 1984). Different approaches to addressing collinearity problems have been developed ranging from deleting variables which may cause errors, collecting additional data and grouping of predictors (Kelley & Maxwell, 2003). As collinearity can potentially have an impact on the validity of the predictors in the models, what is concerning that given the wide range of anthropometric variables that are used within the development of these calibration models, this appears not be a concern or indeed addressed by the authors (Mukherjee & Roche 1984; Kelley & Maxwell, 2003).

It is evident from previous calibration studies that decisions regarding which anthropometric variables are used interchangeably within a calibration model are generally speaking, down to recommendations from previous research studies. What is a concern is using these recommendations are potentially problematic in its own right. As such it is still questionable to whether the majority of these calibration studies are robust when estimating whole body density in professional footballers. In reality there are no hard set rules on what variables to use and how they are used interchangeably, but should ideally be decided whether there (i) is a large enough sample size even after the division of sex and age groupings (ii) any collinearity issues and (iii) at least nine variables per participant (see Section 2.8.4).

2.8.4 Limitation 3 - The sample size employed when developing a calibration model

Too frequently the restrictive nature of the sample sizes raises concern over its practical use with a given population due to its predictive nature of the calibration model (Hawes, 1996; Atkinson, 2005). Research by Mayhew *et al*., (1981), Hawes (1996) and Atkinson (2005) considered the sample sizes that were employed in developing calibration models and suggested that if the sample is small, it is not an adequate basis to develop calibration models, a valid issue worth considering when designing calibration models.

Wilmore and Behnke (1969) for example, gathered over 54 body composition variables around the body which far exceeded other studies of this type. When examining their model's regression equation and methodologies (see Table 5.1 and 5.2), they gathered their 54 measurements on a sample size of n = 133 participants. At this point it is important to consider recommendations by Atkinson (2005) and Sun and Chumlea (2005) where the larger the sample size, the more statistical power. However, in this case, it would appear that these fundamental concerns have not been met. Wilmore and Behnke (1969) did not have a large sample, they did not compartmentalise their variables, and they only used two variables (abdominal skinfold and anterior thigh skinfold) within the model design. When recommendations are to achieve nine participants per variables, Wilmore and Behnke (1969) only achieved 2.4 variables per participant, thereby raising doubt over the models validity (Cohen, 1988; Atkinson, 2005; Sun & Chumlea, 2005).

Likewise Katch & McArdle (1973) measured 25 variables on n = 53 participants providing 2.1 variables per participant and with only three variables used within their models design (triceps skinfold, subscapular skinfold and abdominal skinfold). Forsyth and Sinning (1973b) measured 15 variables on fewer participants (n = 50) providing a slight increase in

statistical power of 3.3 variables per participant and with only three variables used within their models design (subscapular skinfold, biiliocristal breadth and abdominal skinfold). Further investigations of calibration models available in the literature found that the vast majority had less than n = 100 participants in their sample. It would appear that the three examples reported have all statistically broken the rules and ultimately would present a problem when building a model(s). They failed to achieved anywhere near the recommended nine variables per participant. Kelley and Maxwell (2003) claimed that an adequate sample size can range from 5 participants to 50 participants per variable, and as such lead to estimates that will likely be accurate as well as statistically significant. Yet, literature investigated indicated that this this is not the case, thereby questioning the confidence and usefulness of such calibration models on a population of professional footballers (Sun & Chumlea, 2005).

2.8.5 Limitation 4 - The use of inappropriate analytical methods and the lack of cross-validation approaches when designing a calibration model

Previous studies have indicated that indiscriminate use of calibration models on populations that are different to those on which they are derived generally over or under estimate whole body density (Mayhew *et al*., 1981; Wilmore, 1983; Sinning & Wilson, 1984). As male athletes have a higher than average whole body density, if the selection of the model is made by a non-expert, such as a football coach, they may be unaware of the implications for inaccurately estimating whole body density (Heyward, 2000; Rolland, 2013). Even though eating disorders are not common in male footballers, large errors in the estimation of body density could exacerbate this problem thereby endangering not only the football player's career but also their health (Southwick *et al*., 1984; Bell, 1985; Guo *et al.*, 2000; Heyward, 2000). In many instances, researchers such as Katch and Katch

(1980), Cooper (1995) and Heyward (2000) have suggested that there were no ideal solutions that make it easier to estimate whole body density with a high degree of predictive accuracy. If these calibration models are to be useful in a football context, their predictive accuracy for the estimation of whole body density must be established through careful examination using the most appropriate analysis methods (Mayhew *et al.*, 1985; Cooper, 1995; Heyward, 2000).

A typical example that have been used extensively to help derive calibration models aimed at estimating laboratory-determined whole body density has been both linear and multiple regression analyses. The majority of the calibration studies investigated used stepwise linear regression analyses as a method of choice, but none of them discussed why they used it, suggesting a commonly used and validated method. Furthermore, none of the calibration studies employed the Bland and Altman 95% limits of agreement analyses. Given that this approach was first introduced in the biostatistics literature by Altman and Bland (1983), and later refined for a clinical audience by Bland and Altman (1986) and subsequently recommended to the sport science community by Nevill and Atkinson (1997), it is clear that previous calibration models did not have access to these analyses.
The only likely study could have been Withers *et al*., (1987), which suggest a gap in the literature. By employing the Bland and Altman's 95% limits of agreement analyses in the development of calibration models, involves decisions about whether whole body density outcomes are valid and fit for purpose. Some researchers would argue that due to errors associated with calibration models, careful examination to technical and procedural reliability should be exercised by future researchers (Mayhew *et al.*, 1985; Cooper, 1995; Heyward, 2000).

On another note, the majority of whole body density calibration models are strictly speaking only calibration studies, as the original authors did not cross-validate their calibration models (Vincent, 1999; Atkinson & Nevill, 2001). Ideally, the calibration model should be cross-validated by comparing values in a different sample of participants drawn from the population of interest, than those originally used to develop the calibration model, in order to test the accuracy of the prediction results (Vincent, 1999). It has been suggested that before more calibration models are developed to estimate body composition parameters, serious consideration should be given to cross-validating and refining those that already exist (Atkinson & Nevill, 2001). Mayhew *et al*. (1985) concurred with this suggestion providing that the cross-validation yields supportive evidence for the existing calibration models. A number of studies conducted by Jackson *et al*., (1980), Sinning and Wilson (1984), Mayhew *et al*., (1985) and Jürimäe *et al*., (1992) have demonstrated the significant increases in error in the distributions of body composition variables when calibration models are cross-validated on new samples of male participants. Such models have been known to generally underestimate whole body density (g ml^{-1}) in leaner participants with a range from 1.027 to 1.090 g ml^{-1} (Lohman, 1981; Guo *et al*., 2000).

Too frequently however, the sample sizes for cross-validation, and the range of variables considered, have been too restrictive to be effective indicators of the predictive nature of the existing calibration models (Hawes, 1996; Atkinson, 2005). For instance, relatively small sample sizes of n = 50 participants or less, is not an adequate basis upon which to develop calibration models due to the resulting wide confidence intervals (Hawes, 1996; Atkinson, 2005). Moreover Atkinson and Nevill (2001) stressed that studies conducted on large sample sizes are therefore warranted.

Of the fourteen most commonly used calibration models within the literature, only the Jackson and Pollock (1978) model was found to have cross validated their model, where they used a sample of *n* = 308 male participants to develop and *n* = 95 to cross validate their model. Yet the remaining 13 calibration studies did not cross-validate their models. What is of interest is the reason why only one calibration study cross-validated, given its importance. One plausible reason could be that the studies had low sample sizes and cross-validation was not an option. What is unfortunate is none of these studies discussed why cross-validation was not conducted, which in itself is a fundamental flaw.

2.8.6 Football specific calibration model to estimate whole body density of professional footballers

To date there are no calibration models available in the literature to estimate whole body density in professional football players. What is questionable is the reason why the literature does not have any models available, especially given the popularity and income generation with the sport. Potentially attributed to the limitations as previously identified, or what is more probable is the restrictive nature of the sample sizes employed (Hawes, 1996; Atkinson, 2005). As a consequence what has materialised is that researchers have cross-validated previously published calibration models with their own football populations (Sinning & Wilson, 1984; Ramadan & Byrd, 1987; Withers *et al*., 1987; Thomas, 1991; Reilly *et al*., 2000). Generally speaking results indicated that most models that were used had high reliability values, but exploitation of whole body density values occurred with severe underestimation of whole body density (g ml^{-1}) of professional footballers. Sport scientists are cognisant that these calibration models have the potential to provide an insight into players' body composition, thus contributing towards the optimisation of performance potential (Hencken, 2004). Yet, for the accurate monitoring

of body composition changes during training for football this method of cross-validating other calibration models is not fit for purpose (Mayhew *et al*., 1981; Roche, 1984). Hence the need to develop a new sport specific calibration model using reliable anthropometric variables on a large sample of professional footballers is warranted and desirable (Guo *et al.*, 2000; Provyn *et al*., 2012).

2.8.7 The development of a new sports specific calibration model

It has been well established that there is a need for specific body density calibration models for different sports, populations and age's to enhance the optimal level of performance (Lohman, 1982). Yet, due to the limitations previously mentioned (see section 2.8.1.1 – 2.8.1.6), many of these models are not suitable for given sports, let alone professional football players. Some researchers would argue that limitations associated with calibration models present problems with the lack of reliability and validity. As such some authors have even called for a halt to the development of new calibration models unless they examine many of these limitations (Sheng, 1988; Vincent, 1995; Atkinson & Nevill, 2001).

When developing new calibration models, the remedy to these limitations lie in part to careful examination where possible of the following considerations: (i) selecting large heterogeneous sample size (n = > 100 participants) to include the entire playing spectrum of football playing positions; (ii) taking care to stratify individuals studies for the number and range of anthropometric variables to be used as individual components within a calibration model; (iii) consider how the anthropometric variables are to be used interchangeably within a calibration model; (iv) careful examination of the technical and procedural reliability and validity; (v) using sound research principles such as cross-validation procedures; (vi) employ statistical methods to refine the prediction equation

such as multiple regression analyses and finally (vii) involve decisions about whether whole body density outcomes that have been generated are valid and fit for purpose for professional football players by employing the Bland and Altman's 95% limits of agreement analyses.

There are of course exceptions, but the majority of the models investigated had a small sample size with a wide range of ages, frequently used log transformations or Σ of anthropometric variables, resulting in weak statistical power of variables per participant and ultimately failed to cross-validate their models indicating that they had statistically broken the rules and as such there is no trust in these models. Whereas this thesis had a large sample size (n = 206) within a relatively small age range (24.1 ± 5.4 years), n = 28 reliable potential variables as stand-alone measures providing a statistical power of at least 28.0 variables per participant and used robust rigorous research principles including stepwise regression analysis, Bland and Altman 95% limits of agreement approach and cross-validation techniques on n = 140 participants thereby providing confidence in the outcomes. Consequently, when developing a football specific calibration model the main emphasis would be to use a large heterogeneous sample to cross validate, apply the appropriate reliability and validity statistical procedures and consider which reliable variables to be included to ensure the model is fit for purpose (Guo *et al.,* 2000; Provyn *et al*., 2012). That way the model can be used to help monitor whole body density levels of professional football players and ultimately provide as an essential mechanism for football players to reach optimal performance potential.

Chapter 3
General Methods

3.1 Participants and recruitment

Two hundred and six Fédération Internationale de Football Association (FIFA) registered contracted professional football players ($\bar{x} \pm s$; age = 24.1 ± 5.4 years, body mass = 78.8 ± 8.4 kg, stretched stature = 180.1 ± 7.0 cm and whole body density = 1.075 ± 0.010 g ml^{-1}) were recruited from eight professional football clubs that represented Barclays Premiership, npower Championship, npower League One, npower League Two and Blue Square Premier Leagues during the 2007-2008, 2008-2009 and 2009-2010 playing seasons (see Table 3.1).

Players from these clubs underwent body composition assessments as part of an on-going routine physical fitness assessment at the University of Gloucestershire. A letter explaining the intended nature and purpose of the study was given to each Football Club Manager (Appendix A) and following agreement by the Manager, a letter explaining the intended nature of the study was given to each participant (Appendix B). Participants were then asked to complete the Sport and Exercise Laboratories Health Questionnaire (Appendix C), the purpose of which was to gather information about the participants' health and lifestyles. This information was used in processing the completed questionnaire flow diagram (Appendix D) to determine whether the participants were eligible to take part in the testing for which they had volunteered. Participants to be included in the study had to be over 18 years of age and free from disease or illness. If participants were eligible, they were requested to give written informed consent (Appendix E) and agreed to act as participants in the study.

Table 3.1 General summary ($\bar{x} \pm s$) of the characteristics of *n* = 206 participants recruited from eight professional football clubs

Football league and playing zones	No of NC	Age (y)		Body mass (kg)		Stretched stature (cm)		Whole body density (g ml^{-1})	
		$\bar{x} \pm s$	Range	$\bar{x} \pm s$	Range	$\bar{x} \pm s$	Range	$\bar{x} \pm s$	Range
Barclays Premier League									
Goalkeepers (*n* = 3)	0	19.0 ± 1.0	18 - 20	77.0 ± 01.1	76.1 – 78.2	185.6 ± 8.7	175.7 – 192.2	1.072 ± 0.004	1.068 – 1.076
Defenders (*n* = 10)	2	18.9 ± 0.9	18 - 20	76.5 ± 07.0	64.1 – 86.4	179.8 ± 7.6	170.2 – 193.9	1.076 ± 0.014	1.054 – 1.097
Midfielders (*n* = 9)	1	18.8 ± 1.0	18 - 21	69.9 ± 07.3	59.3 – 79.8	176.8 ± 3.2	170.9 – 181.2	1.084 ± 0.010	1.067 – 1.100
Strikers (*n* = 6)	1	18.8 ± 0.8	18 - 20	73.3 ± 04.4	67.9 – 77.8	181.6 ± 5.3	175.1 – 188.5	1.079 ± 0.016	1.063 – 1.105
Total (*n* = 28)	4	18.9 ± 0.8	18 - 21	73.7 ± 06.7	59.3 – 86.4	179.8 ± 6.4	170.2 – 193.3	1.079 ± 0.013	1.060 – 1.080
Npower Championship									
Goalkeepers (*n* = 2)	0	29.0 ± 8.5	23 - 35	86.7 ± 04.7	83.3 – 90.0	180.6 ± 9.2	174.2 – 187.1	1.070 ± 0.013	1.060 – 1.079
Defenders (*n* = 8)	0	28.5 ± 5.2	20 - 35	77.8 ± 07.1	64.7 – 89.3	180.7 ± 7.5	172.3 – 195.0	1.077 ± 0.010	1.070 – 1.095
Midfielders (*n* = 10)	1	24.4 ± 4.2	18 - 33	80.3 ± 04.2	73.3 – 87.9	181.4 ± 4.6	175.1 – 188.3	1.074 ± 0.014	1.050 – 1.103
Strikers (*n* = 8)	2	22.8 ± 4.0	18 - 31	78.6 ± 08.4	70.7 – 92.4	179.3 ± 7.6	169.6 – 188.7	1.074 ± 0.009	1.063 – 1.089
Total (*n* = 28)	3	25.4 ± 5.1	18 - 35	79.6 ± 06.6	64.7 – 92.4	180.5 ± 6.4	169.6 – 195.0	1.075 ± 0.011	1.050 – 1.103
Npower League One									
Goalkeepers (*n* = 3)	0	24.0 ± 5.3	20 - 30	89.7 ± 07.5	81.0 – 94.6	186.6 ± 4.7	181.5 – 190.9	1.061 ± 0.019	1.039 – 1.076
Defenders (*n* = 20)	3	24.3 ± 5.5	18 - 37	82.1 ± 08.3	64.2 – 95.6	183.5 ± 7.7	163.4 – 199.5	1.072 ± 0.015	1.034 – 1.097
Midfielders (*n* = 24)	1	23.0 ± 5.4	18 - 37	74.1 ± 06.2	60.1 – 84.0	177.3 ± 4.8	167.4 – 185.9	1.077 ± 0.013	1.050 – 1.104
Strikers (*n* = 20)	8	24.6 ± 5.6	18 - 38	78.4 ± 09.3	61.5 – 96.8	178.3 ± 8.1	163.8 – 188.3	1.074 ± 0.019	1.037 – 1.110
Total (*n* = 67)	12	23.9 ± 5.4	18 - 38	78.5 ± 08.8	60.1 – 96.8	179.9 ± 7.3	163.4 – 199.5	1.074 ± 0.016	1.034 – 1.110
Npower League Two									
Goalkeepers (*n* = 3)	0	24.7 ± 3.2	21 – 27	93.8 ± 10.9	82.6 – 104.3	191.1 ± 10.3	180.6 – 201.2	1.075 ± 0.004	1.071 – 1.078
Defenders (*n* = 12)	2	26.1 ± 5.7	18 – 36	83.1 ± 04.3	77.0 – 90.3	180.0 ± 5.0	170.3 – 189.1	1.077 ± 0.020	1.052 – 1.132
Midfielders (*n* = 11)	0	24.2 ± 4.1	18 – 31	77.0 ± 08.4	65.9 – 96.5	178.3 ± 7.1	169.5 – 188.8	1.075 ± 0.007	1.067 – 1.089
Strikers (*n* = 6)	2	25.3 ± 5.0	19 – 33	79.1 ± 07.0	72.6 – 91.4	178.9 ± 8.2	172.2 – 193.5	1.090 ± 0.020	1.069 – 1.121
Total (*n* = 32)	4	25.2 ± 4.7	18 – 36	81.3 ± 08.3	65.9 – 104.3	180.2 ± 7.5	169.5 – 201.2	1.079 ± 0.016	1.052 – 1.132
Blue Square Premier League									
Goalkeepers (*n* = 3)	0	22.5 ± 3.5	20 – 25	89.9 ± 05.1	85.0 – 190.0	187.8 ± 2.0	186.1 – 190.0	1.064 ± 0.005	1.060 – 1.070
Defenders (*n* = 17)	1	25.6 ± 4.7	20 – 34	83.3 ± 08.0	72.4 – 98.8	183.9 ± 5.9	172.7 – 192.4	1.068 ±0.014	1.037 – 1.095
Midfielders (*n* = 16)	0	28.1 ± 5.4	20 – 37	78.3 ± 06.3	66.6 – 91.1	179.5 ±5.9	169.2 – 189.0	1.077 ± 0.013	1.053 – 1.116
Strikers (*n* = 15)	1	25.9 ± 5.4	18 – 38	76.7 ± 10.0	62.4 – 102.3	175.9 ± 7.1	162.7 – 192.5	1.078 ± 0.014	1.049 – 1.100
Total (*n* = 51)	2	26.2 ± 5.2	18 – 38	80.1 ± 08.6	62.4 – 102.3	180.3 ± 7.0	162.7 – 192.5	1.073 ± 0.014	1.037 – 1.116

Key: NC = Non Caucasians

3.2 Ethical considerations

Before undertaking the research study, laboratory procedures approval was granted by the University of Gloucestershire Research Ethics Sub-Committee. All measurements were taken in the British Association of Sport and Exercise Sciences (BASES) accredited sports science laboratories at the University of Gloucestershire and by an accredited International Society for the Advancement of Kinanthropometry (ISAK) Level One Kinanthropometrist (1.0 – 6.5 TEM%) (June 2006). Protocols and measurement guidelines followed those ratified by ISAK. Ethical behaviour was adopted to ensure that physical, social and psychological well-being of the participants was not detrimentally affected in the study (Olivier, 1995). For instance, every attempt was made to develop robust operational procedures that accommodated the following steps to minimise risk to participants by: i) acquiring informal consent; ii) guaranteeing confidentiality and anonymity of all data; iii) consideration of participants' privacy and sensitivity and iv) familiarisation of the testing environment.

The study required participants to freely give their informed consent to take part in the study, which in turn granted each participant protection of their rights and allowing them to withdraw from testing at any time. It should never be assumed that all participants wish to take part in the study, especially if they are part of a team or squad of players. At times, this can be an awkward and sometimes sensitive situation, therefore, care was taken through discussions with every participant on a private and individual basis, so that they were not pressurised into participation. Practical steps were undertaken in an attempt to guarantee confidentiality for all participants. This was achieved through having all data and personal information about participants being kept in accordance with the Data Protection Act 1998 and secured in a locked filing cabinet. Anonymity was achieved by

number coding participants, thereby reducing some identifiable characteristics. All personal information and data was only accessible by the primary investigator, although every club received body composition data for each of their players, as part of the on-going routine physical fitness assessments. To avoid participants feeling invaded or uncomfortable, a number of preliminary steps were taken to promote their dignity and make them feel at ease (Norton *et al*., 2000). Firstly, many of the participants were unfamiliar with the laboratory testing environment, therefore, to minimise stress and anxiety, testing was conducted without the presence of unnecessary people (Lohman *et al.*, 1991). Secondly, participants were made aware of what parts of their bodies that would be touched and measured. Thirdly there was an appreciation of the participants' personal space (Norton *et al*., 2000). Fortunately, many of the measurements were taken from the lateral or posterior positions, thereby reducing infringement into their personal space. Due to the practicality of the measurement process, there can be a power imbalance that exists between the primary investigator and the participant, especially with those as previously mentioned, who are unfamiliar within a laboratory environment. An attempt to develop a research relationship through mutual respect and trust was established to help reduce this imbalance.

To minimise extraneous variables that might affect measurements, environmental conditions such as heat, humidity, light and air movement an attempt was made to keep these variables as constant as possible throughout the measurement procedures (Pyke, 2000). For instance, the laboratory was set at a comfortable temperature (approximately 20 – 24^{o}C) with plenty of natural and artificial light provided. Blinds covered the windows and door, with hospital screens used when necessary. A draft excluder was attached to the bottom of the laboratory door to help reduce unnecessary air movements and draughts.

3.3 Measurement and assessment procedure

All participants were asked to arrive at the sports science laboratories at the University of Gloucestershire at least one hour before testing was to begin. Assessments were conducted in the mornings so that the primary investigator could control for diurnal fluctuations and that participants could more easily adhere to the following strict pre-testing procedures:

1) Refrain from consuming food or fluid for at least four hours before assessment
2) Refrain from exercising for a twelve hour period before assessment
3) Refrain from smoking for at least four hours before assessment
4) To empty their bowel and bladder before assessment (Levenhagen *et al.*, 1999; Fields *et al*., 2002)
5) To wear light fitting shorts or underpants and a bathing cap (where appropriate) (Dempster & Aitkens, 1995; Biaggi *et al*., 1999)
6) To remove all jewellery (Biaggi *et al*., 1999; Lockner *et al*., 2000)

For logistical reasons, all participants followed the same testing procedures as illustrated in Figure 3.1. In advance of any testing procedures, the health questionnaire and consent form (see section 3.2) was read, dated and signed by the participant and counter–signed by the primary investigator (Appendices C and E). Before testing, a thorough verbal explanation of the study's aims, duration, consequences of the research and how the results were likely to be disseminated to each participant.

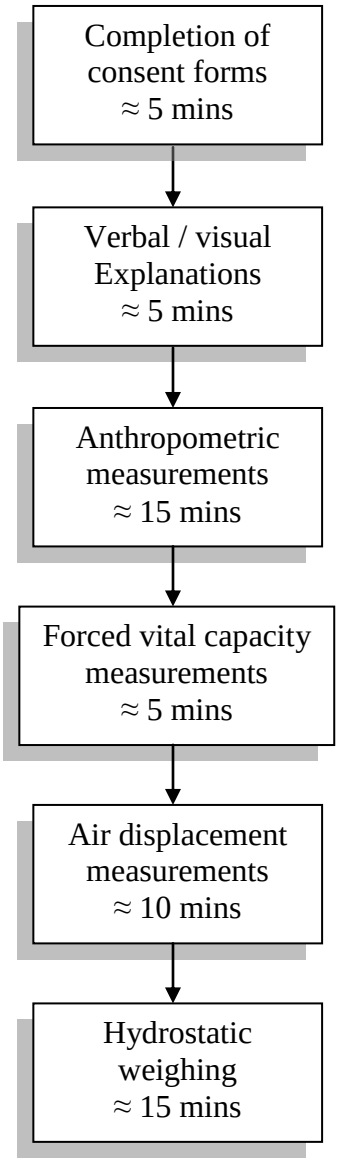

Figure 3.1 Standardised testing schedule

Before commencements of testing, participants were given a verbal explanation and visual demonstration of all procedures (Figure 3.1). Furthermore, they were asked to comment on whether they had an injury(s), bruising, swelling, scaring or muscle atrophy which might impede accurate measurement (Gordan *et al.*, 1991; Lohman *et al.*, 1991). If necessary the injury(s) were documented and it was also noted whether participants had excessive body hair and/or facial hair (Lockner *et al.*, 2000; Fields *et al.*, 2002). All

anthropometric measures (skinfolds, breadths, widths, depths, stretched stature and sitting height) were measured in succession as listed on Kinanthropometric data collection proforma (Appendix F). Data obtained from forced vital capacity and hydrostatic weighing was recorded on the data collection proforma (Appendix G) and the air displacement plethysmography was recorded on the performa (Appendix H). Finally, anthropometric measures, forced vital capacity and the measurement of air displacement were conducted before hydrostatic weighing, to ensure that the participant's skin was dry and lotion free.

A recorder was used to assist the primary investigator wherever appropriate. The recorder was not trained in recording techniques, however, through extensive guidance by the primary investigator, they were able to verify the accuracy of skinfold site location and ensure correct the sequence of measurement sites was adhered to (ISAK, 2011). Attention to detail was improved by the enunciating of each measurement site by the primary investigator. For example, the primary investigator used single numbers such as reading 10.7 as one zero point seven (Norton *et al*., 2000). The recorder was instructed to immediately repeat the value to avoid any misinterpretation (Ross & Marfell-Jones, 1991).

Measurement data was recorded on a Kinanthropometric data collection proforma that followed a similar format to that proposed by Ross and Marfell-Jones (1991) (Appendix F, G and H). The proforma was designed specifically for ease of systematic recording, with clearly identifiable decimal points and designated spaces for numerical data, thus reducing the likelihood of recording error (Ross & Marfell-Jones, 1991). In addition to the recording of personal information (identification number, date of measurement, date of birth and football playing position); recorded measurements included standard

anthropometric measures (stretched stature (cm) and sitting height (cm); skinfold thicknesses (n = 8) (mm); girths (n = 10) (cm); breadths, depths and widths (n = 6) (cm); lung gas volume attempts (l) (n = 3), air displacement plethysmography results (body mass (kg) and body volume (l) and hydrostatic weighing attempts (g ml^{-1}) (n = 10).

Detailed checking of all equipment was performed using strict guidelines and protocols identified in manufacturers' instruction manuals before using any instruments. For some instruments, it was not possible to calibrate them without sending them back to the manufacturer. All remaining checks were undertaken by the primary investigator at the sports science laboratories at the University of Gloucestershire. Instruments used included: a hydrostatic weighing tank for measuring underwater weight and estimating whole body density (section 3.4 and Plates 1 – 4); an air displacement plethysmograph for measuring body mass and estimating body volume and whole density (section 3.5 and Plates 5 – 8); a MicroLoop spirometer for the measurement of forced vital capacity and estimation of residual lung volume (section 3.6 and Plate 9); a Holtain wall mounted stadiometer for measuring stretched stature and a Holtain sitting height stadiometer for measuring sitting height (section 3.7.1 and Plates 10 and 11); Harpenden skinfold calipers (section 3.7.2 and Plate 12) for the measurement of skinfold thickness; a Harpenden anthropometric steel measuring tape (section 3.7.3 and Plate 13) for the assessment of anthropometric girths; a Harpenden anthropometer (section 3.7.4 and Plate 13) for the assessment of anthropometric breadths, widths and depths and an anthropometric box (Plate 14) for participants to sit and stand on.

3.4 Hydrostatic weighing

Hydrostatic weighing and the estimation of whole body density was performed by using a hydrostatic weighing tank. The tank had a wall mounted digital weighing scales, hydraulic hoist, strain gauge, chair and steps that enabled the participant to enter and exit the tank safely (Plates 1 – 4). The area surrounding the densitometer had curtains to ensure privacy and there was a non-slip, hard level floor. There was a panic alarm button and telephone available in case of emergency. On each testing occasion one member of staff who was First Aid trained was present. To ensure that the University of Gloucestershire's health and safety regulations were followed, the tank was emptied and refilled with fresh chlorinated water after a maximum of ten participants had been assessed in any given volume of water. Water chlorination testing and activation of the pumping system was carried out when required by technicians. The water in the tank was kept at a temperature range of 32-36^{o}C for the duration of all measurements. Inevitably there was a loss of water with participants exiting the tank, so the primary investigator added adequate water between assessments to guarantee a minimum volume as determined by the water level mark. The maximum volume was indicated by a water level mark within the tank.

Validation of the digital weighing scale involved resetting the digital weighing scale to zero, placing a 20 kg certified weight from the British Standards Institute (BSI) onto the suspended chair, and validating the value. In the event of any discrepancy of ± 0.02 kg, the digital weighing scale was reset and validation was repeated three times if necessary. Estimation of whole body density (D_b) from hydrostatic weighing was determined as the ratio of body mass (M, g) to body volume (V, ml) ($D_b = M/V$) and was expressed to the nearest 0.001 g ml^{-1}, estimation of which involved sequential steps. Before testing, details of water temperature and the tare weight of the weighing apparatus (suspended seat and

nose clip) were recorded and participants' body mass in air (M_a, kg) was determined (see Appendix I for specifications for assessing participants for body mass). The temperature of the water was taken which allowed for a correction for the density of water (D_W, g ml^{-1}) (Appendix J).

Participants were requested to wear lightweight shorts and a nose clip and to enter the hydrostatic weighing tank via the steps (Plates 1 – 2). Once submerged participants were instructed to get their hair wet and ensure their shorts contained no trapped air. The participants positioned themselves comfortably on the seat and were then lowered via a hydraulic hoist that was operated by the primary investigator so that the water was at the level of the participant's chin (Plates 3 and 15). Participants were asked to initiate their own breathing rate and when ready, take a small inhalation, lean forwards and submerge themselves fully. Once underwater, and keeping as still as possible, the participant was required to exhale maximally (Plate 16). The primary investigator watched for the ending of exhalation bubbles and took the measurement of body mass in water (kg) from the wall mounted digital weighing scale adjacent to the hydrostatic weighing tank (Plate 4). Following the measurement, the primary investigator rapped loudly on the side of the tank thereby instructing the participants to return to the surface (known as the post-submersion exhalation technique, as discussed in section 3.8.2).

If the participant felt able a further nine hydrostatic weighing measurements were taken. Ideally the fourth, fifth and sixth measurement attempts were used to calculate average body mass in water (M_w, kg) (as discussed in section 3.8.3) (see Appendix K for specifications for assessing participants for hydrostatic weighing). If the participant was unable to fulfil these requirements by the tenth attempt, their underwater weight was

consequently estimated by taking the mean of three similar recorded values (Brodie & Eston, 1992). The participant could then leave the tank and their wet lightweight shorts were then weighed on the digital weighing scales and included in the apparatus tare weight calculation (ISAK, 2011).

Adjustments for the gastrointestinal volume (GIV, ml) were determined where a constant 100 ml Body Temperature and Pressure Saturated (BTPS) was used to represent all participants (Buskirk, 1961) (Appendix L). Estimates of residual lung volume (RV, ml) (as discussed in section 3.7.1) and gastrointestinal volume (GIV, ml) were included in the following equation. Thus, whole body density was computed as;

$$\text{Whole body density } (D_b)\ (\text{g ml}^{-1}) = M_a/(((M_a - M_W)/D_W) - (RV + GIV))$$

(Norton & Olds, 2002)

Where: M_a = mass in air (kg); M_w = mass in water (kg) (M_w), D_w = density of water ($g.ml^{-1}$), RV = residual lung volume (l) and GIV = gastrointestinal tract volume (l).

3.5 Air Displacement Plethysmography (BodPod)

The air displacement plethysmograph (BodPod) was used for measuring body mass and estimating body volume and whole body density with the BodPod comprising of a cabin, computer system, monitor, data interface board, software and scales (Hoffman *et al.*, 2001) (Plate 5 – 8). The BodPod is a 750 l fibreglass shell that comprises two chambers. Firstly, the test chamber that accommodates the participant during testing and secondly, the reference chamber that contains instrumentation for measuring changes in pressure between the two chambers (Dempster & Aitkens, 1995; Maddalozzo *et al.*, 2002; Fields *et*

al., 2004). The moulded front seat forms a common wall separating the test and reference chambers, each with an approximate volume of ≈ 450 and 300 l respectively with a volume-perturbing element (a moving diaphragm) connecting the two chambers (Fields *et al*., 2000). As part of the quality assurance process, the BodPod is rigorously tested by the manufacturers, Life Measurement, Inc., to establish accuracy, reliability and linearity for measurements of both volume and mass (Dempster & Aitkens, 1995; Life Measurement Inc., 2008).

These quality assurance processes are undertaken by the manufacturer before distribution, with multiple tests where known masses of 20 kg, 40 kg, 60 kg and 80 kg and volumes of 30 l, 50 l and 90 l are used (Life Measurement Inc., 2008). However in order to maintain the accuracy of the BodPod on a day by day basis, further quality control procedures were undertaken by the primary investigator (Life Measurement Inc., 2006). These quality control procedures consist of a mass and volume calibration conducted before every bout of testing and which are designed to check the stability and performance of the BodPod system (Life Measurement Inc., 2006). Validation of mass and volume were executed following the manufacturer's automated process by inputting measured values via the user interface. The procedure required the primary investigator to perform sequential steps without interruptions with equipment provided by Life Measurement, Inc. (Lockner *et al*., 2000). Manufacturers supplied calibration equipment included, two 10 kg calibration National Institute of Standards and Technology weights that were used on the digital weighing scale to calibrate mass (Plate 17 – 18) and a 50 l calibration cylinder that was used within the BodPod chamber to calibrate volume (Plate 19 – 20 and refer to section 3.8.4 for enhanced checks).

Estimation of whole body density using the air displacement plethysmograph uses the inverse relationship between pressure (P) and volume (V) to derive the body volume of a participant from a 750 l fibreglass shell (Plate 5) (Dempster & Aitkens, 1995). Measurement protocol was rigorously followed in accordance with the step by step instructions given on the BodPod system computer (See Appendix M and Plate 6 for specifications for assessing participants for air displacement plethysmography). The first measurement required the participant to stand on the calibrated electronic scale to determine body mass (Plate 21). Once completed, participants were asked to enter the BodPod and sit quietly on the moulded front seat with an erect posture with their hands folded on their laps and feet placed on the floor of the chamber (Plate 22) (Biaggi *et al*., 1999; McArdle *et al*., 2006). A nose clip was worn by the participant to prevent leaks through the nares. The panic release button was shown to participants should they at any time feel at all claustrophobic (Plate 23). The chamber door was then closed and sealed (Plate 24).

The volume of a participant's body was measured indirectly through the application of Boyle's Law by subtracting the volume of air displaced inside the enclosed chamber (BodPod) when the participant is inside, from the volume of air in the chamber when it is empty (Fields *et al.*, 2004; Vescovi *et al*., 2002; Heymsfield, 2005; Hull & Fields, 2005). During the test, participants were instructed to continue breathing normally whilst a minimum of two 50 s tests were conducted to ensure reliability of measures (known as the spirometry method as discussed in section 3.6.5) (Biaggi *et al*., 1999, Hoffman *et al*., 2001).

3.6 Forced vital capacity and residual lung volume

The measurement of forced vital capacity (FVC) and estimation of residual lung volume (RLV) was assessed using a MicroLoop spirometer (MicroLoop, Micro Medical Spirometer model 3535). The accuracy and precision of the spirometer was in accordance with the requirements of the American Thoracic Society (ATS) and the European Respiratory Society (ERS) (Miller *et al*., 2005). The spirometer was checked and validated daily using a 3 l calibration syringe (Calibration Pump, Jaeger, Hoechberg, Germany), with readings displayed on the spirometer screen.

Estimation of residual lung volume (RLV) involved measurement of forced vital capacity (FVC) and sequential steps. Each participant was fully informed of the procedure to be employed and sat in an upright position whilst holding the spirometer breathing tube in their dominant hand (see Appendix N for specifications for assessing participants for forced vital capacity and Plate 25). A nose clip was worn by the participant to prevent leaks through the nares. All measurements were performed and interpreted according to ATS and ERS guidelines (Miller *et al*., 2005).

The primary investigator called the rate of breathing for the participant comprising of three cycles of inhalation and exhalation. On the third cycle, the primary investigator asked the participant to take a maximal inhalation and then a maximal exhalation that was blown out through the spirometer tube (Plate 26). Verbal encouragement was given throughout the manoeuvre by the primary investigator. A minimum of three acceptable FVC measures were performed. Acceptable measures were free from artefact and had a satisfactory start and end of test. The greatest value was then corrected for Body Temperature and Pressure Saturated (BTPS) determined by using a correction table (Appendix L) (Sinning, 1975).

Residual lung volume was estimated by taking a constant fraction of each participant's FVC and was expressed to the nearest 0.05 l and computed using the Sinning (1975) equation as follows:

RLV = FVC (BTPS) (l) x 0.24 (males)

(Sinning, 1975)

Where: RLV = Residual Lung Volume; FVC = Forced Vital Capacity; BTPS = Body Temperature and Pressure Saturated (Sinning, 1975; Morris *et al*., 1971; Crapo *et al*., 1981; Knudson *et al*., 1983). As previously described, further adjustments for gastrointestinal volume (GIV, l) were made where a constant 100 ml Body Temperature and Pressure Saturated (BTPS) was used to represent all participants (Buskirk, 1961).

3.7 Anthropometry

A complete data set was obtained before repeating the measurements for a second time. Time taken between assessments was long enough to ensure that changes in the compressibility of the skinfold was avoided (≈ 15 – 20 minutes) (Baumgartner & Jackson, 1987; ISAK, 2011). In addition, it is common practice within the protocols ratified by ISAK and the International Working Group of Kinanthropometry (IWGK) to complete a data set before repeating the assessment for the second time (Lohman *et al*, 1981, Ross & Marfell-Jones, 1991, Hencken & White, 2006). This practice also allowed the primary investigator to forget the original assessment value, thereby minimising primary investigator bias. After measurements were taken, the mean value was determined for subsequent data analysis was in accordance with ISAK protocols (ISAK, 2011). At the time of data collection, ISAK (2001) protocols were followed. However, it should be acknowledged that after all data collection took place, new ISAK guidelines (2011) where in force.

3.7.1 Stretched stature and sitting height

Stretched stature were measured using a Holtain stadiometer which was attached to a wall and had a gliding ball bearing Brocca plate 6 cm wide and had a hard level floor surrounding the area (Plate 10). The sitting height Holtain stadiometer was attached to a wall and the floor and had a gliding ball bearing Brocca plate 6 cm wide and had a hard level surface so that the participant could be in the sitting position, with their legs hanging from the edge (Plate 11). Readings for both stadiometers were in cm and measured to the nearest 0.1 cm. The maximum limit for the stadiometer and sitting height stadiometer was 220 cm and 120 cm respectively. Validation of the both stadiometers was made before every measurement session by extending the Brocca plate to a predetermined height whilst measuring it against a known certified height of 1m from the BSI. Stretched stature and sitting height were measured in succession as listed on the Kinanthropometric data collection proforma (Appendix F) (See Appendix O and P and Plates 27 – 28 for specifications for assessing stretched stature and sitting height). After measurements were taken, the mean value was determined for subsequent data analysis.

3.7.2 Skinfold thickness

The Harpenden skinfold caliper gradations are in 0.2 mm divisions, but measurements were taken to the nearest 0.1 mm (ISAK, 2011) (Plate 12). A full sweep of the needle corresponds to a measure of 20 mm, with the dial indicator permitting 2½ revolutions. Validation of the skinfold caliper involved exerting a constant downscale jaw pressure of 10 g mm^{-2}, on five separate foam rubber blocks with uncompressed thicknesses of 15.0, 25.0, 35.0, 45.0 and 55.0 mm as recommended by Norton and Olds (2004) as standard validation values (Gore, *et al*., 1995; Carlyon, *et al*., 1999 and 2000). The foam rubber blocks were held in a vertical position whilst applying the caliper jaws at a right angle and

the caliper dial read 2 s after application of full jaw pressure. Acceptable downscale jaw pressure ranged from 7.7 – 8.4 g mm^{-2} at 5 mm of jaw gap and 7.3–8.0 g mm^{-2} at 40 mm of jaw gap (Carlyon *et al*., 2000). If the jaw pressure fell outside this acceptable range, the caliper was sent back to the manufacturer for servicing.

Skinfold thickness (n = 8) were measured in succession as listed on the Kinanthropometric data collection proforma (Appendix F) and whilst the participant maintained the universal anatomical position (Plates 29 and 30). Anatomical landmarks are identifiable skeletal points that generally lie close to the body's surface and identify the exact location of the measurement site, or from which a soft tissue site is located and are found by palpation (Norton *et al*., 2000; ISAK, 2011). Consequently, the primary investigator's fingernails were kept short for the comfort of the participant, as identifying landmarks were found with the thumb or index finger. Once the site was found, the primary investigator released the site to remove any distortion of the skin, and then immediately relocated and marked a thin line using a dermograhic pen (Plate 13), directly over the landmark. It is important to note that some of the landmarks are short lines, while others are X's. In some cases, short vertical or horizontal lines are used as reference marks (Norton *et al*., 2000; ISAK, 2011). When landmarks were made using an anthropometric steel measuring tape, the mark was made at the top edge of the tape while the tape is held at a right angle to the limb axis. All landmarks were identified before any skinfold measurement was made (See Appendix Q and Plates 31 – 36 for specifications for marking and assessing participants for anthropometric landmarks).

All skinfold thicknesses were taken systematically on the right hand side of the bodies of all participants unless injury(s), bruising, swelling, scaring or muscle atrophy which might impede accurate measurement (see Appendix R and Plates 37 – 54 for specifications for assessing skinfold thicknesses) (Gordan *et al.,* 1991; Lohman *et al.,* 1991). For consistency, the right side of the body was always used for measurements irrespective of the dominant playing side of the participant. This is common practice within the protocols ratified by ISAK and the IWGK. The body can assume a variety of postures, therefore, the correct anthropometric description always refers to the anatomical position, that requires the participant to stand with their head and eyes directed forwards, the upper limbs hanging by their sides, thumbs pointing away from the sides, with fingers pointing directly downwards, feet together and the toes pointing directly forwards (Plate 29 – 30) (Ross & Marfell-Jones, 1991). Sometimes it was impracticable to use the right side due to injury, therefore the measurement was taken on the opposite side and noted by the recorder.

The technique used to measure skinfold thickness required the pinching and lifting of a double fold layer of skin and underlying subcutaneous adipose tissue perpendicular to the surface of the body. The fold was held firmly with the thumb and index finger of the left hand at the marked site, with the back of the hand facing the primary investigator. The size of the two skin surfaces produces a parallel sided fold. If difficulty was encountered the participant was asked to tense then relax the underlying muscle until the primary investigator was confident that only skin and subcutaneous tissue were in the grasp. Since a double fold of skin was being measured, some variability was attributed to variations in skin thicknesses at different sites over the body and among different participants (Martin *et al.,* 1985) and thicker skinfolds (Harrison, *et al.,* 1991). Practice was necessary to ensure the same size of skinfold is grasped at the same location for repeat measures. It is worth

noting that there were some participants for whom certain skinfold measures could not be accurately taken. This might be due to factors such as extremely tight skin, large subcutaneous adiposity or injury (ISAK, 2011). If consecutive skinfold measurements become smaller, the adipose tissue is likely being compressed where the intra and extracellular fluid content is gradually being reduced (Heyward, 2000). This most often occurs in fatter participants. In this instance, the primary investigator either moved to the next site or returned to the original site after several minutes thus minimising potential errors (see Plates 50 – 52 for different methods at anterior thigh skinfold site).

The Harpenden skinfold calipers were held with the right hand at a 90^{o} angle to the surface site at all times while the skinfold was elevated with the left hand. The caliper branches were then placed over the skinfold with the caliper jaws perpendicular to its long axis, and they were allowed to exert their full pressure (10 g mm^{-2}) at a position 1 cm below the fingers (Plate 56). The primary investigator ensured their hand was grasping the skin and holding the fold firmly while the caliper was in contact with the skin and aligned correctly. The nearest edges of the contact faces of the caliper were applied 1 cm away from the edge of the thumb and finger. Care was taken by the primary investigator not to apply the caliper too deep or too shallow as incorrect values may be recorded. Skinfold thickness have been shown to vary by an average of 2-3 mm when the caliper is placed 2.5 cm from the correct site (Gore *et al.*, 2000) (Plate 55). Therefore, according to ISAK (2011) mid-fingernail was used as an approximate depth (Plate 55).

Measurements were recorded approximately 2 s after the full pressure of the caliper was applied and to the nearest 0.1 mm (Kramer & Ulmer, 1981). The primary investigator's technique ensured that the fingers that were resting on the caliper trigger did not prevent

the full caliper pressure from being exerted (ISAK, 2011) (Plate 56). In the case of large(r) skinfolds, the caliper needle might have a tendency to keep moving, as such the standardisation of needle movement and reading was adopted in accordance with the recommendation of ISAK (2011).

3.7.3 Anthropometric girths

Anthropometric girths were measured using a flexible steel tape had coequal metric identification marks on one side, and a blank strip of at least 4 cm prior to the zero line (Plate 13). The tape was at least 1.5 m in length and no wider than 7 mm with an automatic retraction. Measurements were taken to the nearest 0.1 cm. The tape was validated before every measurement session by taking the zero end of the tape in one hand and extending the tape to a predetermined length in the other hand whilst measuring it against a known certified length of 1.0 m from the BSI. Girths (n = 10) were measured in succession as listed on the kinanthropometric data collection proforma (Appendix F). All girth measurements were taken systematically on the right hand side of the bodies of all participants, unless injury(s), bruising, swelling, scaring or muscle atrophy which might impede accurate measurement (see Appendix S for specifications for marking and assessing girths and Plates 57 – 67) (Gordan *et al.,* 1991; Lohman *et al.,* 1991).

The cross handed technique was used for all girth measurements (Norton & Olds, 2002; ISAK, 2011). During measurement, the anthropometric tape was pulled out of its case and passed around the body segment and held by the primary investigator's left hand. The reading edge of the tape was transferred to the right hand and held perpendicular to the long axis of the limb or body segment (Lohman *et al*., 1988; Norton & Olds, 2002). Orientation of the tape was made with the middle fingers of both of the primary

investigator's hands to find the designated landmark. The left hand resumed control of the stub end and made any further adjustments so the stub end and scale calibrations were in juxtaposition (Norton & Olds, 2002). Finally juxtaposition of the tape ensured that the zero end was easily read and thus a recording could be made (Plate 68) (Norton & Olds, 2002; ISAK, 2011). To improve reliability, the positioning and tension of the anthropometric tape needed careful attention (Lohman *et al*., 1988). An example of positioning difficulties is that of the girth of the torso as measures are being taken at various phases of the respiratory cycle (MacDougall *et al*., 1991; ISAK, 2011). Furthermore, the tension of the anthropometric tape was problematic in the assessment of the hip girth. The anthropometric tape was pulled tightly to compress the clothing worn as well as the soft tissues of the participant. For all other girth measurements, the tape was held tight to the body segment, but not tight enough to compress the subcutaneous adipose tissue or alter the contour of the segment (MacDougall *et al*., 1991; ISAK, 2011).

3.7.4 Anthropometric breadths, depths and widths

Anthropometric breadths, depths and widths were measured using a harpenden anthropometer which has two sets of branches (straight and curved arms) that can be attached for breadth, depth and width measures (Plate 13). The branches are at least 40 cm in length and are graded in 0.2 mm divisions (Norton & Olds, 2002; ISAK, 2011). Readings were recorded in mm, and measured to the nearest 0.1 mm. The anthropometer was validated prior to every measurement session by extending the branches to a predetermined length whilst measuring it against a known certified length of 1 m from the BSI. Anthropometric breadths (n = 2), depths (n = 2) and widths (n = 2) were measured in succession as listed on the kinanthropometric data collection proforma (Appendix F). All measurements were taken systematically and on the right hand side of the bodies of all

participants unless injury(s), bruising, swelling, scaring or muscle atrophy which might impede accurate measurement (see Appendix T – V for specifications for marking and assessing breadths, depths and widths and Plates 69 – 74) (Gordan *et al.,* 1991; Lohman *et al.*, 1991). The operation of the harpenden anthropometer is best used when the caliper braches are lying on the backs of the primary investigator's hands and the thumbs rested against the inside edge of the arms, and the index fingers were able to lie along the outside edges. Whilst in this position the middle fingers were able to exert considerable pressure to reduce the thickness of any underlying soft tissue and free to palpate the bony landmarks on which the caliper faces were to be positioned (Plates 75 – 76) (Norton & Olds, 2002). Before making any measurements the primary investigator inspected both caliper points to ensure there was no movement away from the landmark and was still in the correct position (ISAK, 2011). Firm pressure was maintained, ensuring minimal skin, fat and muscle contribution at each measurement site.

3.8 Methodological protocol considerations

Evidence suggests that there are many contentious issues that can impact significantly upon body compositional assessments (Demura *et al*., 2007). Researchers such as Sheng (1988); De Lorenzo *et al*., (2000); Dewit *et al*., (2000); Vescovi *et al*., (2002); Collins *et al*., (2004) and Demura *et al*., (2007) have all addressed some of these issues, but there is still much uncertainty and significant challenges in terms of measurement reliability during laboratory and field-testing situations. Therefore, due to the unresolved issues relating to the reliability and precision of body composition assessments, it was necessary to conduct a series of pilot investigations. A sample of volunteers (n = 22) (n = 10 male and n = 12 female) was recruited from the University of Gloucestershire, Department of Sport and Exercise, undergraduate programmes. All participants were over 18 years of age and all

were free from disease, illness or injury ($\bar{x} \pm s$; age = 20.5 ± 1.7 years, body mass = 68.7 ± 1.5 kg and stretched stature = 172.0 ± 8.3 cm). Participants were tested at the sports science laboratories at the University of Gloucestershire over a two week period. All participants followed the identical testing procedure as illustrated in Figure 3.2.

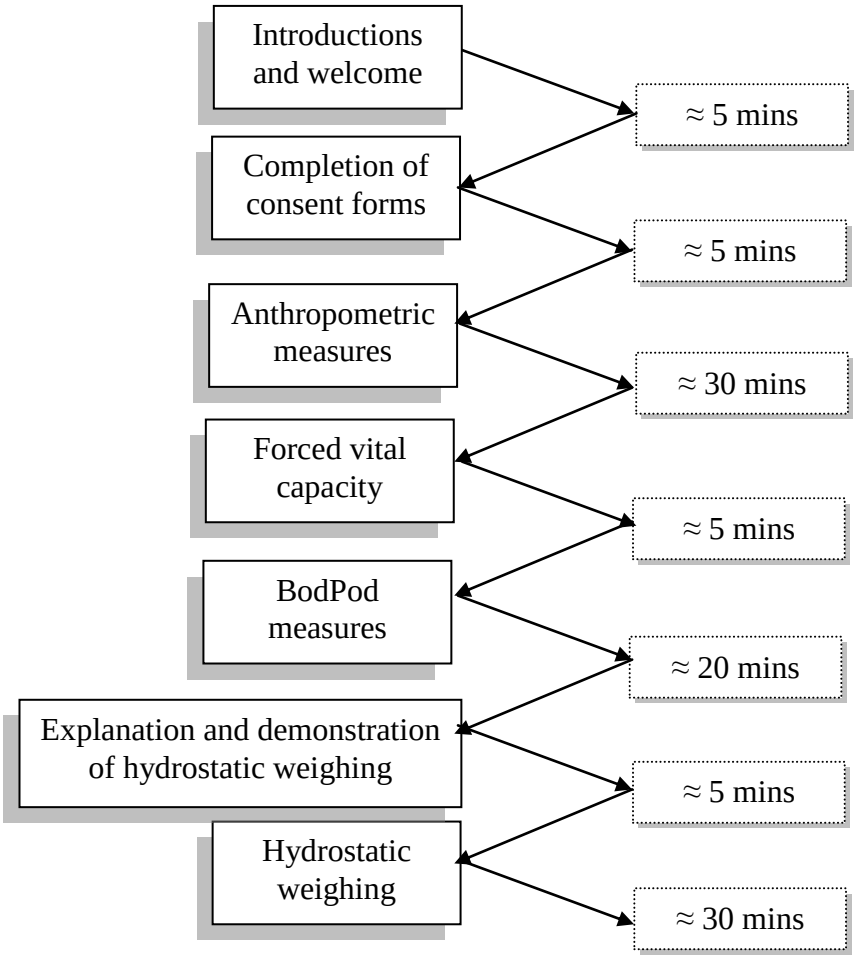

Figure 3.2 Standardised testing schedule for the pilot investigations

The following pilot investigations were carried out in an attempt to reduce measurement errors before undertaking measurements related to the main studies:

Investigation A: Assessment method for obtaining body mass

Aim: To examine the agreement between three different methods of measurement of body mass via the Schonelle digital weighing scale, BodPod electronic scale and hydrostatic weighing tank digital suspended weighing scale.

Investigation B: Agreement between methods to determine procedure for maximal exhalation during hydrostatic weighing

Aim: To examine the agreement between two separate Hydrostatic weighing techniques: pre-submersion exhalation technique and post-submersion exhalation technique to determine body mass in water

Investigation C: Number of underwater measurement attempts needed to determine average body mass in water

Aim: To investigate the optimal approach (number of underwater measurement attempts) needed to estimate the average body mass in water.

Investigation D: Linearity of the scale for mass and volume within the BodPod

Aim: To examine the calibration approaches and to independently determine both the accuracy and linearity of mass measurement and the accuracy and linearity of volume measurement throughout the potential measurement range.

Investigation E: Agreement between methods to estimate thoracic gas volume

Aim: To determine the most appropriate estimation of thoracic gas volume, from three possible approaches including: i) a value that has already been predetermined through another source of testing (entered), ii) a value that is conducted via the BodPod panting manoeuvre (measured), and iii) a value based on an algorithm using variables of age and stature (predicted).

3.8.1 Investigation A: Assessment method for body mass

Investigation context

The main studies within this thesis required data to be gathered from various anthropometric measurements, some of which were direct measures and others used to derive other values. Further scrutiny of the list of required variables revealed that body mass was required for three separate elements within the variable list. This reliance on the same measure raised a question as to whether it was possible to reduce the number of repeat measurements of body mass. The use of a single measurement approach would be advantageous in eliminating a potential confounding variable when exploring the agreement between different techniques to determine whole body density. Therefore, the aim of this investigation was to establish whether it was possible to use a single measurement of body mass for all derived variables requiring body mass as part of their computation.

Investigation design

In order to examine the agreement between different methods of measurement of body mass, participants performed three consecutive measurements using three different methods: i) using the Schonelle digital weighing scale, a universal piece of equipment used within the sports science field; ii) the BodPod electronic scale as part of the standardised procedure employed in for the air displacement model; and, (iii) the hydrostatic weighing tank digital suspended weighing scale for determining body mass in air and when submerged in water (see Appendix K). The agreement of all measured variables was illustrated by constructing scatter plots showing deviation from the line of identity and by applying the Bland and Altman 95%, limits of agreement method to quantify the bias, random variation and heteroscedasticity between aforementioned measures of body mass.

Investigation results

Body mass values ranged between 53.8 and 116.6 kg for the Schonelle digital weighing scales, 54.0 – 116.6 kg for the BodPod electronic scales and 53.8 – 116.7 kg for the hydrostatic weighing tank suspended weighing scales. Scatter plots are provided in Figure 3.3 for illustrative purposes to demonstrate the linear relationship between the three separate measures of body mass.

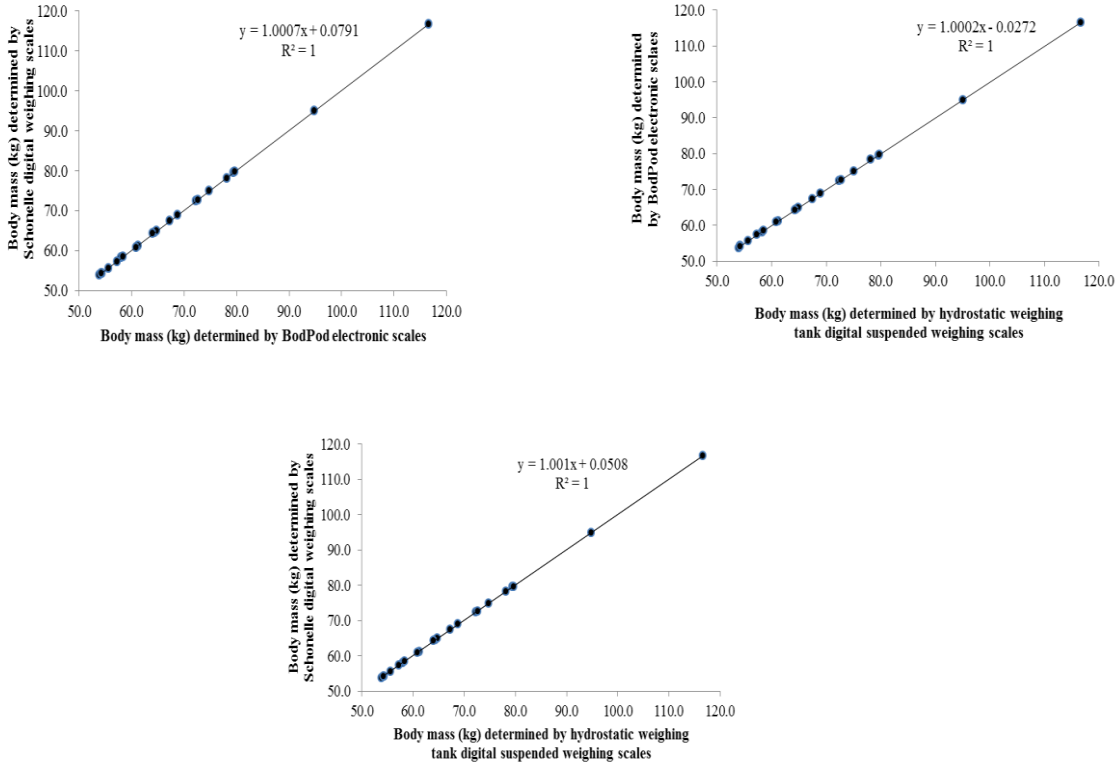

Figure 3.3 Scatter plots for the linear relationship between body mass determined by the Schonelle digital weighing scales and the BodPod electronic scales; between the BodPod electronic scales and the hydrostatic weighing tank digital suspended weighing scales and between the Schonelle digital weighing scales and the hydrostatic weighing tank digital suspended weighing scales measures

Inspection of Figure 3.3 did not show any deviation from the line of identity between the body mass values. Consequently there were linear relationships between the three body mass measures, although this linear relationship was expected given that they are measuring the same variable. Therefore, further investigations were needed to determine the agreement between the three different methods of body mass. Bias, random variation and 95% limits of agreement approaches were used, as illustrated in Figure 3.4 and summarised in Table 3.2.

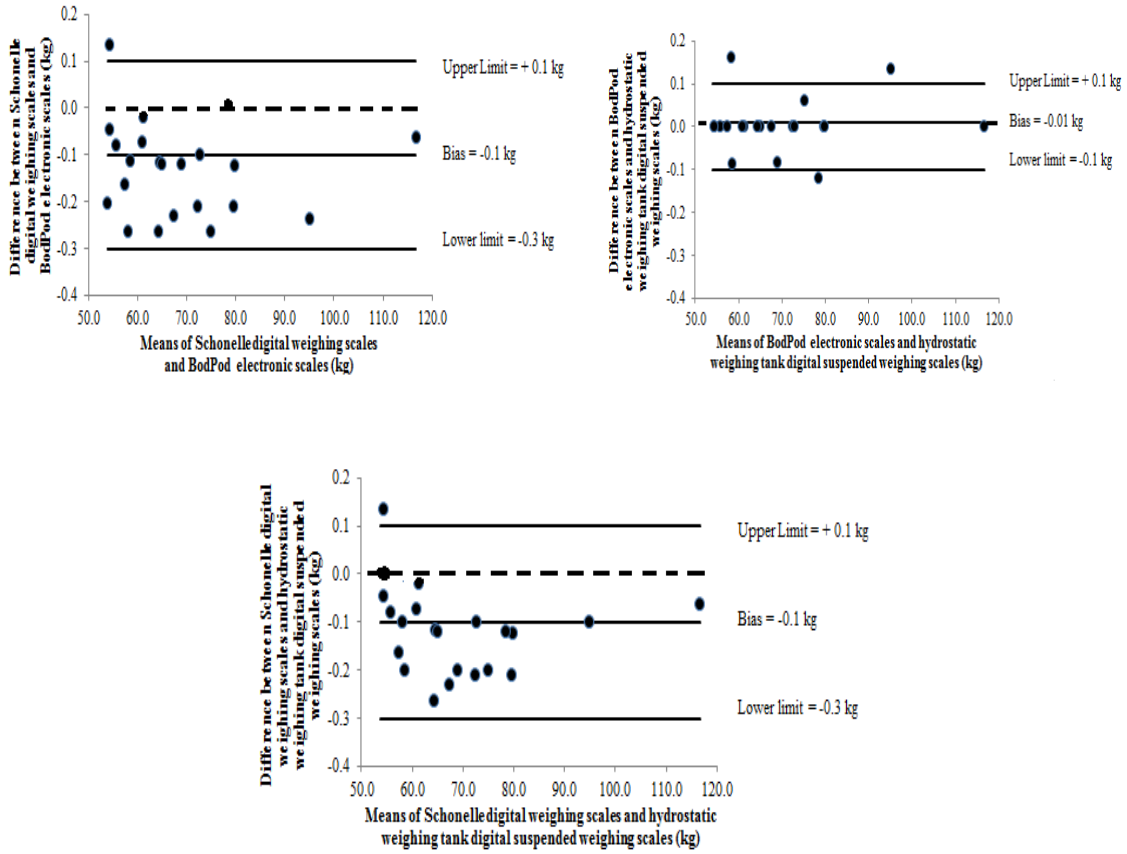

Figure 3.4 Bland and Altman plot showing bias and 95% limits of agreement for the Schonelle digital weighing scales and the BodPod electronic scales; between the BodPod electronic scales and the hydrostatic weighing tank digital suspended weighing scales and between the Schonelle digital weighing scales and the hydrostatic weighing tank digital suspended weighing scales measures (kg)

Table 3.2 Bias (kg) and 95% limits of agreement (kg) between the three body mass measurements techniques

Body mass measurement comparisons	Bias	(95%) Lower Limit	(95%) Upper Limit
Schonelle digital weighing scales and BodPod electronic scales (kg)	-0.1	0.1	-0.3
BodPod electronic scales and hydrostatic weighing tank digital suspended weighing scales (kg)	-0.01	0.1	-0.1
Schonelle digital weighing scales and hydrostatic weighing tank digital suspended weighing scale (kg)	-0.1	0.1	-0.3

Evidence from Figure 3.4 and Table 3.2 indicated there was a bias of -0.1, -0.01 and -0.1 kg for the Schonelle digital weighing scales, the BodPod electronic scales, and the hydrostatic weighing tank digital suspended weighing scales and limits of agreement of 0.1 to -0.3, 0.1 to -0.1 and 0.1 to -0.3 kg respectively. If a new participant from the pilot investigations population (not one from the n = 22 sample) measured 72.0 kg for body mass there is a 95% probability that when measured using the Schonelle digital weighing scales, the BodPod electronic scales and the hydrostatic weighing tank digital suspended weighing scales body mass can be estimated as low as 72.0 kg – 0.1 = 71.9 kg to as high as 72.0 kg + 0.3 = 72.3 kg; 72.0 kg – 0.1 = 71.9 kg to as high as 72.0 kg + 0.1 = 72.1 kg and 72.0 kg – 0.1 = 71.9 kg to as high as 72.0 kg + 0.3 = 72.3 kg respectively.

Investigation Implications

The findings from investigation A show agreement between the three separate body mass measurements (± 200 g at most) and bias was modest (130 g at worst), with the best agreement was between the BodPod electronic scales and the hydrostatic weighing tank digital suspended weighing scale. Furthermore, the BodPod electronic scales have the highest resolution. It was therefore concluded that the BodPod electronic scale would be the measurement approach of choice for determination of body mass in air.

3.8.2 **Investigation B:** Agreement between methods to determine procedure for maximal exhalation during hydrostatic weighing

Investigation context

Hydrostatic weighing can be demanding on the participant even after an initial period of familiarisation (Jackson & Pollock, 1977; Demura *et al.,* 2002; Slater *et al.,* 2006). For instance, the weighing procedure requires the participant's cooperation whilst totally submerged in water (Jüurimäe *et al.,* 1992; Demura *et al.,* 2002). Being submerged can be a daunting experience for participants, particularly as they are required to exhale maximally whilst keeping as still as possible in a crouched seated position (Katch & Katch, 1980; Jüurimäe *et al.,* 1992). These procedural difficulties were reported by Jüurimäe *et al.,* (1992), Demura *et al.,* (2002) and Slater *et al.,* (2006) who suggested that some participants were unable to maximally exhale due to uncertainty, and in some cases apprehension, induced by the required technique. In other words, this apprehension can result in the deliberate retention of surplus air in the lungs, thereby influencing measurement results, making collected data unreliable.

The ability of the primary investigator to achieve complete compliance should improve the criterion validity of the hydrostatic weighing procedure (Jüurimäe *et al.,* 1992; Demura *et al.,* 2002; Slater *et al.,* 2006). Hence, the requirement for complete compliance has resulted in researchers using various body positions and breathing manoeuvres that improve comfort and reduce apprehension for participants. Therefore, the aim of the investigation B was to compare two commonly used exhalation techniques for the hydrostatic weighing procedure.

Investigation design

Participants undertook two separate hydrostatic weighing technique trials in a cross-over order with five minutes break between each trial. One trial involved a 'pre-submersion exhalation' technique and the other trial involved a 'post-submersion exhalation' technique, with each trial comprised of ten attempts at the technique. For both trials participants sat in an upright position, applied a nose clip and held the ropes of the hydrostatic weighing weight tank seating system. They were submerged to chin level via a hydraulic hoist that was operated by the primary investigator. Rest intervals between each measurement attempt were given at the discretion of the primary investigator dependent on whether the participant felt able to repeat the measurement.

Pre-submersion exhalation technique

The rate of breathing for each participant was called by the primary investigator and comprised of three cycles of normal inhalation and exhalation. On the third cycle the primary investigator asked the participant to take a maximal inhalation immediately followed by a maximal exhalation. The participant was then instructed to blow out maximally just below the surface of the water to avoid temptation of inhalation prior to submerging the head. When the participant felt that they could no longer force any more air out of their lungs, they were instructed to submerge their head fully and keep as still as possible underneath the water. Once submerged, the primary investigator took the measurement of the participant's body mass in water (kg) from the wall mounted digital weighing scale adjacent to the hydrostatic weighing tank. Following the measurement reading, the primary investigator rapped loudly on the side of the tank thereby instructing the participant to return to the surface.

Post-submersion exhalation technique

Participants were asked to initiate their own breathing rate and when ready, take a small inhalation, lean forwards and submerge themselves fully. Once underwater and keeping as still as possible the participant exhaled maximally. The primary investigator watched for the ending of exhalation bubbles and took the measurement of the participant's body mass in water (kg) from the wall mounted digital weighing scale adjacent to the hydrostatic weighing tank. Following the measurement, the primary investigator rapped loudly on the side of the tank instructing the participants to return to the surface. The agreement between the average underwater weight (from ten attempts) for each participant across both measurement techniques was illustrated in the form of a scatter plot (Figure 3.6). The bias, residual error and heteroscedasticity between the two techniques are illustrated in Figure 3.7 to determine whether significant differences (under-reporting) were evident between the exhalation techniques.

Investigation results

Results from the pre-submersion exhalation technique revealed that four participants were unable to successfully carry out a single attempt and the remaining participants were only able to complete a mean average of four hydrostatic weighing attempts. Participant's claimed that this technique was uncomfortable and stressful, thereby questioning the usefulness of this measurement. Conversely, the primary investigator found that all participants using the post-submersion exhalation technique were able to perform a mean average of nine Hydrostatic weighing attempts.

All participants albeit subjectively, claimed that this measurement was far more comfortable. When comparing body mass in water values between the two exhalation

techniques, results indicated systematic bias (lower value for post-submersion technique). There was a significant difference in body mass values between pre-submersion technique (Mean ± SD = 2.6 ± 1.2 kg) and post-submersion technique (2.2 ±1.1 kg), $t_{21} = 4.19$ $P < 0.01$ (Figures 3.5 and 3.6).

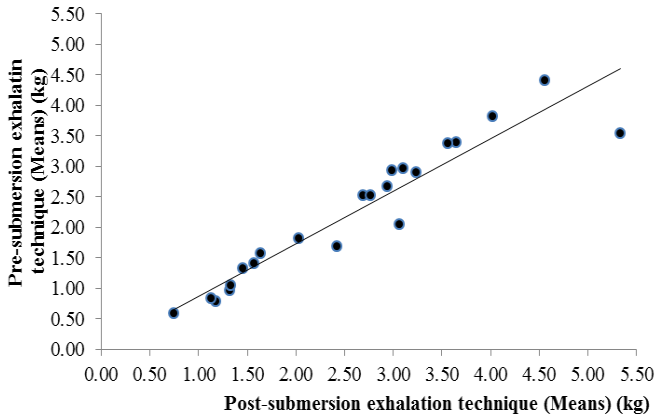

Figure 3.5 Comparison of pre-submersion and post-submersion exhalation techniques for hydrostatic weighing

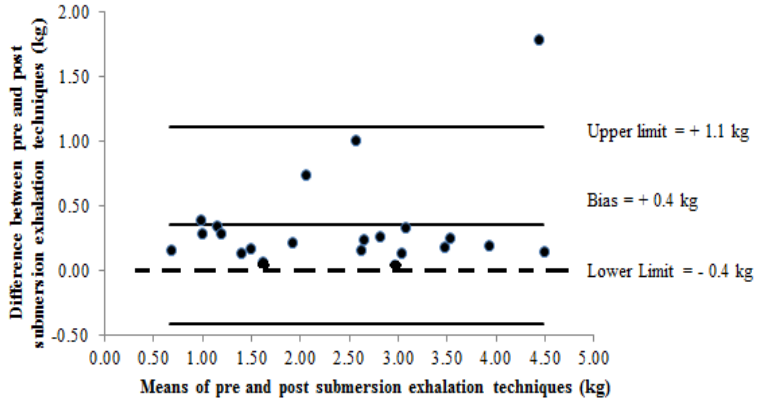

Figure 3.6 Bland and Altman plot showing bias and 95% limits of agreement for the pre-submersion and post-submersion exhalation techniques for hydrostatic weighing
Note: positive bias indicates lower values for post-submersion technique

Investigation implications

The post-submersion exhalation technique was associated with less apprehension, greater comfort and reduced water disturbance than the pre-submersion method, thus resulting in more reliable values for underwater weight. Since higher values for underwater weight are a reflection of more a complete exhalation cycle, it was decided that the post-submersion exhalation technique was the preferred technique for all future testing in the present thesis.

3.8.3 Investigation C: Number of underwater measurement attempts needed to determine average body mass in water

Investigation context

Reports from previous research have alluded to many issues that can arise with consecutive hydrostatic weighing attempts that are needed to determine average body mass in water (Brodie, 1988; Katch & Katch, 1980; Demura *et al.,* 2002; Slater *et al.,* 2006). An issue often referred to in this procedure is the assumption that there is systematic bias associated with successive attempts at hydrostatic weighing (Demura *et al.,* 2002; Slater *et al.,* 2006). Such effects can be accounted for by researchers, by implementing practice attempts before any measurements are recorded.

The opportunity for the participant to experience what is expected of them (orientation) during the testing procedure provides the primary investigator with a more reproducible value of body mass in water (Jüurimäe *et al.,* 1992; Slater *et al.,* 2006). Another contentious issue relates to the number of measurement attempts from which the average underwater weight is derived. A primary investigator would typically select three similar values from a series of values from which to determine an average underwater weight, with higher values known to be most reliable (participant's weighing more in water after

maximal exhalation). As such, research by Katch (1969), Behnke and Wilmore (1974), Brodie (1988), Jüurimäe *et al.,* (1992), Demura *et al.,* (2002) and Slater *et al.,* (2006) have suggested that a max10 attempts are enough as a participant's ability to expire maximally can deteriorate through fatigue with excessive efforts.

Researchers must therefore strike a balance; too few attempts can result in substantial bias towards underestimation of body mass whilst too many attempts might not be representative of the real or true underwater weight (Katch, 1969, 1980; Behnke & Wilmore, 1974; Demura *et al.,* 2002; Slater *et al.,* 2006). In contrast, evidence by Katch (1969 and 1980), Behnke and Wilmore (1974) and Brodie (1988) have suggested that the most efficacious protocol to adopt is to disregard the first two attempts and latter attempts (typically ninth and 10^{th}) mainly due to systematic bias (under-reporting). However, this notion is not supported by other researchers, who claim that a practice protocol (orientation) will avoid unnecessary weighing attempts and eliminate the need to disregard values (Brodie, 1988; Jüurimäe *et al.,* 1992; Demura *et al.,* 2002; Slater *et al.,* 2006). Therefore, the link between an orientation protocol and the number of hydrostatic weighing attempts continues to be of on-going concern amongst Kknanthropometrists and as such is the focus of the investigation C. Specifically, the aim of investigation C was to determine the optimal approach to reveal the average underwater weight value of a participant.

Investigation design

Participants were informed that they should initiate their own breathing rate and when ready, they were to take a small inhalation, lean forwards and submerge themselves fully. Once underwater and keeping as still as possible the participant was to exhale maximally.

The primary investigator watched for the ending of exhalation bubbles and took the measurement of body mass in water (kg) from the wall mounted digital weighing scale adjacent to the hydrostatic weighing tank. The primary investigator then rapped loudly on the side of the tank which instructed the participant to return to the surface. Participants were asked to complete a maximum of 10 hydrostatic weighing attempts as illustrated in Figure 3.7

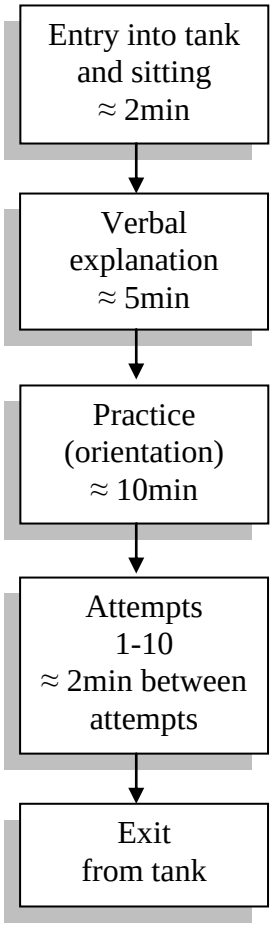

Figure 3.7 Hydrostatic weighing protocol

Investigation results

The average underwater weight values taken from the first two attempts (underwater weighting attempt A = A_1) A_1 vs A_2 revealed a small difference of 0.2 kg (See Figure 3.8). However, compared to the higher values forthcoming in A_4, A_5, and A_6, A_1 and A_2 were clearly underreporting by as much as 0.4 kg (Figure 3.8). This underreporting was likely due to participants retaining surplus air in their lungs during exhalation, despite the inclusion of a (≈ 10mins) orientation protocol.

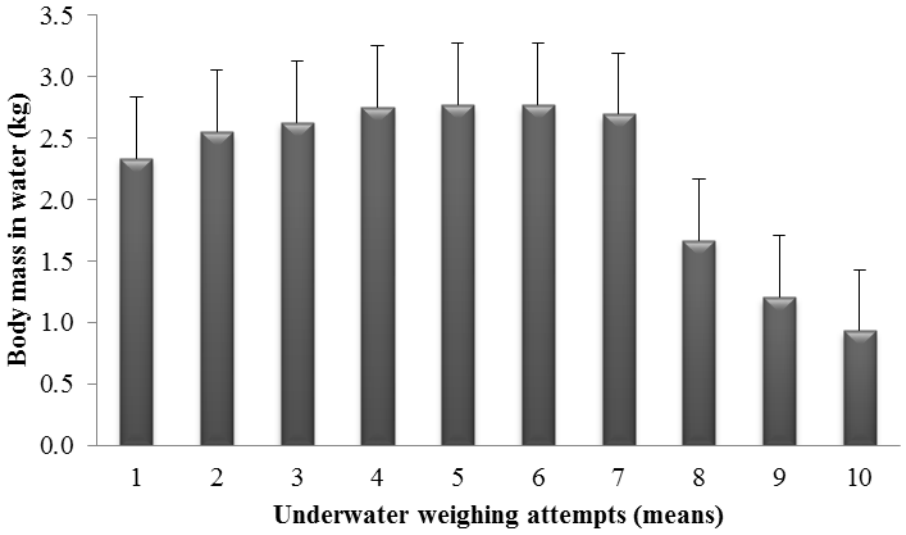

Figure 3.8 Hydrostatic weighing attempts

The fourth, fifth and sixth weighing attempts yielded comparable values where: $_{A4}$ vs $_{A5}$, A_5 vs A_6, A_4 vs A_6 revealed very small differences of 0.01 kg, 0.0 kg and 0.1 kg respectively (Figure 3.8). They also provided the primary investigator with the highest underwater weight values, indicating that these attempts gave results closer to the 'true' underwater weight. A_3 and A_7 attempts were similar in agreement, but they differed slightly from values from attempts A_4, A_5 and A_6 by 0.1 kg and 0.1 kg (See Figure 3.8). The final three attempts (A_8, A_9 and A_{10}) were also lower than proceeding attempts with

values underreporting by as much 1.8 kg. This is not surprising since participants reported that they might have retained surplus air in their lungs during exhalation (See Figure 3.8) (Withers *et al.,* 1987; Demura *et al.,* 2002 and Slater *et al.,* 2006). Even though adequate rest (≈ 2mins) was allowed between attempts, fatigue appeared to be become a factor during the latter attempts.

Investigation Implications

The primary investigator established that the first two attempts (A_1 and A_2) and the last three attempts (A_8, A_9 and A_{10}) at hydrostatic weighing underreported body mass in water. This finding was likely due to participants retaining surplus air in their lungs during exhalation, even though the primary investigator conducted an orientation protocol and there was adequate rest allocated between attempts to minimise fatigue. Results indicated that the A_4, A_5 and A_6 hydrostatic weighing attempts gave the primary investigator higher body mass in water (kg) values and a thereby closer estimation of the 'true' body mass in water. A_3 and A_7 were useful but they were not dissimilar to the highest values found in A_4, A_5 and A_6 although they were known to be slightly underreported.

In conjunction with recommendations made by Behnke and Wilmore (1974), Katch (1980), Withers *et al.,* (1987), Brodie (1988), Demura *et al.,* (2002) and Slater *et al.,* (2006) the primary investigator concluded that the first two attempts and the last three attempts would not be used to determine the mean underwater weight value in the present thesis as they are all known to be underreported. In conclusion, the fourth, fifth and sixth hydrostatic weighing attempts would be those used to calculate average body mass in water in the present study. The values from these attempts demonstrated very small between-attempt differences and the highest values of hydrostatic weighing, suggesting

therefore that participants were more likely to have maximally exhaled thereby providing the closest estimation of a 'true' underwater weight. Although not ideal, the third and seventh attempts could be used but only if the primary investigator was unable to obtain the three highest values from the fourth, fifth and sixth attempts.

3.8.4 **Investigation D:** Linearity of the scale for mass and volume within the BodPod

Investigation Context

As part of the quality assurance process, the BodPod was rigorously tested by the manufacturers, Life Measurement, Inc., to establish accuracy, reliability and linearity for both volume and mass measurements (Dempster & Aitkens, 1995; Life Measurement Inc., 2008). These quality assurance processes are undertaken by the manufacturer before installation of the BodPod, where multiple tests of 20 kg, 40 kg, 60 kg and 80 kg masses and 30 l, 50 l and 90 l volumes are conducted (Life Measurement Inc., 2008). However, in order to maintain the accuracy of the BodPod on a day-to-day basis, further quality control procedures are required *in situ* (Life Measurement Inc., 2006). These quality control procedures consist of a mass and volume calibration which are conducted before every testing bout and are designed to check the linearity and reliability of the BodPod system (Life Measurement Inc., 2006). These calibration techniques are executed following the manufacturer's recommendations and thus require the primary investigator to perform sequential steps without interruptions using equipment provided by Life Measurement, Inc. (Lockner *et al*., 2000). The calibration equipment included supplied two 10 kg calibration National Institute of Standards and Technology (NIST) weights that are used on the digital weighing scale to calibrate mass (Plate 17 – 18) and a 50.110 l calibration cylinder that is used within the BodPod chamber to calibrate volume (Plate 19 – 20).

Given the low mass calibration weight and the single point calibration for volume, in order to critically and independently review the suggestion from Dempster and Aitkens (1995) and Life Measurement Inc., (2008) that the BodPod is rigorously calibrated, the primary investigator sought permission to have access to the manufacturer's quality assurance data for linearity of mass and volume scales. Regrettably Life Measurement, Inc. was unwilling to grant the primary investigator access to their data for further independent analysis (Appendix W). Therefore, given the central importance of accurate estimation of body mass and body volume in determining body composition, and the single point calibration volume in particular, the aim of investigation D was to further examine the calibration approaches and to independently determine both the linearity and reliability of mass and volume measurements throughout the potential measurement range.

Investigation design

Measurement procedure for mass

Following the routine mass calibration procedure, the primary investigator was able to sequentially add known (actual) calibration masses ranging between 10 kg to 30 kg. Although not ideal, given the likely range of measurements in practice, the relationship between actual and predicted mass could be plotted (0 – 30 kg) and extrapolated linearly to likely measurement values within a realistic range.

Measurement procedure for volume

Following the routine volume calibration procedure where calibration is repeated if two of the five mean volume measures are not between 49.900 l and 50.100 l (Life Measurement Inc., 2008). The primary investigator was able to sequentially add up to ten known (actual) volumes corresponding to 118.40 l (i.e., 11.84 l, 23.68 l, 35.52 l, 47.36 l, 59.20 l, 71.04 l,

82.88 l, 94.72 l, 106.56 l and 118.40 l). The known volumes were established using balloons that were each inflated with 12 l of air using a Morgan Medical 3 l calibration syringe (Ferrari's Cardio Respiratory Ref 0413, Morgan Medical Ltd, Rainham, Kent, England) (i.e., 4 x 3 l = 12 l volume of air into each balloon). Unfortunately due to the practicalities of the inflation procedures, releasing of the syringe and tying of each balloon resulted in χ 0.16 l of air being lost. Each balloon was verified as having a known volume of 11.84 l through the normal BodPod calibration process of five volume measurements in succession (as previously described).

A scatter plot of actual (known) against predicted (measured) mass values was produced to illustrate the agreement between the predicted mass and actual mass measures and extrapolated between 40 to 120 kg (Figure 3.9). Figure 3.10 illustrates the agreement between the actual (known) against predicted (measured) volume values and the linearity through the likely (practical) measurement range. The bias and 95% limits of agreement between the actual (known) against the predicted (measured) volumes are illustrated in Figure 3.11. Paired *t*-tests were undertaken to determine whether significant differences were present between the known and measured volumes.

Investigation results

Results revealed that for all mass measurements between 10.00 – 30.00 kg the known mass and measured mass were in agreement (Figure 3.9). Furthermore, measures of mass between 40.00 – 120.00 kg extrapolated (Figure 3.10) to estimate the value of masses outside the range tested.

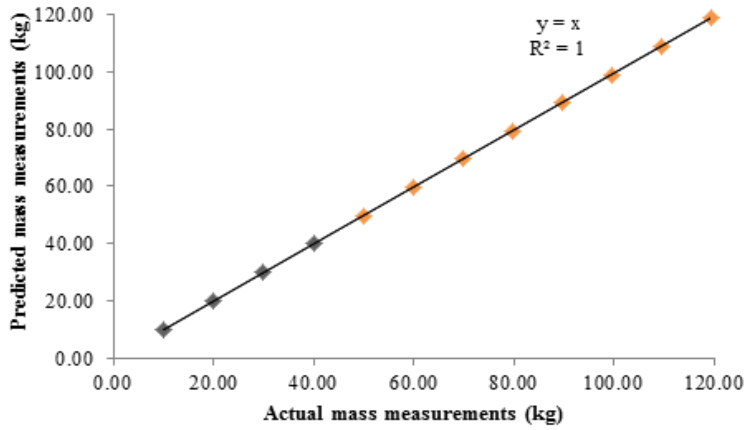

Figure 3.9 Actual (known) versus predicted (measured) mass (◆) and extrapolation (◆) for the BodPod through the likely measurement range
Note: Extrapolated from 40.00 – 120.00 kg

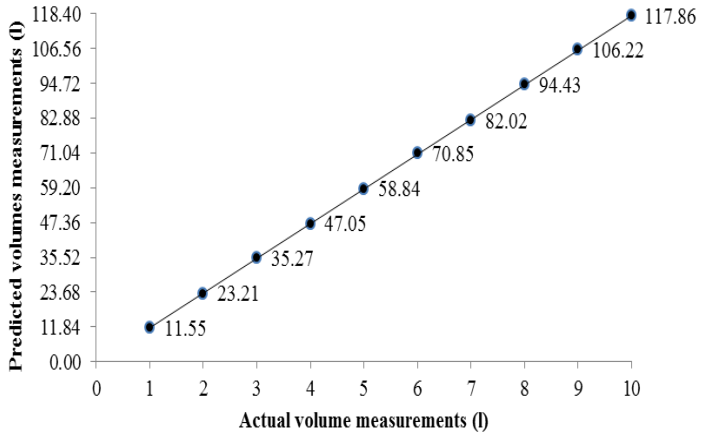

Figure 3.10 Actual (known) and predicted (measured) volumes from the BodPod through the likely measurement range

Results revealed that for all volume measurements, the predicted (measured) volume differed from the actual (known) volume by as little as 0.2 l and as much as 0.9 l (Figure 3.10). When comparing the agreement between the actual (known) volumes against the predicted (measured) volumes, results indicated systematic bias whereby the predicted (measured) volumes were underreported compared with the actual (known) volumes (Figure 3.11). There was a difference between actual (known) ($\bar{x} \pm s$ = 65.1 ± 35.9 l) and predicted (measured) (64.7 ± 35.8 l), $t_9 = 6.35$ $P < 0.01$.

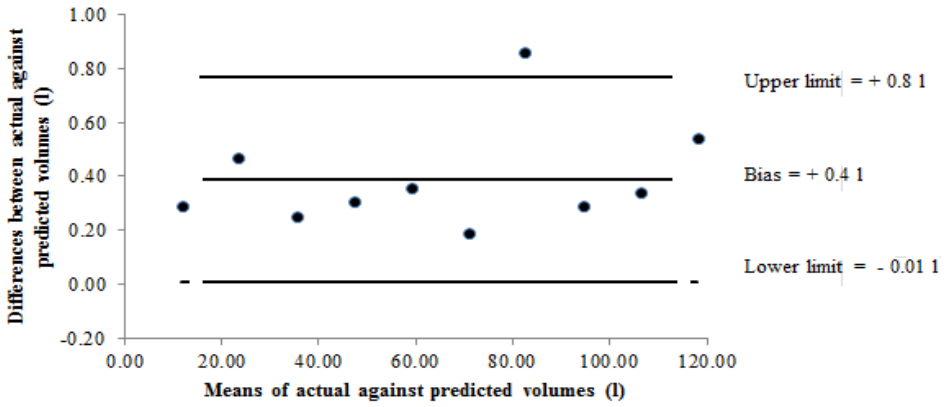

Figure 3.11 Bland and Altman plot showing bias and 95% limits of agreement between the actual (known) against the predicted (measured) volume for BodPod
Note: A positive bias indicates higher actual (known) values in relation to the predicted (measured) values

Investigation Implications

With regards to mass, one might question the relevance of only being able to calibrate a measurement tool to a maximum of 30 kg, especially when the body mass of participants are certainly in excess of 30 kg (participants ranged between 60.1 kg – 104.3 kg), however, calibration masses from 10.00 – 30.00 kg were in agreement. Similarly, the accuracy and linearity of the volume scale is measured within the BodPod system at 30 l, 50 l and finally 90 l, yet Life Measurement Inc only provide a 50 L calibration cylinder. Results from the adapted volume calibration trial using balloons revealed underreporting of predicted (measured) volumes by 0.4 l, which slightly exceeds the Life Measurement Inc., recommended calibration range between 0.01 – 0.21 l. It is unfortunate that there is no facility for the primary investigator to test the BodPod for the linearity of the mass and volume scale with increased rigour. However, on the basis of the present investigations, involving a reasonable level of rigour, it is possible to be broadly confident in the measurement outcomes from the BodPod.

3.8.5 **Investigation E:** Agreement between methods to estimate lung gas volume

Investigation context

Although it is impossible to determine total lung volume practically, residual volume in the lungs following maximal exhalation has been commonly used as an estimation of thoracic volume (Nunez *et al*, 1999; Dewitt *et al*., 2000; Lockner *et al*., 2000; Van Der Ploeg, 2000; Fields *et al*., 2002; Heyward and Wagner, 2004; Pesola *et al*., 2004). Even residual volume requires estimation rather than direct measurement, and the estimation methods vary considerably in complexity (Mathur *et al*., 1990; Quanjer *et al*., 1993; Pesola *et al*., 2004; Demura *et al*., 2006). For example, 'gold standard' criterion methods involve the dilution of inert gases within the residual volume, and require the use of complex algorithms with some assumptions (see Chapter 2.5) (Crapo *et al*., 1992; Stocks & Quanjer, 1995; Demura *et al*., 2007). Practically, therefore, many studies have used alternative estimation techniques, including application of regression equations following spirometry measurement (spirometry method), application of regression equations following panting manoeuvres (panting method) and general predictive equations based on age, gender, ethnicity, body mass and stature (prediction method) (Mathur *et al*., 1990; Quanjer *et al*., 1993; Pesola *et al*., 2004).

The aim of investigation E was therefore to explore the agreement between a spirometry method (Quanjer *et al*., 1993; Pesola *et al*., 2004; Demura *et al*., 2006), a panting method (Nunez *et al*, 1999; Dewitt *et al*., 2000; Lockner *et al*., 2000; Fields *et al*., 2002) and a prediction method (Donnelly *et al*., 1991; Crapo *et al*., 1992; Stocks & Quanjer, 1995; Demura *et al*., 2006, 2007).

Investigation design

In order to examine the agreement between different methods of estimation of residual lung volume, the required measurements were made using procedures described in Appendix Q. The data required included age and stature (for the 'prediction' method), together with forced vital capacity (FVC) (for the 'spirometer' method) and the result of the panting procedure (for the 'panting' method).

The prediction equation was:

LV_{pred} (l) = 0.410 x (stature (cm)) – (0.210 x age (years)) – 26.31

Where: LV = lung volume

(Crapo *et al*., 1982)

The spirometry equation (for males) was:

LV_{spir} = FEV (BTPS) (l) x 0.24

Where: LV = lung volume; FVC = Forced expired volume; BTPS = body temperature and pressure saturated

(Sinning, 1975)

The panting equation was:

(LV_{pant} = (TV/2 (l) + FRC (L)

Where: LV = lung volume; TV = tidal volume; FRC = functional residual capacity

(Life Measurement Inc., 2006)

The linear relationship and agreement between the three estimation methods was illustrated by constructing scatter plots showing deviation from the line of identity and by applying the 95% Limits of Agreement (LoA) method to quantify the bias, random variation and heteroscedasticity (see Figures 3.12 – 3.13).

Investigation results

Scatter plots are provided for illustrative purposes to demonstrate the linear relationship between the three separate measures of lung gas volumes (Figure 3.12).

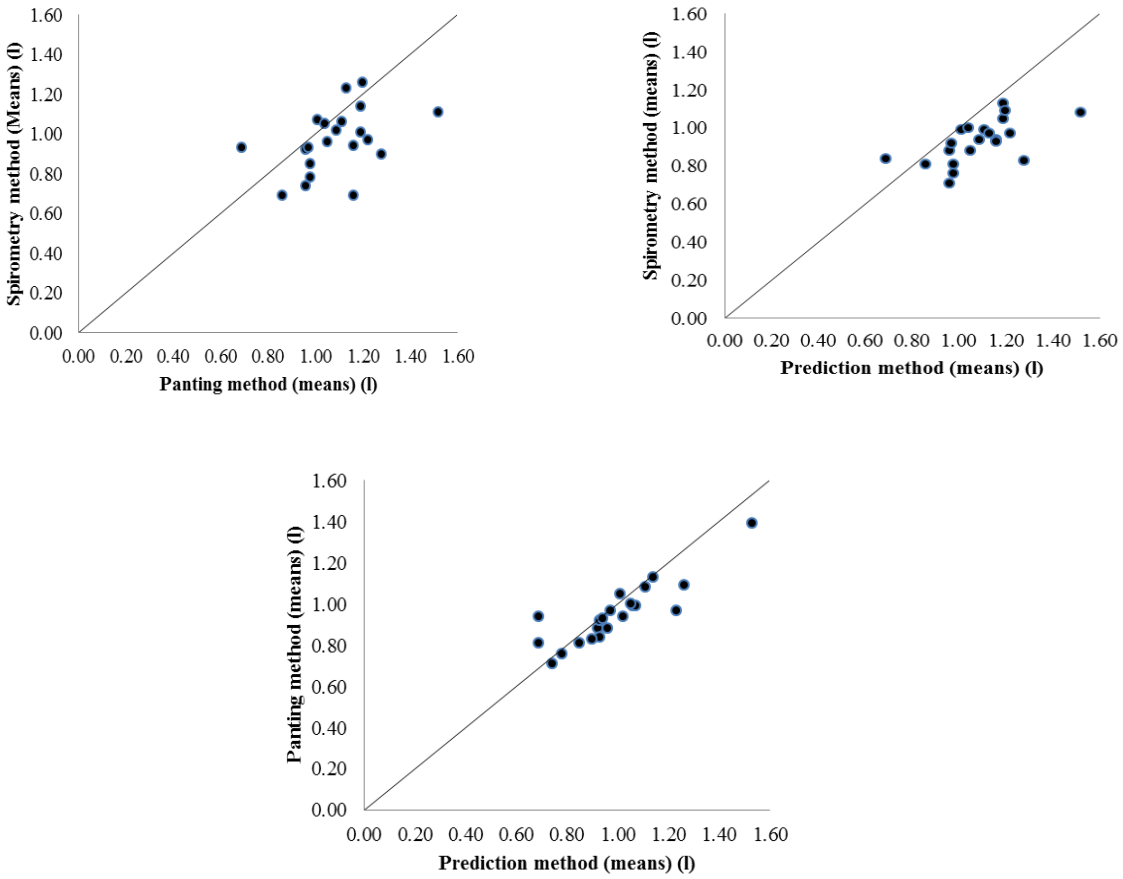

Figure 3.12 Comparison between spirometry and panting methods; spirometry and prediction methods and panting and prediction methods for estimating lung volumes (l)

Inspection of Figure 3.12 did show some deviation from the line of identity between the three lung volumes measures. Consequently, there were linear relationships between the three lung volume measures, although this linear relationship was expected given that they are measuring the same variable. Therefore, further investigations were needed to determine the agreement between the three different estimation methods of lung volumes. Bias, random variation and 95% limits of agreement approaches were used, as illustrated in Figure 3.13 and summarised in Table 3.3.

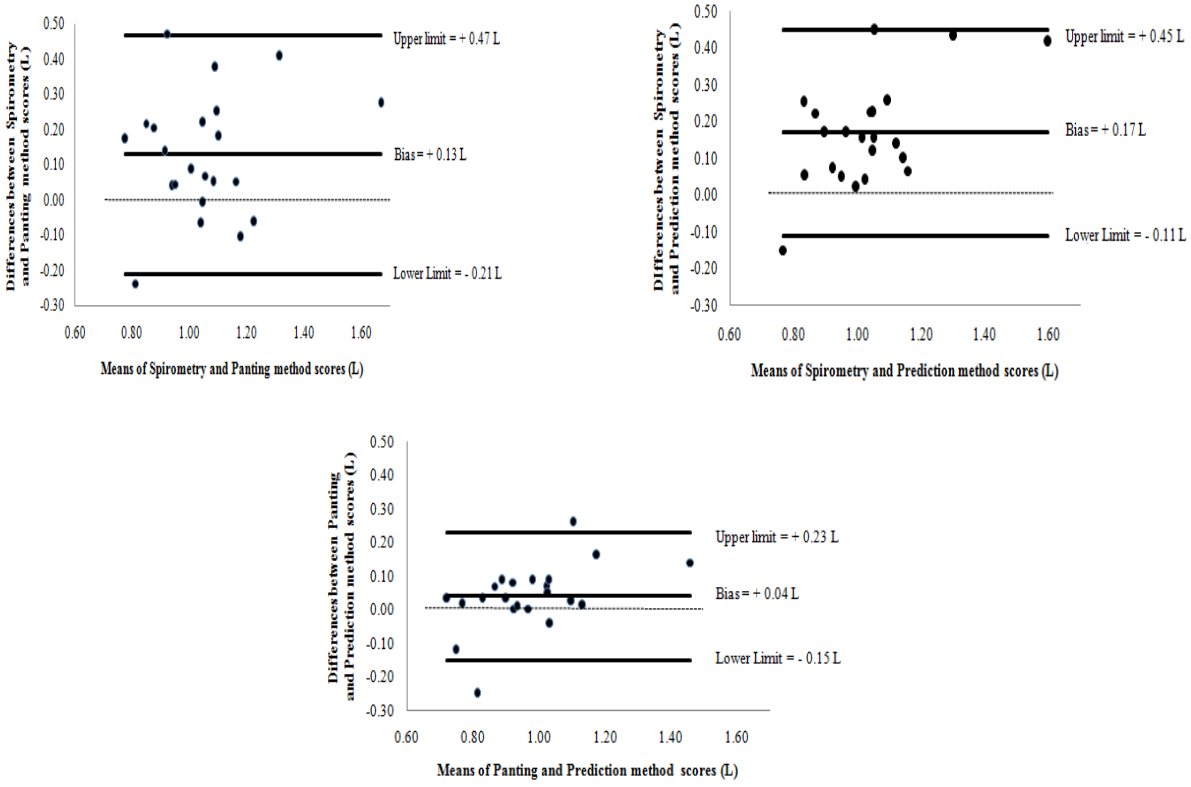

Figure 3.13 Bland and Altman plot showing bias and 95% limits of agreement for the spirometry and panting methods (note: direction of bias [panting – spirometry]); spirometry and prediction methods (note: direction of bias [prediction – spirometry]) and panting and prediction methods (note: direction of bias [prediction – panting]) for lung volumes (l)

Table 3.3 Bias and 95% limits of agreement (l) between the three lung volume estimation techniques

Lung volume estimation techniques	Bias	(95%) Lower Limit	(95%) Upper Limit
Direction of bias [panting – spirometry]	0.13	0.47	-0.21
Direction of bias [prediction – spirometry]	0.17	0.45	-0.11
Direction of bias [prediction – panting]	0.04	0.23	-0.15

Evidence from Figure 3.13 and Table 3.3 indicated there was a bias of 0.13, 0.17 and 0.04 l for the panting, spirometry and prediction estimation techniques and limits of agreement of 0.47 to -0.21, 0.45to -0.11 and 0.23 to -0.15 1 respectively. If a new participant from the pilot investigations population (not one from the n = 22 sample) measured 1.2 l for residual lung volume there is a 95% probability that when measured using the panting, spirometry and prediction estimation techniques estimation of residual lung volume can be estimated as low as 1.2 l – 0.47 = 0.73 l to as high as 1.2 l + 0.21 = 1.4l l; 1.2 l – 0.45 = 0.75 l to as high as 1.2 l + 0.11 = 1.31 l and 1.2 l – 0.23 = 0.97 l to as high as 1.2 l + 0.15 = 1.35 l respectively.

Investigation implications

The findings from investigation D show moderate agreement between the spirometry and panting methods and the spirometry and prediction methods for estimating lung volumes, however, agreement between the panting and the prediction methods (Figure 3.13) to establish lung volume. In addition, the bias was modest (0.17 l at worst), with the spirometry method giving lower values than both the predicted and the panting methods respectively. The best agreement (negligible bias and lowest limits of agreement) was

between the panting and the prediction methods (0.04 ± 0.19 l). Given the absence of a criterion measure and therefore no definitive answer provided regarding which method should be the one used in the present study, practical considerations were used to determine the method of choice in the present thesis. In brief, the panting method requires the use of the BodPod, whilst undertaking an unusual and sometimes problematic breathing technique. The prediction method is reliant on regression equations without practically measuring any lung volumes.

Consequently, because the spirometry method uses standard (and the simplest) techniques to determine lung volumes, and is the most widely used method within research determining whole body density from hydrostatic weighing, it was concluded that the spirometry method would be the measurement approach of choice for determination of lung volumes in the present thesis, and that comparison of findings with those from studies that used alternative methods should be treated with caution. In particular, studies which used the prediction and panting methods are likely to overestimate lung volumes and therefore underestimate whole body density.

3.9 Study overview and design

The studies comprising the present thesis are designed in a way to inform one another. Study 1 attempt to identify and quantify the primary investigator's measurement error, systematic bias, random variation, heteroscedasticity, reliability and precision in making 27 standard anthropometric measures used in calibration models to determine whole body density on professional football players. Once quantified, these 27 standard measures help inform Study 2, an investigation of the validity of 17 pre-published calibration models for the estimation of whole body density in men. These models are statistically analysed

comparing each to whole body density values derived using the hydrostatic weighing method in the sample. The agreement between measured values and those calibration models is estimated from and a judgement is made about their usefulness in the population. Once agreement is determined, Study 3 follows from the preceding studies, by reporting on the development and cross-validation of a new calibration model to predict whole body density in professional football players.

Chapter 4

Study 1

Measurement reliability

4.1 Introduction

It is well reported the importance of reliability and measurement error within sports science and it is not uncommon to encounter reliability issues ranging from equipment calibration to technical execution and repeatability (Gore, 2000; Perini *et al*., 2005). Reliability is magnitude of error recorded by a single rater in repeated trials under the same conditions on the same participant(s), and is sometimes referred to as precision, repeatability and reproducibility. There are two types of measurement reliability that are frequently encountered in sport science, namely relative reliability (consistency) and absolute reliability (accuracy) (Baumgartner, 1989). When estimating the impact of reliability on the outcome of a given measurement, the sport scientist has to appreciate how practical and suitable these measures are for further analyses or in the context of this thesis, for the development of calibration models (Atkinson, 2003). In other words, what the particular measurement error actually represents in practice.

Evidence has indicated that some anthropometric variables which are reproducible in calibration models. Subsequently establishing accuracy and reliability of anthropometric measures will enable to sport scientist to be confident in making sound judgements on each variable and whether they are as error free as possible (Gore, 2000; Perini, *et al*., 2005). Furthermore, if these measures have any detrimental effect when applying to a sample population, thereby providing confidence in a practical sense, to determine which variables should be included in the development of calibration models to estimate whole body density. Within sports science there could be a number of issues related to what implications poor reliability could have on collecting measurement data.

One of the most popular methods of statistical analyses involves the estimation of intra-observer reliability and is routinely referred to in methodological studies as the test-retest method (Gore, 2000; Hume & Marfell-Jones, 2008). The test-retest method involves repeating measures on the same participants under identical testing circumstances (Hopkins, 2000; Perini, *et al*., 2005). This method of obtaining reliability data is often used by anthropometric rater's when conducting studies on their own ability to measure anatomical variables consistently and accurately (Norton, 2002). When measurements are performed in this manner, neither the test nor the re-test will provide an unequivocally correct measure and are subject to some form of error (British Standards Institution, 1987). Incidences of error can generally be caused by measurement and biological variables such as gathering of data, human frailty, accuracy of measurement equipment and tools, biological variation of the participants and the ability, confidence and experience of the rater (Hopkins, 2000; Perini *et al*., 2005). Very often in sport science, sensitive electronic and mechanical equipment used for anthropometric measurement that was really developed to be used in clinical settings can often perform erratically in a physical activity setting and can therefore become a major source of error. The identification of the various sources of errors, can offer greater confidence in rater reliability (Gore, 2000).

One of the most common ways of expressing measurement reliability and which identifies various sources of error is Bland and Altman's 95% limits of agreement (Bland & Altman, 1986). Bland and Altman (2003) identified that in developing the 95% limits of agreement method, they would be able to identify and quantify the amount of agreement, that is the systematic bias, and the amount of random variation inherent in the measured data (Hopkins, 2000). In other words, it is possible for the rater to observe the extent to which there is error in their measures (Atkinson & Nevill, 1998; Thomas & Nelson, 2001).

More often than not, sport scientists' work with data measured on either an interval or a ratio scale. In such data it is common to observe a relationship between an increase in the magnitude of values and an increase in variability between values. This situation is known as heteroscedasticity. Bland and Altman (1986) maintain that heteroscedasticity can be visually detected and quantified by establishing whether a positive linear relationship exists (r_{XY}) between the absolute differences (errors/residuals) between test-retest values (Y) and the mean of the test-retest values (X) for each participant plotted on an XY scatter plot. The issue of heteroscedasticity is important here because when limits of agreement are calculated, there is an assumption that the original test or measurement data are in fact homoscedastic (the condition of equal residual variances) and that the limits of agreement will therefore remain constant throughout the range of measurements for which they were calculated.

Another appropriate statistical analysis that identifies various sources of error and measurement reliability in kinanthropometry is by means of the technical error of measurement (TEM) (Perini, *et al*., 2005; Stewart & Sutton, 2012). TEM is an index of absolute reliability and it can be used to represent test and retest values respectively on a particular measurement. These analyses are also adopted and reinforced by the International Society for the Advancement of Kinanthropometry (ISAK) for the accreditation of kinanthropometrist. ISAK accreditation is based on examination(s) and continuous practice to help minimise measurement error, where there is a four level hierarchy for accreditation and it is based on standardised anthropometric techniques where a rater must demonstrate landmarking, equipment manipulation and knowledge of a measurement profile (ISAK, 2001; Stewart & Sutton, 2012).

Without reliable measurements, it is impossible to use them within calibration models and would not support a sound foundation from which other studies in this thesis (Study 2 (Chapter 5) and Study 3 (Chapter 6) could be based (Perini *et al*., 2005). By identifying these various sources of error, through the central focus on the Bland and Altman 95% limits of agreement method (relative reliability) and TEM% (absolute reliability) on test-retest values of anthropometric measures, can potentially establish whether a range of error of this magnitude would have any detrimental effect on the practical use of values gathered with this population of participants and is therefore the main aim of this study.

4.2 Methods

4.2.1 Participants and recruitment

Two hundred and six Fédération Internationale de Football Association (FIFA) registered contracted professional football players ($\bar{x} \pm s$; age = 24.1 ± 5.4 years, body mass = 78.8 ± 8.4 kg, stretched stature = 180.1 ± 7.0 cm and whole body density = 1.075 ± 0.010 g ml^{-1}) were recruited from eight professional football clubs that represented Barclays Premiership, npower Championship, npower League One, npower League Two and Blue Square Premier Leagues during the 2007-2008, 2008-2009 and 2009-2010 playing seasons. Sampling included players who were all over 18 years of age, free from disease or illness and who agreed to act as participants for the study by giving their written informed consent. Signs and symptoms of disease and diagnosed disease were determined through health screening procedure involving completion of a health screening questionnaire. Ethical considerations were carried out using robust operational procedures as previously reported in Section 3.2.

4.2.2 Data collection procedures

Data collection procedures followed those described in Section 3.3 by an accredited International Society for the Advancement of Kinanthropometry (ISAK) Level One Kinanthropometrist (1.0 – 6.5 TEM%) (June 2006). In sport science research the amount of time allocated between administrations of the test and the retest in reliability studies is often dictated by how strenuous the test is to perform (MacDougall *et al*., 1991; McArdle *et al*., 1991). Although, generally this is not a primary consideration for anthropometric protocols, it is important that the time between assessments should be long enough that changes in the compressibility of the skinfold does not occur (Baumgartner & Jackson, 1987; ISAK, 2011). In addition, it is common practice within ISAK protocols to complete a full range of measurements before repeating the assessment for the second or third time (Hencken & White, 2006). This practice minimises the likelihood the primary investigator remembered values, thereby minimising potential rater bias. For the purpose of this reliability study, involved a trial-to-trial protocol with the same interval of time (≈ 15 - 20 mins) allocated between each assessment to provide the primary investigator with an index of internal consistency.

The following measurements were selected to offer a wide range of measures to investigate the test-retest reliability of the primary investigator's ability: stretched stature (cm); sitting height (cm); skinfold thicknesses (mm, n = 8); girths (cm, n = 10); breadths, depths and widths (mm, n = 6); underwater weighing (g ml^{-1}), residual lung volume (l) (estimated from forced vital capacity) and air displacement plethysmography (body mass (kg) and body volume (l)). Stretched stature and sitting height measurement procedures followed those described in section 3.7.1. Skinfold thickness, girths, breadths, depths and widths testing procedures followed those described in section 3.7. All measurements were taken

systematically and on the right hand side of the body for all participants. After measurements were taken, the mean value was determined for subsequent data analysis. Hydrostatic weighing procedures followed those described in section 3.4. From a reliability point of view, underwater weight readings from attempts 1, 2 or 10 were not used (see Section 3.8) (Katch, 1980). Forced vital capacity (FVC) testing procedures followed those described in section 3.6. Participants were given a minimum of three attempts to record an acceptable FVC measure and to obtain their best value. The greatest value was then corrected for body temperature and pressure saturated (BTPS) determined by using a correction table (Appendix L) (Sinning, 1975). Residual lung volume was estimated by taking a constant fraction of each participant's FVC and was expressed to the nearest 0.05 l and computed using the equation proposed by Sinning (1975). The air displacement plethysmography measurement protocol was rigorously followed with step-by-step instructions displayed by the BodPod computer system (see section 3.5). During the assessment, participants were instructed to continue breathing normally whilst a minimum of two 50s tests were conducted to ensure consistency (Biaggi *et al*., 1999). Once the assessments were completed, derivation of body volume, correction for residual lung volume together with measurement of body mass, permitted this derivation of an estimate for body density (Dempster & Aitkens, 1995; Biaggi *et al*., 1999).

4.3 Statistical analyses

Summary results (mean, standard deviation and range) are presented for all participants and measurement values cited in the proceeding sections were calculated via Microsoft Office Excel (version 2010). The reliability of all directly measured variables was investigated by applying the 95% limits of agreement (LoA) method (relative reliability). This method relies on the assumptions that the $\bar{x}$ and s of the differences between test and

re-test scores are constant. As it is a parametric method, it is also predicated on the assumption that the differences between the test and re-test values follow a normal distribution in the population from which the sample were drawn (Bland & Altman, 1986; Atkinson & Nevill, 2001). Bland and Altman (1986) recommend that identification of the three components of agreement should be considered first and involves plotting the differences between test and retest values on the *Y*-axis and the mean of participants' test and retest scores on the *X*-axis of an *XY* scatter plot (see Figures 4.1 – 4.9). This plot has become known as a Bland and Altman plot and from which it is possible for the sport scientist to observe the three components of agreement i) the extent to which there is systematic bias, ii) the extent to which the bias is influenced by random variation, and, iii) the condition of unequal residual variance (see Table 4.8). At this stage it is important to consider that the raw values (original test-retest values) do not need to be normally distributed in this population but the differences between these values do. Additional interpretation can be used at this point to provide visual evidence of heteroscedasticity.

Quantification first supports this identification of the extent of systematic bias in the collected anthropometric data from the mean of the differences between test-retest values, for each participant ($\bar{x}_{diff}$). Random variation between test-retest values is related to the standard deviation of the differences and provided the differences are confirmed as being normally distributed in the population form which the sample was drawn can be expressed to a 95% probability – 1.96 x (s_{diff}). The extent to which heteroscedasticity is present in these values can be quantified by correlating absolute differences against mean values for test-retest measures and can be illustrated on a scatter plot of these two variables (see Figures 4.10 – 4.18). The scatter plot included the slope of the best-fit line, R^2, *r* and *P* values and the distribution line to allow a visual overview of the linear relationship

between the absolute differences and means values (see Table 4.9). Within kinanthropometry the TEM% is often expressed relatively as a percentage and can be used to generate 68% or 95% bands of tolerance, thus providing an objective method to evaluate the competency of a rater (Klipstein-Grobusch *et al*., 1997; Gore, 2000). In this case, the TEM% indicates that, when the error scores are normally distributed, 68.26% of the time, a measurement should come within ± the value of the TEM. Ross and Marfell-Jones (1991) and Norton (2002) suggest that TEM%s for skinfold thicknesses of ± 5% are acceptable, for breadths it is ± 1% and for other anthropometric measures it is ± 1.0%. TEM was used as an index of absolute reliability by establishing the degree of precision between the primary investigator against TEM% values established by a level 4 ISAK experienced kinanthropometrist (the criterion measurer) (absolute reliability). The degree of precision between two values generated by primary investigator against the criterion measurer as an index of inter-tester reliability and was calculated using a programmed Microsoft Office 1998 Excel spread sheet constructed by ISAK where TEM% = (TEM/ $\bar{x}_1$) × 100 ((Marfell-Jones, 1991; ISAK, 2001; Norton, 2002).

TEM% was obtained by comparing two measurement values on each anthropometric variable on a study sample of n = 20 participants from the current study sample for an ISAK level 1 accreditation. ISAK four levels of accreditation serve different purposes as illustrated in Table 4.1 and include: Level 1 – anthropometrist (technician – restricted measurement profile); Level 2 anthropometrist (technician – full profile); Level 3 anthropometrist (instructor) and Level 4 anthropometrist (criterion anthropometrist) (ISAK, 2001; Stewart & Sutton, 2012). It is important to highlight at this point that the primary investigator had not obtained ISAK level 2 accreditation but the data collected for level 1 accreditation was transferred for analysis purposes.

Table 4.1 Target inter- and intra-tester TEM%s for ISAK accreditation assessments

Level	Assessment	Skinfolds	Other measurements
1	Inter-tester (exam)	12.5%	2.5%
	Intra-tester (post-exam)	7.5%	1.5%
2-4	Inter-tester (exam)	5.0%	1.0%
	Intra-tester (post-exam)	5.0%	1.0%

(Adapted from ISAK, 2011 and Stewart & Sutton, 2012)

Anthropometric measurements included a comparison of *n* = 17 common variables against the level 1 ISAK criterion. These measures included *n* = 8 skinfold thicknesses (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, anterior thigh and medial calf); *n* = 5 girths (arm (flexed), arm (relaxed), waist, hips and calf); *n* = 2 widths (humerus and femur), body mass and stretched stature. Levels 2-4 reliability standards require more advanced technical expertise than those of level 1, where minimum requirements (post examination) involve a rater being able to prove that they can: i) repeat anthropometric measures with a TEM% better than ≤ 7.5% for skinfolds and ≤ 1.5% for girths, breadths and widths for level 1 accreditation and ≤ 5.0% for skinfolds and ≤ 1.0% for girths, breadths and widths for level 2-4 accreditation, and ii) establish the degree of precision between values generated by two kinanthropometrists, in this instance, the TEM% of ≤ 2.5% between the rater and the criterion as illustrated in Table 4.1 (Perini, *et al*., 2005). Further analyses were made against the level 2/3 ISAK criterion with the previous *n* = 17 measures and an additional *n* = 11 anthropometric measures (*n* = 28 in total), including *n* = 6 girths (neck, forearm, wrist, chest, thigh and ankle); *n* = 2 breadths (biacromial and biiliocristal); *n* = 2 depths (transverse chest and anterior-posterior chest) and sitting height.

The issue for the primary investigator was to judge, whether the identification and quantification of agreement outcomes were narrow enough for the anthropometric measures to provide practically reliable values. That is, whether a range of error of this magnitude would have any detrimental effect on the practical use of values gathered with this population of participants. Therefore the primary investigator established *a priori* consideration for both the Bland and Altman 95% LoA method (relative reliability) and TEM% (absolute reliability) that presented acceptable tolerable limits within the context of this study. Under review from ISAK (2001) and previous literature, the Bland and Altman 95% LoA method, *a priori* criteria was set at ± 3.8%, $P < 0.05$ (g ml^{-1}) and TEM% better than < 5.0% for skinfolds and < 1.0% for girths, breadths and widths as acceptable limits.

4.4 Results and discussion

Summary results for general characteristics of all n = 206 football players can be seen in Table 4.2 and Table 4.3 and illustrates a summary of all the participants' primary anthropometric measures. Results summarised in Table 4.2 indicate that participants were within an age range between 18 – 38 years which is typical of professional football players. With body mass, stretched stature and sitting height ranging from 59.3 – 104.3 (kg), 162.7 – 201.2 (cm) and 79.5 – 109.4 (cm) respectively, suggesting the requisites for a variety of football playing positions.

Table 4.2 General summary ($\bar{x} \pm s$) characteristics for (n = 206) football players

Variables	$\bar{x} \pm s$	**Range**
Age (yr)	24.1 ± 5.4	18.0 – 38.0
Body mass (kg)	78.8 ± 8.4	59.3 – 104.3
Stretched stature (cm)	180.1 ± 7.0	162.7 – 201.2
Sitting height (cm)	93.5 ± 4.8	79.5 – 109.4

Table 4.3 Summary of anthropometric ($\bar{x} \pm s$) measures for (n = 206) football players

Variable	$\bar{x} \pm s$	Range
Skinfolds (mm)		
Triceps	8.3 ± 3.1	3.7 – 18.1
Subscapular	10.2 ± 2.5	6.1 – 17.7
Biceps	4.4 ± 2.0	2.1 – 11.5
Iliac crest	15.5 ± 6.2	3.8 – 39.2
Supraspinale	9.7 ± 3.9	4.1 – 26.5
Abdominal	14.6 ± 6.0	5.1 – 34.4
Anterior thigh	12.1 ± 4.4	4.5 – 29.5
Medial calf	7.0 ± 2.5	3.0 – 15.7
Girths (cm)		
Neck	38.4 ± 1.6	34.4 – 44.0
Arm (relaxed)	31.9 ± 2.2	19.8 – 37.7
Arm (flexed)	34.2 ± 2.3	29.4 – 40.2
Forearm	28.3 ± 1.7	24.1 – 39.4
Wrist	17.5 ± 0.8	15.4 – 19.9
Chest	99.0 ± 4.8	82.5 – 109.7
Waist	81.9 ± 6.3	24.0 – 98.6
Hip	94.0 ± 4.5	75.0 – 106.9
Thigh	55.7 ± 3.8	21.4 – 63.3
Calf	38.2 ± 2.5	29.7 – 57.4
Ankle	23.1 ± 1.3	18.9 – 26.0
Breadths (cm)		
Biacromial	43.4 ± 2.0	33.8 – 49.9
Biiliocristal	29.6 ± 1.7	25.0 – 33.8
Depths (cm)		
Transverse chest	30.9 ± 1.8	26.2 – 38.1
Anterior-posterior chest	20.7 ± 1.8	16.0 – 31.3
Widths (cm)		
Humerus	7.3 ± 0.7	6.2 – 10.3
Femur	9.6 ± 0.6	6.6 – 10.9

Results from Table 4.3 indicated that the iliac crest, supraspinale, abdominal and anterior thigh skinfolds (mm) had, as anticipated, the largest values and ranges. A situation previously reported by Martin *et al.,* (1985), Brodie (1988a), Harrison, *et al.,* (1991) and Heyward (2000), suggesting larger deposits of localised storage fat. The girth measurements at the chest, hip and waist had the greatest range of mean values with 99.0 ± 4.8 cm, 94.0 ± 4.5 cm and 94.0 ± 4.5 cm respectively. Given the nature of the sport and the physiological demand placed upon the legs with a variety of football playing positions, the anterior thigh and medial calf girths showed a large range of 21.4 – 63.3 and 29.7 – 57.4 cm respectively. Breadths, depths and width values (cm) were within ranges previously reported by Casajus and Bosco (2001) and Loucks (2004) with the anterior-posterior chest depth with a 20.7 ± 1.8 cm and range from 16.0 – 33.8 cm for professional football players.

A summary of forced vital capacity and subsequently derived residual lung volume estimation values can be seen in Table 4.4. Results indicated that forced vital capacities and estimated residual lung volumes ranged between 2.0 – 6.8 l and 0.6 – 2.1 l respectively. Although residual lung volume has been assumed to have a constant value of 0.9 – 1.6 l in a normal healthy adult male population, recognised individual differences such as stature, race, age and general fitness contribute greatly in the estimation of residual lung volume (Roca *et al*., 1998; Lockner *et al*., 2000; Fields *et al*., 2002). With regards to the latter and within the context of the present thesis, general fitness is a major factor when reporting on professional athletes, due to the varying aerobic demands that are required for football as Table 4.4 illustrates (Pesola *et al*., 2004; Wanger *et al*., 2005; Demura *et al.,* 2006).

Table 4.4 Summary of forced vital capacity ($\bar{x} \pm s$) measures and derived residual lung volume estimation values for (n = 206) football players

Variable	$\bar{x} \pm s$	Range
Forced vital capacity (l)	4.6 ± 0.7	2.0 – 6.8
Residual lung volume (l)	1.4 ± 0.2	0.6 – 2.1

Table 4.5 illustrates the air displacement plethysmography estimated values of whole body volume (l) and whole body density (g ml^{-1}). Body volume and body density values results illustrated in Table 5.4 have a range of between 58.4 – 93.2 l and 1.050 – 1.100 g ml^{-1} respectively. Perhaps an indication of the range of body density values could be alluded to by the research of Schutte *et al*., (1984), Donnelly *et al*., (1991), Fields *et al*., (2000), Demura *et al*., (2001), Utter *et al*., (2003) and Collins *et al*., (2004). These authors reported that non-Caucasian populations have fat-free masses that are denser with assumed body density values of (on average) 1.113 g ml^{-1} when compared with Caucasian populations body density of (on average) 1.100 g ml^{-1} (Schutte *et al*., 1984; Donnelly *et al*., 1991; Fields *et al*., 2000). In fact Fields *et al*., (2000) had already stressed the need for more research to estimate body density among ethic populations and given that the present study had a total of n = 25 non-Caucasian participants, these findings cannot be ignored.

Table 4.5 Summary of air displacement plethysmography whole body volume and whole body density ($\bar{x} \pm s$) measures for (n = 206) football players

Variables	$\bar{x} \pm s$	Range
Body volume (l)	75.1 ± 7.01	58.4 – 93.2
Body density (g ml^{-1})	1.071 ± 0.008	1.050 – 1.090

Table 4.6 provides an overview of the hydrostatic weight attempts (kg) that were conducted on all *n* = 206 participants in order to assess for body mass underwater. Results illustrated that all participants attempted all but the final underwater weighing. Evidence suggested that as consecutive weighing attempts continued certainly past the sixth attempt the values began to reduce. Given the outcome from the investigation C (in section 3.8.3) the first two and the last three attempts were not used to determine mean underwater weight as they are known to underreport (Demura *et al.,* 2002; Slater *et al.,* 2006). The favourable weighing attempts were the fourth, fifth and sixth as they demonstrated very small between-attempt differences and in general the highest values of underwater weighing, thereby providing the closest estimation of a 'true' underwater weight.

Table 4.6 Summary of hydrostatic weighing ($\bar{x} \pm s$) measures for (*n* = 206) football players

Variable	$\bar{x} \pm s$	**Range**
Hydrostatic weight attempt 1 (kg)	3.37 ± 3.85	0.13 – 7.80
Hydrostatic weight attempt 2 (kg)	3.68 ± 3.73	0.36 – 7.81
Hydrostatic weight attempt 3 (kg)	3.86 ± 3.85	0.10 – 7.80
Hydrostatic weight attempt 4 (kg)	3.92 ± 3.37	1.12 – 7.83
Hydrostatic weight attempt 5 (kg)	3.90 ± 2.98	1.06 – 7.02
Hydrostatic weight attempt 6 (kg)	3.82 ± 2.65	1.14 – 6.43
Hydrostatic weight attempt 7 (kg)	3.88 ± 1.94	1.73 – 5.60
Hydrostatic weight attempt 8 (kg)	3.91 ± 1.39	2.44 – 5.21
Hydrostatic weight attempt 9 (kg)	4.05 ± 1.01	3.07 – 5.09
Hydrostatic weight attempt 10 (kg)	0.00 ± 0.00	0.00 – 0.00*
Mean hydrostatic weight (kg)	3.84 ± 1.04	1.12 – 6.22

* No values were obtained

To avoid a disjointed approach when reporting outcomes for individual anthropometric measures, TEM% values are discussed alongside the Bland and Altman plots. The TEM% overview of ISAK level 1 and 2/3 accreditation criteria are shown in Table 4.7. Bland and Altman plots for the individual reliability of each procedure gained from anthropometric measures including stretched stature and sitting height, skinfolds, girths, breadths, depths and widths are illustrated in Figures 4.1 – 4.9.

Table 4.7 Overview of primary investigator measurements against the level 1 and 2/3 TEM% values for ISAK accreditation criteria

Variable	Level 1			Level 2		
	Primary investigator	**ISAK target**	**diff**	**Primary investigator**	**ISAK target**	**diff**
Stretched stature (cm)	0.0	1.5	1.5	0.0	1.0	+1.5
Sitting height (cm)	-	-	-	0.1	1.0	1.4
Body mass (kg)	0.0	1.5	1.5	0.0	1.0	1.5
Skinfolds (mm)						
Triceps	1.5	7.5	6.0	1.5	5.0	3.5
Subscapular	1.2	7.5	6.3	1.2	5.0	3.8
Biceps	1.0	7.5	6.5	1.0	5.0	4.0
Iliac crest	1.8	7.5	5.8	1.75	5.0	3.3
Supraspinale	1.5	7.5	6.0	1.5	5.0	3.5
Abdominal	1.5	7.5	6.0	1.5	5.0	3.5
Anterior thigh	1.5	7.5	6.0	1.5	5.0	3.5
Medial calf	1.5	7.5	6.0	1.5	5.0	3.5
Girths (cm)						
Neck	-	-	-	0.2	1.0	0.8
Arm (relaxed)	0.3	1.5	1.2	0.3	1.0	0.7
Arm (flexed)	0.4	1.5	1.1	0.4	1.0	0.6
Forearm	-	-	-	0.2	1.0	0.8
Wrist	-	-	-	0.2	1.0	0.8
Chest	-	-	-	0.2	1.0	0.8
Waist	0.2	1.5	1.3	0.2	1.0	0.8
Hip	0.5	1.5	1.0	0.5	1.0	0.5
Thigh	-	-	-	0.2	1.0	0.8
Calf	0.2	1.5	1.3	0.2	1.0	0.8
Ankle	-	-	-	0.2	1.0	0.8
Breadths (cm)						
Biacromial	-	-	-	0.2	1.0	0.8
Biiliocristal	-	-	-	0.3	1.0	0.7
Depths (cm)						
Transverse chest	-	-	-	0.4	1.0	0.6
Anterior-posterior chest	-	-	-	0.3	1.0	0.7
Widths (cm)						
Humerus	0.2	1.5	1.3	0.2	1.0	0.8
Femur	0.3	1.5	1.2	0.3	1.0	0.7

The stretched stature and sitting height measurements shown in Figure 4.1 indicated a bias of +0.0 cm and +0.05 cm and 95% limits of agreement of -0.1 cm to +0.1 cm and -0.0 cm to +0.2 cm respectively. If for example a new participant from this population of interest (not one of the *n* = 206 sample) was measured via anthropometry for a sitting height of 83.5 cm at the time of the test there is a 95% probability that the sitting height at the retest could be measured as low as 83.5 – 0.1 = 83.4 cm to as high as 83.5 + 0.2 = 83.7 cm. There was little evidence of systematic bias, random variation or heteroscedasticity from both plots, which was anticipated given the similarity in measurement process. Therefore, as the differences between the test and re-test values were normally distributed and according to the study is *a priori* criteria these findings are well within acceptable limits.

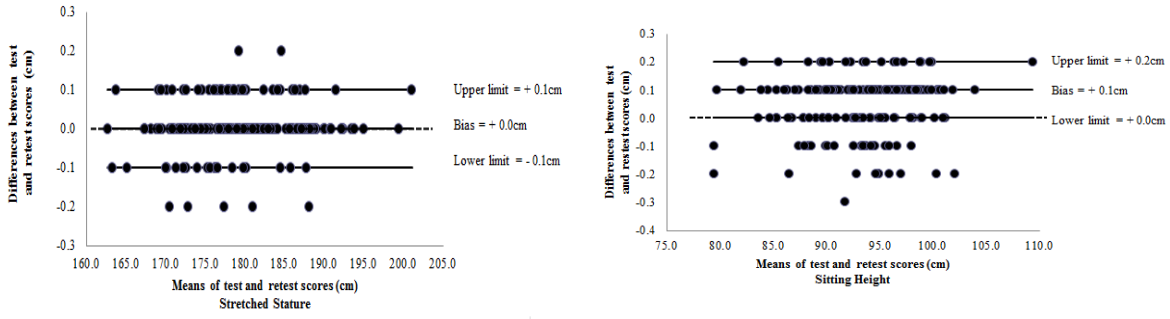

Figure 4.1 Bland and Altman plots summarising the 95% limits of agreement for the reliability of stretched stature and sitting height (cm)

Evidence from Table 4.7 indicated that the TEM% for stretched stature against the level 1 ISAK criterion and stretched stature and sitting height against the level 2/3 ISAK criterion were 0.09% and 0.14% respectively. TEM% recommended target for level 1 and 2/3 ISAK standard values against the criterion indicated a 1.5% difference, with the primary investigator having achieved TEM% targets well within acceptable limits as demonstrated in Table 4.7.

Figure 4.2 exhibit the triceps, subscapular, biceps and iliac crest skinfold thicknesses (mm) where there is a bias of +0.05 mm, +0.05 mm, +0.02 mm and +0.01 mm and 95% limits of agreement of –0.2 to +0.2 mm, –0.2 to +0.2 mm, –0.1 to +0.1 mm and –0.2 to +0.2 mm respectively. When determining whether a new participant from this population of interest (not one of the *n* = 206 sample) was measured for the triceps skinfold at 8.3 mm at this time of the test there is a 95% probability that the skinfold thickness measured at the re-test could be as low as 8.3 – 0.2 = 8.1 mm to as high as 8.3 + 0.2 = 8.5 mm. Similar results would be found for the subscapular, biceps and iliac crest. There is some evidence of systematic bias, random variation and heteroscedasticity where there are data plots that lie above and below the zero line, but the distances of these range to 0.2 mm. The differences between the test and re-test values were normally distributed, therefore the study's *a priori* criteria propose that these findings are well within acceptable limits.

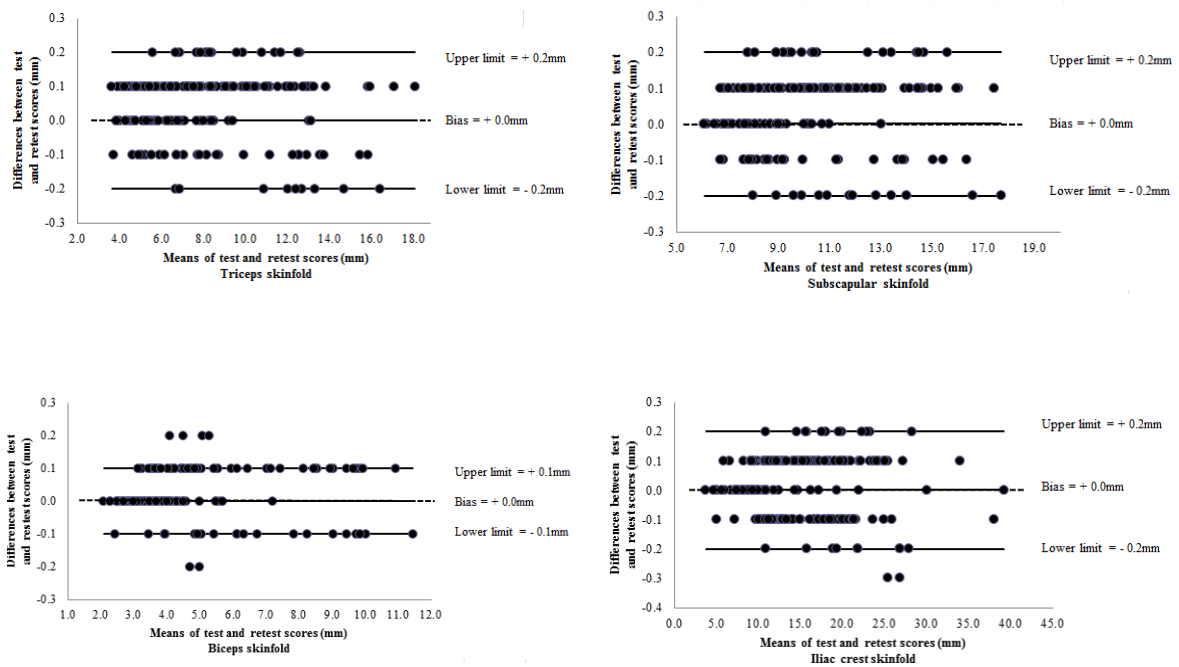

Figure 4.2 Bland and Altman plots summarising the 95% limits of agreement for the reliability of triceps, subscapular, biceps, and iliac crest skinfolds (mm)

%TEM values revealed from Table 4.3 that the triceps, subscapular, biceps and iliac crest measures of 1.5%, 1.2%, 1.0% and 1.8% and differences of 6.0% 6.3% 6.5% and 5.8% against the ISAK criterion for level 1 and 3.5%, 3.8%, 4.0% and 3.3% against level 2/3 ISAK criterion respectively. Measurements from previous studies including Gordan *et al.*, (1991), Lohman *et al.*, (1991) and Norton *et al*., (2000) have indicated that the measurement of skinfold thickness have the greatest variability mainly due to measurement error and poor repeatability. Hence the probable TEM% target of 7.5% for the level 1 and 5.0% for the level 2/3 criteria set by ISAK to help reduce these errors (ISAK, 2001; Norton *et al*., 2000). Results indicated that the highest values of the triceps and iliac crest skinfolds were still lower than the ISAK recommended TEM% by as much as 3.3%, and although some of the highest differences established compared to the ISAK TEM% targets, the primary investigator attained TEM% targets well within acceptable limits for these skinfolds.

The supraspinale, abdominal, anterior thigh and medial calf skinfold thicknesses (mm) exhibited in Figure 4.3 provided a bias of +0.0 mm, +0.08 mm, +0.03 mm and +0.01 mm and 95% limits of agreement of –0.2 to +0.2 mm, –0.3 to +0.3 mm, –0.1 to +0.1 mm, and -0.1 to +0.1 mm respectively. Were a new participant from this population of interest (not one of the n = 206 sample) to be measured at the time of the test for the abdominal skinfold by the primary investigator at 14.6 mm there is a 95% probability that at the time of the retest the skinfold thickness could be as low as 14.6 – 0.3 = 14.3 mm or as high as 14.6 + 0.3 = 14.9 mm. It can be seen from both the direction and the size of the data scatter around the zero line from Figure 4.3 that supraspinale, abdominal, anterior thigh and medial calf skinfolds, and in particular the abdominal skinfold shows some evidence of systematic bias and random variation. Previous evidence has suggested that with certain

sites there is measurement error. For instance, as values get bigger (due to increased skinfold thicknesses) this can cause more variance and greater error between test and re-test values. Yet, this study established that the test and re-test values were normally distributed and well within acceptable limits according to with the study's *a priori* criteria.

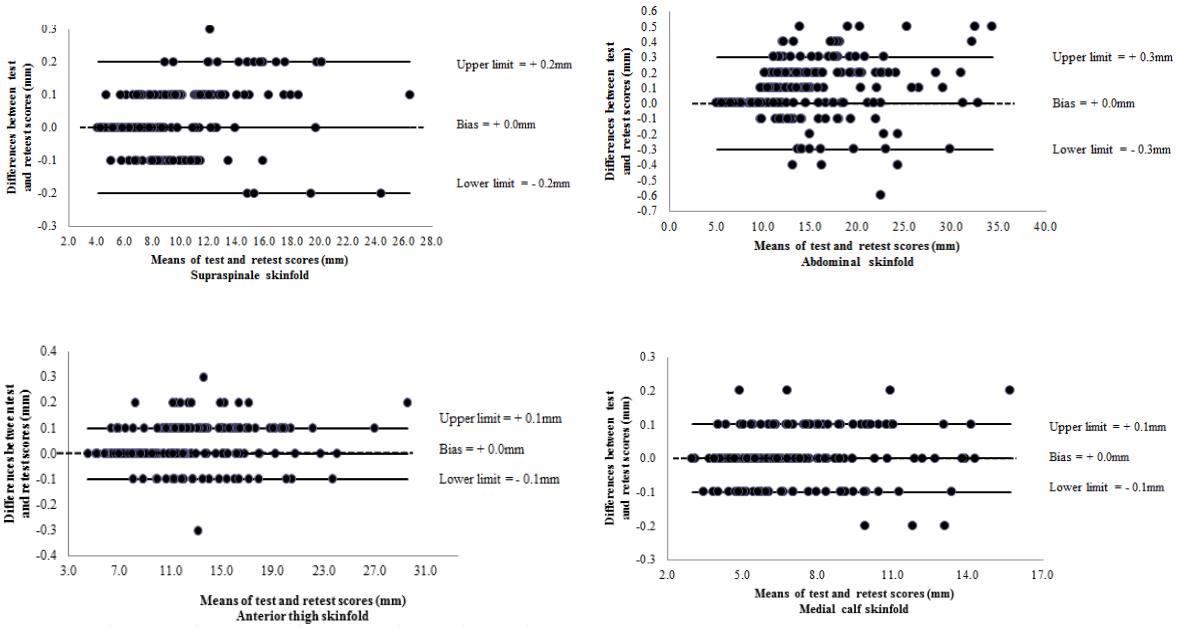

Figure 4.3 Bland and Altman plots summarising the 95% limits of agreement for the reliability of supraspinale, abdominal, anterior thigh and medial calf skinfolds (mm)

TEM% for supraspinale, abdominal, anterior thigh and medial calf skinfolds exhibited in Table 4.7 against the level 1 and the 2/3 ISAK level criteria were all 1.5% respectively. The TEM% recommended target for Level 1 and the level 2/3 ISAK standard values against the criteria indicated differences of 3.5% for all of the above mentioned skinfolds, but suggest the need for closer scrutiny of these measures in the main study. These results provided some of the highest differences compared to ISAK criteria, although this indicated that the primary investigator has achieved TEM% targets well within acceptable limits.

Figure 4.4 exhibit the neck, arm (relaxed), arm (flexed) and forearm girths (cm) where there is a bias of +0.01 cm, +0.02 cm, +0.02 cm and +0.01 cm, and 95% limits of agreement of -0.2 to +0.2 cm, -0.1 to +0.1 cm, -0.2 to +0.2 cm and -0.2 to +0.2 cm, respectively. In contrast if a new participant from this population of interest (not one of the *n* = 206 sample) was measured for arm (relaxed) girth at the time of the test at 33.4 cm there is a 95% probability that the arm girth at the time of the re-test could be measured as low as 33.4 – 0.1 = 33.3 cm or as high as 33.4 + 0.1 = 33.5 cm. There is evidence of systematic bias and random variation in a positive direction. All differences between test and re-test values were normally distributed and well within acceptable limits relating to the *a priori* study criteria.

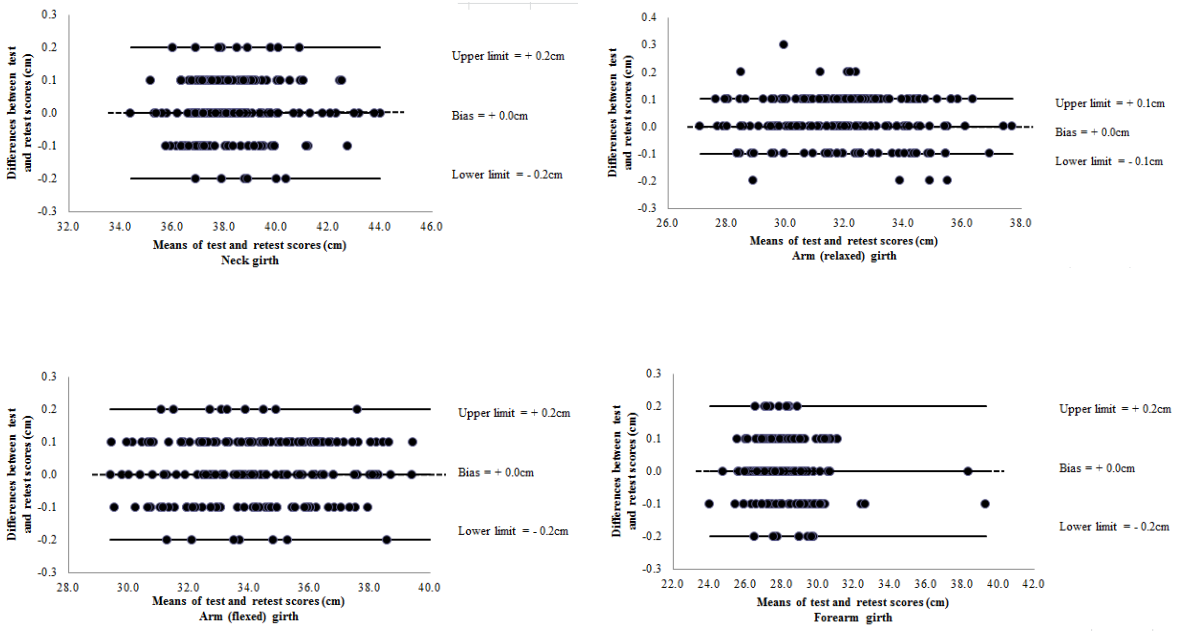

Figure 4.4 Bland and Altman plots summarising the 95% limits of agreement for the reliability of neck, arm (relaxed), arm (flexed) and forearm girth (cm)

The TEM% for arm (relaxed) and arm (flexed) girths against the level 1 and were 0.3% and 0.4% with a ISAK target of 1.5%, indicating a difference of 1.2% and 1.1% respectively (see Table 4.7). The TEM% recommended target for level 2/3 ISAK standard values of 1.0% against the criterion indicated differences of 0.8%, 0.7%, 0.6% and 0.8%. Although the arm (flexed and relaxed) girth provided one of the lowest TEM% compared to ISAK criteria, these results were within acceptable TEM% targets.

Figure 4.5 illustrates the wrist, chest, waist and hip girths (cm) where there is a bias of +0.01 cm, +0.02 cm, +0.02 cm and +0.01 cm, and 95% limits of agreement of -0.2 to +0.2 cm, -0.1 to +0.1 cm, -0.2 to +0.2 cm and -0.2 to +0.2 cm respectively. If for example a new participant from this population of interest (not one of the *n* = 206 sample) was measured via anthropometry for chest girth at the time of the test at 99.0 cm there is a 95% probability that the girth at the time of re-test could be measured as low as 99.0 – 0.2 = 98.8 cm or as high as 99.0 + 0.4 = 99.4 cm.

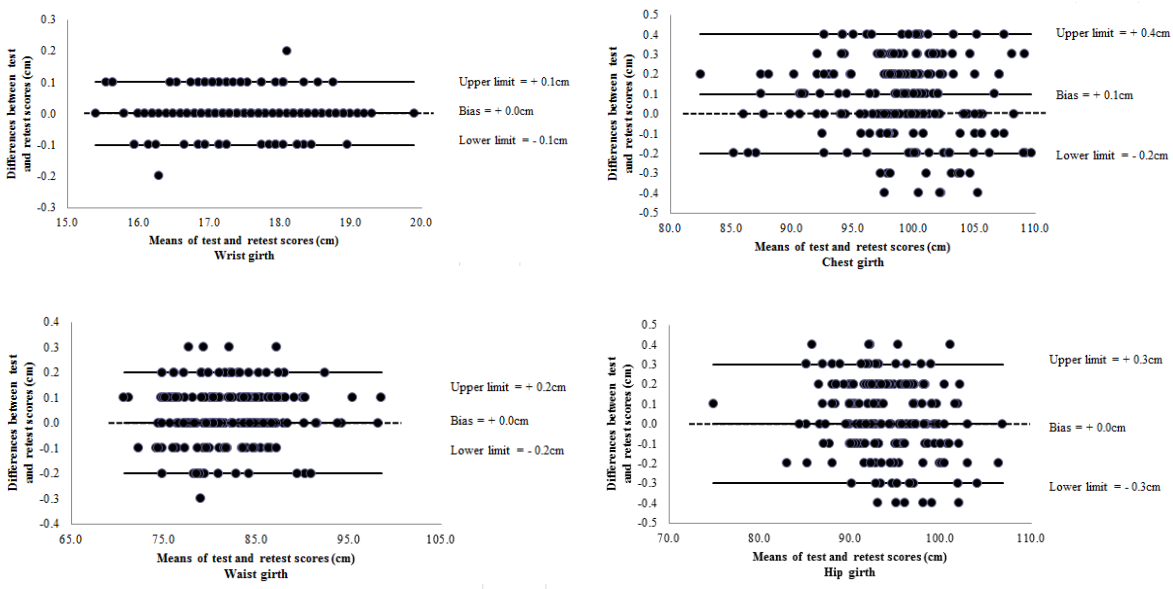

Figure 4.5 Bland and Altman plots summarising the 95% limits of agreement for the reliability of wrist, chest, waist and hip girth (cm)

As was to be expected the direction and size of the data scatter around the zero line suggests evidence of systematic bias in the values particularly of the chest and hip girths. These girths can be problematic particularly due to the chest movement during inhalation and exhalation processes and with participants wearing light clothing in the hip region, thus causing greater variance in test and re-test scores. Although all differences between test and re-test values were normally distributed and according to the *a priori* study finds these results are well within acceptable limits.

For illustrative purposes, Table 4.7 provides the TEM% for the waist (0.2%) and hip (0.5%) girths against the level 1 ISAK criteria at 1.5% providing differences of 1.3% and 1.0% respectively. The wrist, chest, waist and hip girths were compared against level 2/3 ISAK criterion values of 0.2% for the wrist, chest and waist and 0.5% for the hips with a TEM% recommended target at 1.0% providing differences against the criterion differences of 0.8% for the wrist, chest and waist and 0.8% for the hips, but suggest the need for closer scrutiny of the latter measure in the main study. These results indicated that the primary investigator has achieved TEM% targets within acceptable limits when compared to ISAK criteria.

Figure 4.6 show the thigh, calf and ankle girths (cm) where there is a bias of +0.02 cm, +0.01 cm and +0.02 cm and 95% limits of agreement of -0.2 to +0.2 cm, -0.1 to +0.1 cm and -0.1 to +0.1 cm respectively. If for example a new participant from this population of interest (not one of the n = 206 sample) was measured via anthropometry for thigh girth at the time of this test of 58.2 cm there is a 95% probability that the girth at the time of re-test could be measured as low as 58.2 – 0.2 = 58.0 cm to as high as 58.2 + 0.2 = 58.4 cm. There is some evidence of systematic bias and random variation predominantly with the

anterior thigh girth as with problem variables such as this (due to measurement accuracy with location site and application of measuring tape) greater error in test and re-test values can occur. Therefore, there is a need for closer scrutiny of these measures in the main study. Never-the-less, the test and re-test values were normally distributed and well within acceptable limits according to with the study *a priori* criteria.

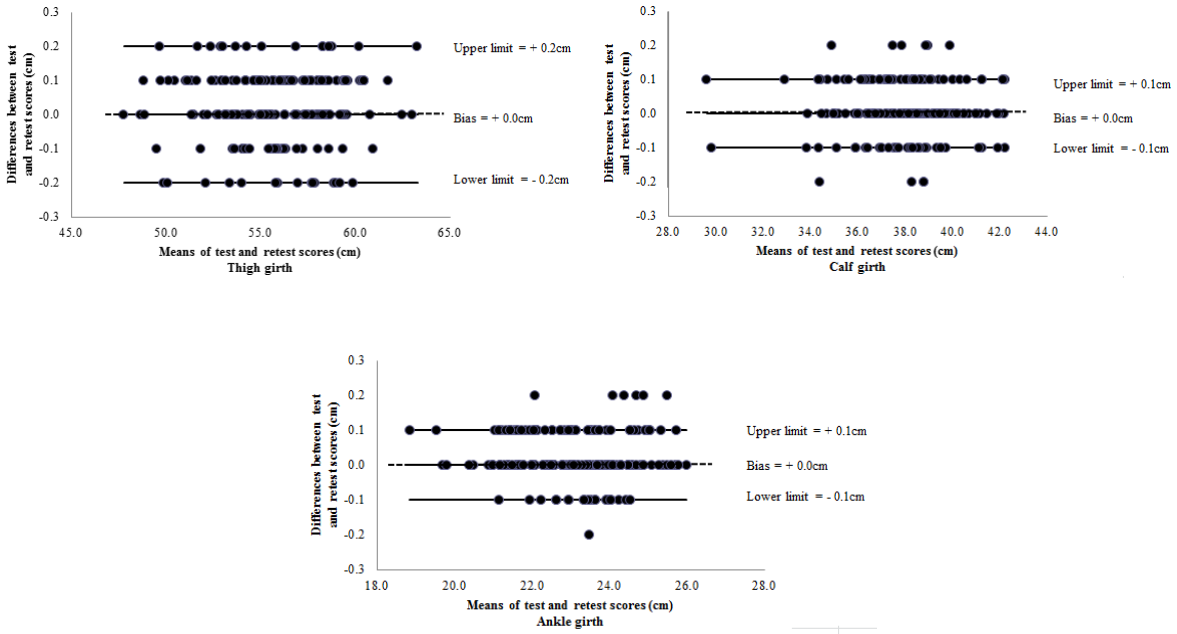

Figure 4.6 Bland and Altman plots summarising the 95% limits of agreement for the reliability of thigh, calf and ankle girths (cm)

TEM% for the calf against level 1 ISAK criteria were 0.2% with ISAK target set at 1.5% providing a difference of 1.3%. When the thigh, calf and ankle girths were compared against level 2/3 ISAK criterion values were 0.5%, 0.2% and 0.2% respectively with a TEM% recommended target at 1.0% providing differences against the criterion differences of 0.8% for all of the above mentioned girths, but suggest the need for closer inspection of these measures in the main study, especially with the thigh girth. These results indicated that the primary investigator has achieved TEM% targets within acceptable limits.

Figure 4.7 exhibit the biacromial and biiliocristal breaths (cm) where there is a bias of + 0.01 cm and + 0.06 cm and 95% limits of agreement of –0.1 to +0.1 cm and –0.2 to +0.4 cm respectively. If for example a new participant from this population of interest (not one of the *n* = 206 sample) was measured via anthropometry for the biiliocristal at the time of the test of 29.7 cm there is a 95% probability that the breadth at the time of the retest could be measured as low as 29.7 – 0.2 = 29.5 cm to as high as 29.7 + 0.4 = 30.1 cm.

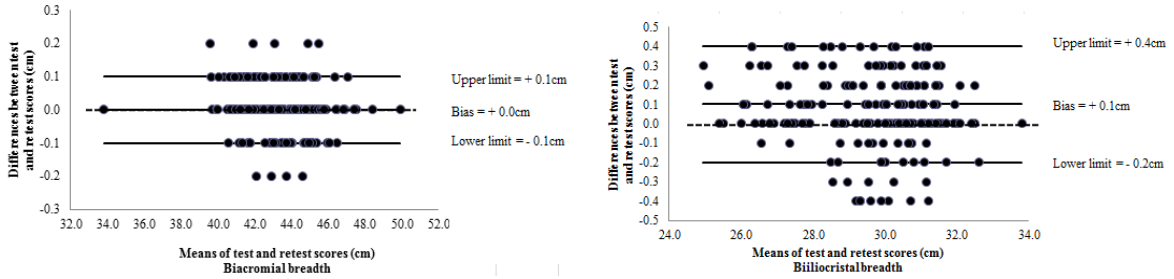

Figure 4.7 Bland and Altman plots summarising the 95% limits of agreement for the reliability of biacromial and biiliocristal breadth (cm)

The 95% probability for the biacromial would provide slightly less results. The direction of the data scatter around the zero line for the biiliocristal breadth in particular indicates some evidence of systematic bias and random variance. Although the differences between the test and re-test values were normally distributed and according to the study priori these findings are well within acceptable limits. Table 4.7 exhibits TEM% for biacromial and biiliocristal breadths against level 2/3 ISAK criterion were all 0.2% and 0.3% respectively. TEM% recommended target for Level 2/3 ISAK standard values 1.0% against the criterion indicated differences of 0.8 and 0.7% for both breadths. These results indicate that the primary investigator has achieved TEM% targets within acceptable limits.

Figure 4.8 exhibit the transverse chest depth and anterior-posterior chest depth (cm) where there is a bias of + 0.05 cm and + 0.01 and 95% limits of agreement of – 0.3 to + 0.3 cm, and – 0.1 to + 0.1 cm respectively. If for example a new participant from this population of interest (not one of the *n* = 206 sample) was measured via anthropometry for the transverse chest at the time of the test of 30.9 cm there is a 95% probability that the depth could be measured at the time of the retest as low as 30.9 – 0.3 = 30.6 cm to as high as 30.9 + 0.3 = 31.2 cm. The 95% probability for the anterior-posterior chest depth would provide slightly less results. Data scatter around the zero line for the transverse chest depth specifically, indicates systematic bias and random variation. Although there were normal distribution of the differences between the test and re-tests and the study *a priori* criteria found these findings to be well within acceptable limits.

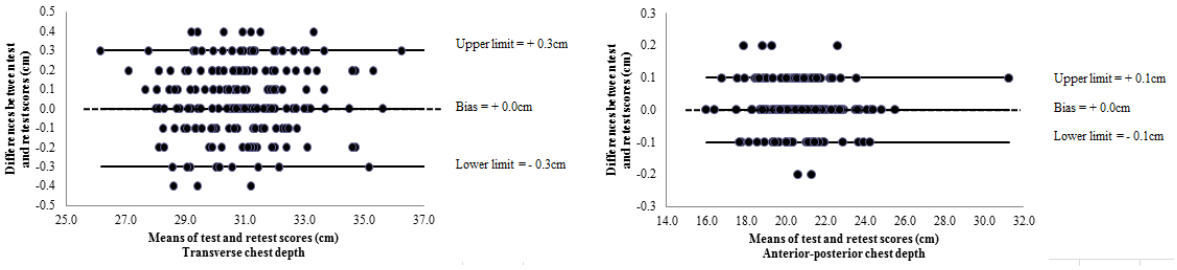

Figure 4.8 Bland and Altman plots summarising the 95% limits of agreement for the reliability of transverse chest and anterior-posterior chest depth (cm)

Table 4.7 exhibits TEM% for transverse chest and anterior-posterior chest depth against level 2/3 ISAK criterion were all 0.4% and 0.3% respectively. TEM% recommended target for Level 2/3 ISAK standard values of 1.0% against the criterion indicated differences of 0.6% and 0.7% for both breadths. Although some of the lowest differences established, although compared to the ISAK targets these results indicate that the primary investigator has achieved TEM% targets within acceptable limits.

Figure 4.9 exhibit the humerus and femur widths (cm) where there is a bias of + 0.0 mm and + 0.01 mm and 95% limits of agreement of – 0.1 to + 0.1 mm and – 0.2 to + 0.2 mm respectively. If for example a new participant from this population of interest (not one of the *n* = 206 sample) was measured via anthropometry for the femur at the time of the test of 9.6 mm there is a 95% probability that the bone width could be measured at the time of the retest as low as 9.6 – 0.2 = 9.4 mm to as high as 9.6 + 0.2 = 9.8 mm.

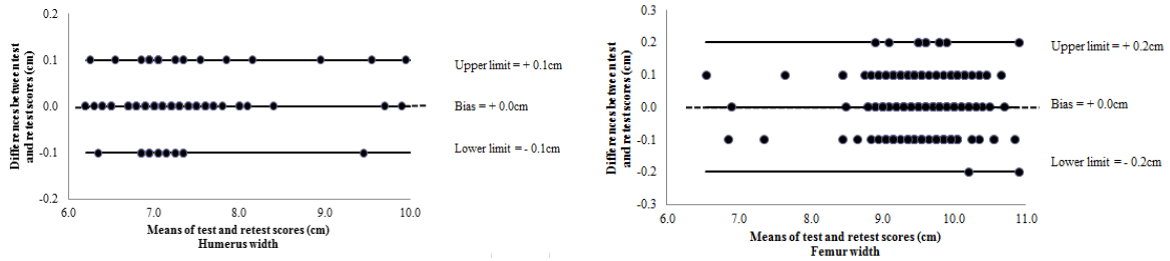

Figure 4.9 Bland and Altman plots summarising the 95% limits of agreement for the reliability of humerus and femur width (cm)

The 95% probability for the humerus width would provide similar findings. There was minimal data scatter around the zero line possibly due to these measures being conducted on bone surfaces and providing less variance. All differences between test and re-test values were normally distributed and well within acceptable limits when using the study priori criteria. Table 4.7 exhibits TEM% for humerus and femur width against level 1 and 2/3 ISAK criterion were all 0.2% and 0.3% respectively. TEM% recommended target for Level 1 of 1.5% with differences of 0.8 and 0.7 and 2/3 ISAK standard values of 1.0% against the criterion indicated differences of 0.8% and 0.7% for humerus and femur widths respectively. These differences also provided some of the lowest differences, however given the low TEM% ISAK criteria, results indicate that the primary investigator has achieved TEM% targets well within acceptable limits.

Table 4.8 provides an overview of bias and the width of 95% limits of agreement for all anthropometric variables measured during the present study (Figures 4.1 – 4.9).

Table 4.8 Overview of upper and lower 95% limits of agreement and bias indices for anthropometric measures

Variables	Bias	(95%) Lower Limit	(95%) Upper Limit
Stretched stature (cm)	+ 0.0	- 0.1	+ 0.1
Sitting height (cm)	+ 0.1	- 0.0	+ 0.2
Skinfolds (mm)			
Triceps	+ 0.0	- 0.2	+ 0.2
Subscapular	+ 0.0	- 0.2	+ 0.2
Biceps	+ 0.0	- 0.1	+ 0.1
Iliac crest	+ 0.0	- 0.2	+ 0.2
Supraspinale	+ 0.0	- 0.2	+ 0.2
Abdominal	+ 0.0	- 0.3	+ 0.3
Anterior thigh	+ 0.0	- 0.1	+ 0.1
Medial calf	+ 0.0	- 0.1	+ 0.1
Girths (cm)			
Neck	+ 0.0	- 0.2	+ 0.2
Arm (relaxed)	+ 0.0	- 0.1	+ 0.1
Arm (flexed)	+ 0.0	- 0.2	+ 0.2
Forearm	+ 0.0	- 0.2	+ 0.2
Wrist	+ 0.0	- 0.1	+ 0.1
Chest	+ 0.1	- 0.2	+ 0.4
Waist	+ 0.0	- 0.2	+ 0.2
Hip	+ 0.0	- 0.3	+ 0.3
Thigh	+ 0.0	- 0.2	+ 0.2
Calf	+ 0.0	- 0.1	+ 0.1
Ankle	+ 0.0	- 0.1	+ 0.1
Breadths (cm)			
Biacromial	+ 0.0	- 0.1	+ 0.1
Biiliocristal	+ 0.1	- 0.2	+ 0.4
Depths (cm)			
Transverse chest	+ 0.0	- 0.3	+ 0.3
Anterior-posterior chest	+ 0.0	- 0.1	+ 0.1
Widths (cm)			
Humerus	+ 0.0	- 0.1	+ 0.1
Femur	+ 0.0	- 0.2	+ 0.2

It has been well documented by researchers such as Atkinson and Nevill (1998), Gore (2000), Hopkins (2000), Norton *et al*., (2000) and Perini *et al*., (2005) of the importance for sport scientists to make some attempt to estimate measurement reliability and measurement error. Indeed, better reliability implies better precision of measurements, although within the field of anthropometry it is not uncommon to encounter extensive amounts of random variation (Hopkins, 2000; Perini *et al*., 2005). These variations can arise due to mechanical and calibration issues with equipment, technique execution and measurements gathered from repeated applications (Atkinson & Nevill, 1998). As a consequence there can be a high incidence of measurement error, and should be reduced or corrected for with careful calibration and consistent measurement technique.

The issue here is one of accepting that you cannot eliminate error entirely. So, if error exists, the question remains as to whether this error is so great that it will be detrimental to what has to be said about the primary investigator measurements and/or the present study population's values. Therefore, sport scientists must strive for reliability through intensive training and periodic quality control of measurement techniques to help reach higher accuracy and hence more optimal reliability (Perini *et al*., 2005). The manner in which these measurement errors are best analysed and reported has been a matter of some debate amongst researchers (Gore, 2000; Perini *et al*., 2005). Atkinson and Nevill (1998) have made useful contributions to this debate, with the consensus of opinion suggesting that when assessing measurement reliability, Bland and Altman's (1986) 95% limits of agreement method is the most appropriate statistic to report (Nevill & Atkinson, 1997).

The important elements of measurement error considered in the research designs employed in this study have been the amount of systematic bias between the test and retest values and probably more importantly because it might have had a direct effect upon this bias, the amount of random error between the test-retest values. Indeed, it has been the focus of this study to investigate these outcomes by applying the limits of agreement method. The purpose of using the 95% limits of agreement method was to interpret the quantification of measurement reliability. By plotting the absolute differences between the test and re-test and the means the primary investigator could identify any error in the *XY* scatter plot. For instance, the pitch and deviations from the line of best fit indicate error and scedasticity between test and re-test values. In other words, the steeper the line of best fit the more heteroscedastic the data, as opposed to the nearer the horizontal line the more homoscedastic. The error and scedasticity is easier to observe in a XY scatter plot. If the correlation between the test and re-test was found to be significant ($P = < 0.01$) there would a problem that needed a resolution. If however, the data was homoscedastic this would demonstrate that there is no problem as there is equal residual variance about the range of the values and there were agreements between test and re-test measures.

Investigations were needed to establish heteroscedastic errors, with Figures 4.10 – 4.18 illustrating scatter plots of the absolute differences between participant's test-retest values of each procedure gained from anthropometric measures including stretched stature and sitting height, skinfolds, girths, breadths, depths and widths.

Figure 4.10 illustrates the extent of heteroscedasticity with *r* values of -0.185 and -0.073 and R^2 (%) coefficients of 3.4% and 0.5% for stretched stature and sitting height respectively. Both measures indicated statistical significance of *P* = <0.001 and narrow deviations from the line of best fit, suggesting very little evidence of heteroscedasticity.

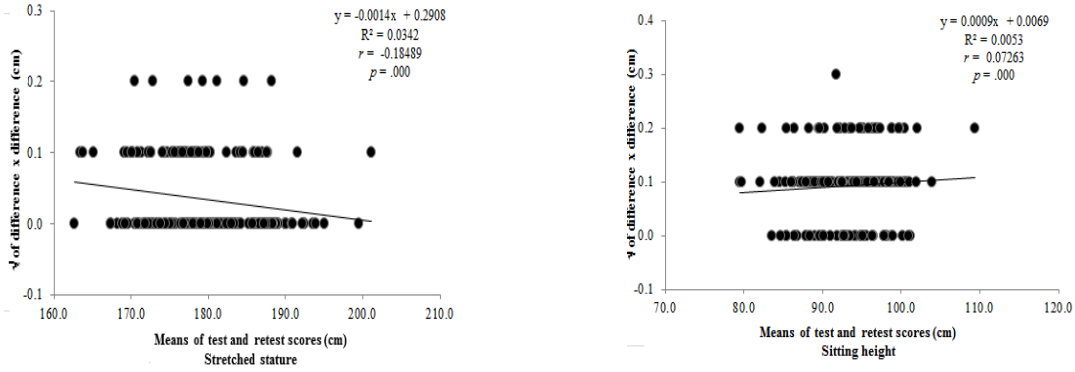

Figure 4.10 Scatter plots for heteroscedasticity of stretched stature and sitting height

Heteroscedasticity for the triceps, subscapular, biceps and iliac crest skinfolds is shown in Figure 4.11 with *r* values of 0.331, 0.366, 0.306 and 0.500 and R^2 (%) coefficients of 10.9%, 13.9%, 30.6% and 21.2%. All measures indicated statistical significance of *P* = < 0.001. These skinfolds illustrated evidence of heteroscedasticity as there is more variance in the data values and greater error between test and re-test values with some deviations from the line of best fit. At this stage a decision was needed whether to log transform or not. The simple interpretation of these plots indicated that there was no issue, furthermore, these values illustrated statistical significance of *P* = < 0.001. Therefore, on balance, there was no need to log transform, although the primary investigator was cautious of these skinfold measures.

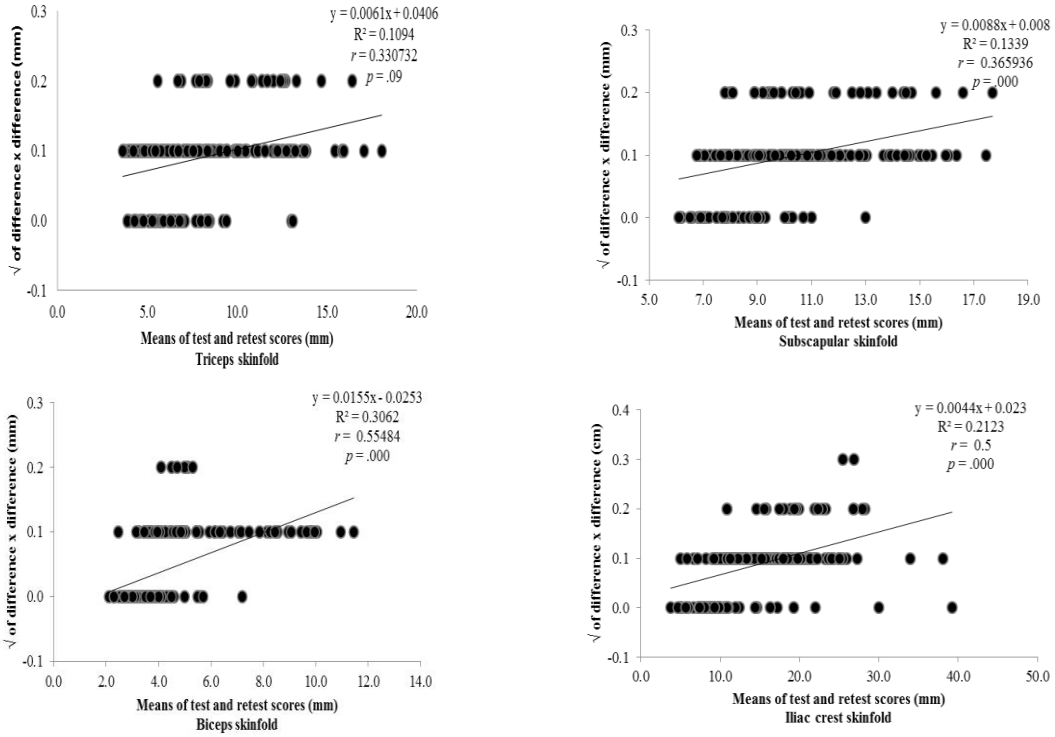

Figure 4.11 Scatter plots for the heteroscedasticity of triceps, subscapular, biceps, iliac crest calf skinfold

Figure 4.12 illustrates the extent of heteroscedasticity and *r* values of 0.611, 0.483, 0.400 and 0.304 and R^2 (%) coefficients of 37.3%, 23.3%, 14.7% and 9.2% for the supraspinale, abdominal, anterior thigh and medial calf respectively. All measures indicated statistical significance of $P = < 0.001$. As to be expected these skinfolds illustrated some heteroscedastic data as there is more variance in the values and greater error between test and re-test values, with wider deviations from the line of best fit especially prevalent in the abdominal skinfold. Reiterating previous explanations from Figure 4.11, log transformation was not warranted for the supraspinale, abdominal, anterior thigh and medial calf skinfolds and the primary investigator was cautious of these measures.

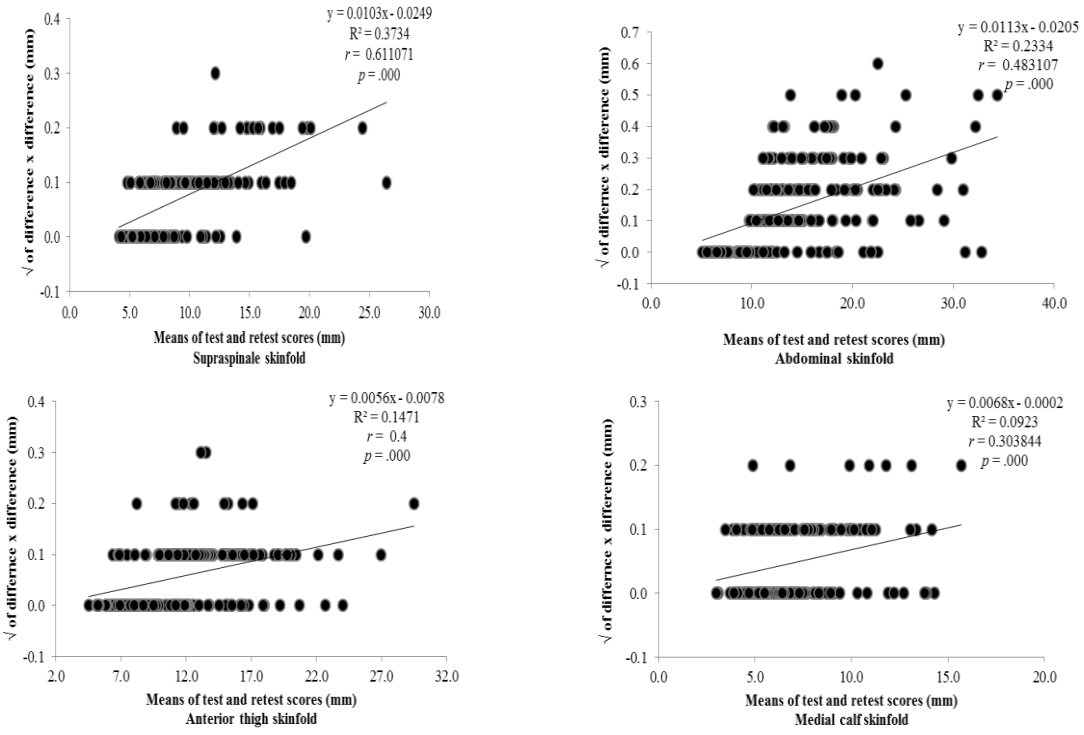

Figure 4.12 Scatter plots for the heteroscedasticity of supraspinale, abdominal, anterior thigh and medial calf skinfold

Scatter plots illustrating the extent of the heteroscedasticity of the neck, arm (relaxed), arm (flexed) and forearm girths are shown in Figure 4.13 and exhibit *r* values of -0.365, 0.100, -0.500 and 0.060 and R^2 (%) coefficients of 0.1%, 0.3%, 0.2% and 0.3%. All measures indicated statistical significance of *P* = < 0.001 and very little evidence of heteroscedasticity as the data provided very little variance and narrow deviations from the line of best fit in the values and lower error between test and re-test values.

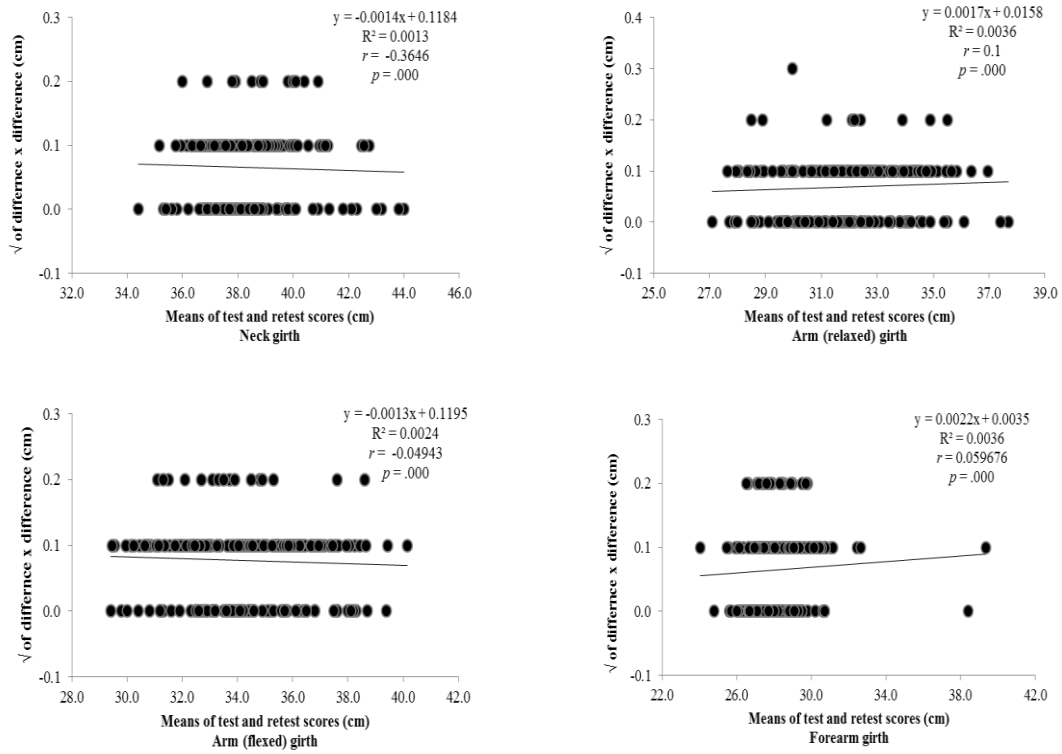

Figure 4.13 Scatter plots for the heteroscedasticity of neck, arm (relaxed), arm (flexed), forearm girth

Figure 4.14 exhibits heteroscedasticity for the wrist, chest, waist and hip girth with *r* values of -0.126, 0.090, -0.053 and -0.007 and R^2 (%) coefficients of 0.1%, 0.8%, 0.2% and 0.000005% respectively. All measures indicated statistical significance of $P = < 0.001$. Wider deviations from the line of best fit were especially prevalent in the waist and hip girths, but with little evidence of heteroscedasticity.

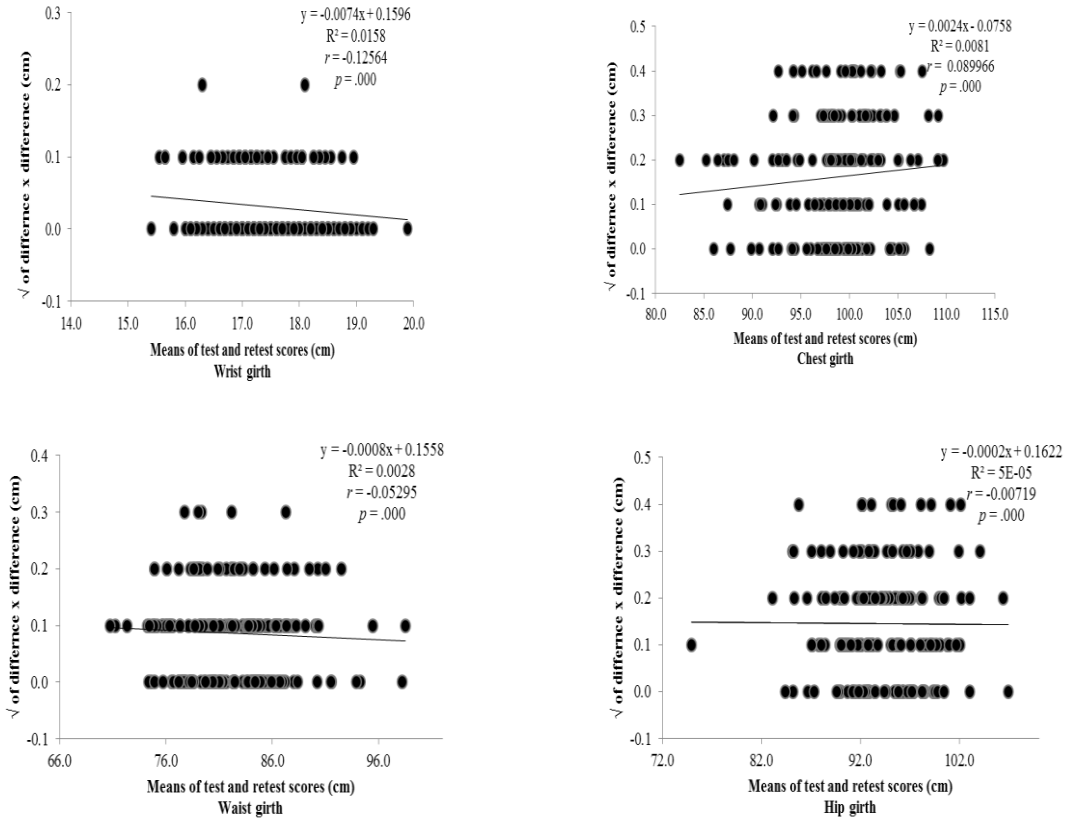

Figure 4.14 Scatter plots for the heteroscedasticity of wrist, chest, waist and hip girth

Heteroscedasticity for the thigh, calf and ankle girths are shown in Figure 4.15 with *r* values of 0.017, -0.138 and 0.085 and R^2 (%) coefficients of 0.3%, 1.9% and 0.7% for thigh, calf and ankle girths respectively. All measures indicated statistical significance of $P = < 0.001$. These girths illustrated minimal variance and narrow deviations from the line of best fit in the values due to the little error and between test and re-test values.

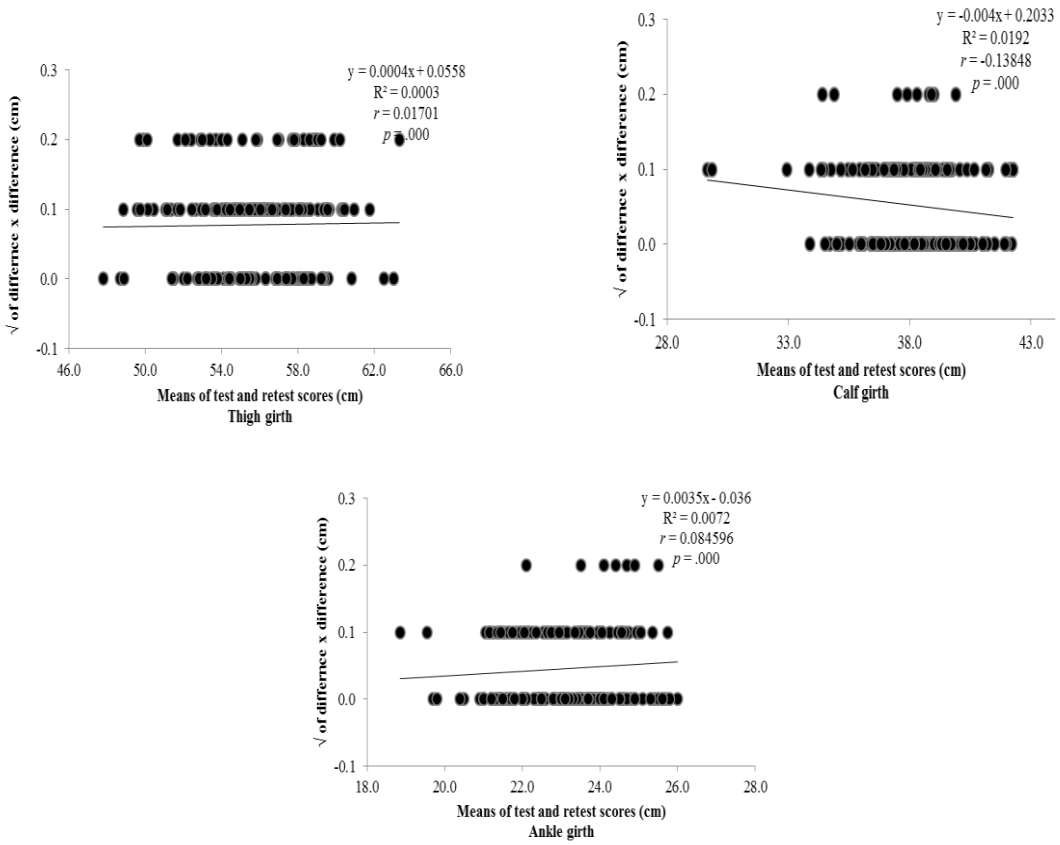

Figure 4.15 Scatter plots for the heteroscedasticity thigh, calf and ankle girth

Figure 4.16 exhibits heteroscedasticity for the biacromial and biiliocristal breadths with *r* values of -0.045 and -0.047and R^2 (%) coefficients of 0.2% and 0.2% respectively. All measures indicated statistical significance of $P = < 0.001$. Wider deviations from the line of best fit were especially prevalent in the biiliocristal, but little evidence of heteroscedasticity.

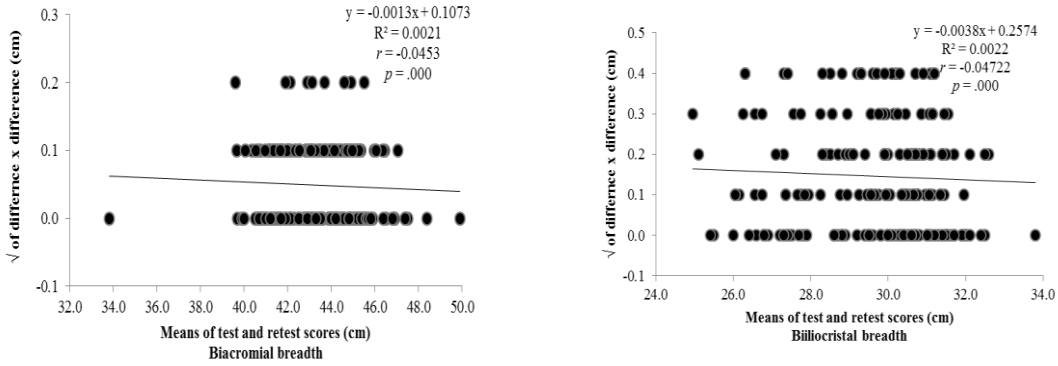

Figure 4.16 Scatter plots for the heteroscedasticity of biacromial and biiliocristal breadth

Heteroscedasticity for the transverse chest and anterior-posterior chest depths are shown in Figure 4.17 with *r* values of -0.022 and -0.003 and R^2 (%) coefficients of 0.5% and 0.005% respectively. All measures indicated statistical significance of $P = < 0.001$ with minimal variance and narrow deviations from the line of best fit observed suggesting very little heteroscedasticity.

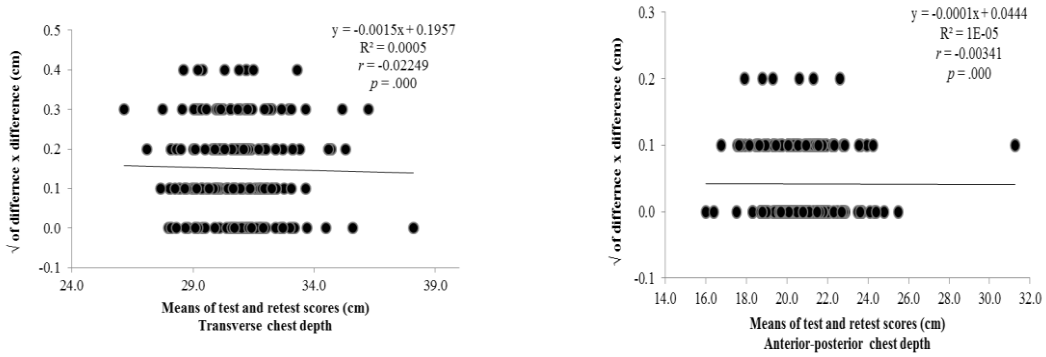

Figure 4.17 Scatter plots for the heteroscedasticity of transverse chest and anterior-posterior chest depth

Figure 4.18 exhibits heteroscedasticity for the humerus and femur width with *r* values of 0.166 and 0.003and R^2 (%) coefficients of 2.7% and 0.000006% respectively. All measures indicated statistical significance of $P = < 0.001$. These widths illustrated minimal deviations from the line of best of fit and variance in the values due to the little error between test and re-test values, indicating very little evidence of heteroscedasticity.

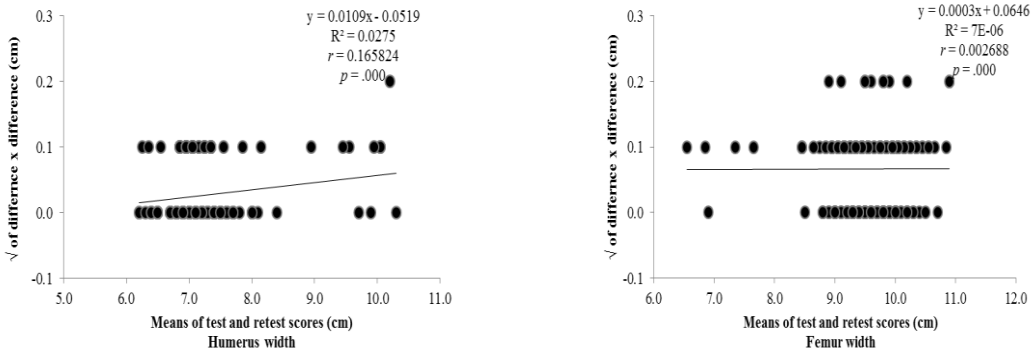

Figure 4.18 Scatter plots for the heteroscedasticity of humerus and femur width

Table 4.9 exhibits an overview of the scatter plots (Figures 4.10 – 4.18) R^2 (%), *r* and *P* values for all anthropometric measurements.

Table 4.9 Overview of scatter plots R^2, *r* and *P* values for anthropometric skinfolds (*n* = 8) measures

Variables	*r*	R^2 (%)	*P*
Stretched stature (cm)	-0.185	3.4	0.001
Sitting height (cm)	0.073	0.5	0.001
Skinfolds (mm)			
Triceps	0.331	10.9	0.001
Subscapular	0.366	13.9	0.001
Biceps	0.306	30.6	0.001
Iliac crest	0.5	21.2	0.001
Supraspinale	0.611	37.3	0.001
Abdominal	0.483	23.3	0.001
Anterior thigh	0.4	14.7	0.001
Medial calf	0.304	9.2	0.001
Girths (cm)			
Neck	-0.365	0.1	0.001
Arm (relaxed)	0.1	0.3	0.001
Arm (flexed)	-0.050	0.2	0.001
Forearm	0.060	0.3	0.001
Wrist	-0.126	0.1	0.001
Chest	0.090	0.8	0.001
Waist	-0.053	0.2	0.001
Hip	-0.007	0.000005	0.001
Thigh	0.017	0.3	0.001
Calf	-0.138	1.9	0.001
Ankle	0.085	0.7	0.001
Breadths (cm)			
Biacromial	-0.045	0.2	0.001
Biiliocristal	-0.047	0.2	0.001
Depths (cm)			
Transverse chest	-0.022	0.5	0.001
Anterior-posterior chest	-0.003	0.005	0.001
Widths (cm)			
Humerus	0.166	2.7	0.001
Femur	0.003	0.000006	0.001

Inspection of Figures 4.12 – 4.20 and Table 4.9 illustrated statistical significance for all 27 anthropometric values of $P = < 0.001$. At this stage it is important to note that having a population sample of $n = 206$ participants, both Ntoumanis (2006) and Bryman and Cramer (2009) suggest that this P value is not necessarily a problem as there is less than one in a thousand chance of being wrong and gauging statistical significance can be referred to the slope of the line of best fit. R^2 values ranged from 0.1 to 37.3 and r values ranged from -0.003 to 0.611. Wider deviations from the line of best fit were especially prevalent in the abdominal skinfold, waist girth, chest girth, hip girth and biiliocristal breath. Figures 4.1 – 4.9 and 4.12 – 4.20 illustrated both the direction, size and distances of the data scatter around the zero line (Y axis) and indicated some evidence of systematic bias in these values and that the bias is in a positive direction.

Upon closer scrutiny of more contentious measurements of the iliac crest skinfold, supraspinale skinfold, anterior thigh skinfold, chest girth, hip girth and biiliocristal breadth there could be some possible heteroscedastic issues. As these skinfold measures illustrated evidence of heteroscedasticity, a judgement was needed to establish whether the data needed to be log transformed or not. The data was too symmetrical around the horizontal axis of the Bland and Altman plots and were statistically significant ($P = < 0.001$) and were within the 95% confidence limits between the two repeated measures. Consequently, there was no need to carry out log transformation as there was no issue and statistical analyses demonstrated excellent reliability.

As there are obvious patterns of distribution within each case, the primary investigator used a hypothetical anthropometric value for each measure. For instance, sitting height has a 95% probability that it could be measured as low as 83.5 – 0.1 = 83.4 cm to as high as

83.5 + 0.2 = 83.7 cm. In immediate contrast, the abdominal skinfold and one measure that demonstrated possible heteroscedasticity, is a 95% probability that the skinfold thickness could be measured as low as 14.6 – 0.3 = 14.3 mm to as high as 14.6 + 0.3 = 14.9 mm. When expressed in this way, Atkinson and Nevill (1998) believe that the 95% limits of agreement are actually an estimate of total error (bias + random error). Indeed the question that anthropometrist need to ask is, are the 95% limits of agreement narrow enough for measurements to be of practical use.

4.5 Summary of main findings

As far as the primary investigator is aware, no calibration models exist in the literature to estimate whole body density (g ml^{-1}) on professional football players. Subsequently there is a need to establish such practical model(s) to make sound body composition judgements. The organic nature of this thesis contributes to knowledge with the development of calibration models on a large sample of professional football players, moreover with its unique application of cross-validation methods. However, without establishing the accuracy and reliability of anthropometric measures from study 1, there would not be a foundation on which to build study 2 or study 3. The primary investigator needed above all to have confidence in the reliability of such anthropometric measures in order to make sound judgements about professional football players' body composition. Therefore the purpose of this study was to judge whether the identification and quantification of agreement was narrow enough for n = 27 anthropometric measures to be providing practically reliable values. That is, whether a range of error of this magnitude would have any detrimental effect on the practical use of values gathered with this population of participants.

- The primary investigator achieved highly reliable TEM% standard values against those of the ISAK level 1 criterion indicated as high as 6.5% and as low as 1.0% differences and against TEM% level 2/3 criterion with differences as high as 3.8% and as low as 0.6%. The humerus and femur widths provided some of the lowest differences, possibly due to measures being conducted on bone surfaces and providing less variance. However, there are some measures that have greater variability due to measurement error and poor repeatability. In acknowledgement of these concerns, ISAK increased the TEM% to help reduce errors. Nevertheless, the skinfolds of the biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, anterior thigh and the girths of the waist and hips were still lower than the ISAK recommended TEM% by as much as 3.8%, and although illustrated some of the highest differences, the primary investigator was well within acceptable limits for these skinfolds. There was recognition that the primary investigator had not obtained accredited ISAK level 2 status, indicating that n = 11 variables did not formally go through the training and accreditation process. However, data collected followed strict ISAK (2001) protocols for all variables and for the purposes of statistical analyses data was compared to ISAK level 2 and displayed in Table 4.7. Once TEM% was calculated the primary investigator had confidence that they were operating within ISAK level 2 standards for all n = 28 variables. Therefore, the primary investigator achieved reliable TEM% values, indicating measurement precision and competency for anthropometric measurements well within acceptable ISAK TEM% targets (see Table 4.7) (ISAK, 2011).

- Statistical analysis determined via Bland and Altman's 95% limits of agreement method was used to determine the bias and random variation of *n* = 27 anthropometric measures. Anthropometric measures including stretched stature, sitting height, triceps skinfold, biceps skinfold, subscapular skinfold, iliac crest skinfold, medial calf skinfold, neck girth, arm (relaxed) girth, arm (flexed) girth, forearm girth, wrist girth, calf girth, ankle girth, biacromial breadth, biiliocristal breadth, transverse chest depth, anterior-posterior chest depth, humerus width and femur width, illustrated obvious differences between the test and re-test values, but all were found to be normally distributed, with some evidence of systematic bias and random variation. In general, bias ranged from + 0.01 to + 0.08 mm for skinfolds, - 0.01 to + 0.07 (cm), for girths and 0.1 to + 0.06 (cm) for breadths, depths and widths. Remaining *n* = 7 anthropometric measures of the supraspinale skinfold, abdominal skinfold, anterior thigh skinfold, medial calf skinfold, chest girth, waist girth and hips girth, required closer scrutiny. For instance, the chest girth, can be problematic due to the inhalation and exhalation processes and the hips girth due to participants wearing light clothing in that region, which could potentially impact on test-retest values.

- The study's *a priori* criterion was set at ± 3.8% as acceptable limits for the Bland and Altman 95% limits of agreement method (Bland & Altman, 1986; ISAK, 2001; Marfell-Jones, 2013). According to the study's *a priori* criteria, the primary investigator was well within acceptable limits for all *n* = 27 anthropometric measures.

- Bland and Altman 95% limits of agreement approaches were used to determine heteroscedasticity with the n = 27 anthropometric measures. The contentious measurements of the iliac crest skinfold, supraspinale skinfold, anterior thigh skinfold, chest girth, hip girth and biiliocristal breadth suggested possible heteroscedasticity issues with highest r values of 0.611 and R^2 (%) coefficients of 37.3%. However, when investigated further, these plots did not exhibit heteroscedasticity because there is equal residual variance about the range of the values and were statistically significant (P = < 0.001). As a consequence, there was no need to find a cause of heteroscedasticity and resolve it by log transformation. It can therefore be concluded that following appropriate Bland and Altman limits of agreement statistical analysis and dealing with heteroscedasticity issues, all twenty seven anthropometric test and re-test measures were statistically significant (P < 0.001) and within the 95% limits of agreement and demonstrated agreement and reliability.

- It is well documented of the importance of reliability and measurement error. Indeed, better reliability suggests better precision, although within the area of body composition, it is not uncommon to encounter such random variation. These variations include anything from equipment calibration to technical execution and repeatability. Therefore, in order for this thesis to be as applied as possible, confidence in reliability judgements on n = 27 anthropometric measures was crucial. Overall, the primary investigator established reliability of measures and provided a sound foundation on which to build study 2 and study 3.

Chapter 5

Study 2

Validity of calibration models to estimate whole body density

5.1 Introduction

To date there are many calibration models that exist in the scientific literature used to predict whole body density and they have been developed for various populations, ranging from athletic to sedentary (Brožek & Keys, 1951; Forsyth & Sinning, 1973; Durnin & Womersley, 1974; Jackson & Pollock, 1978; Katch & Katch, 1980) and from children to the aged (Wilmore & Behnke, 1969; Lohman, 1981; Wang *et al.,* 2000). Many of these calibration models are based on the measurement of one or more indirect variable(s) such as body mass, stretched stature, various skinfold thicknesses, body circumferences and girths, or a combination of these (Russo *et al.,* 1992). When combined with a direct method such as hydrostatic weighing, these variables can contribute towards the estimation of whole body density. If these calibration models for the estimation of whole body density are to be useful in a football or indeed a sporting context, their validity must be established. From a sport science research perspective, questions remain about measurement validity and in retrospect how they can affect the confidence of what sport scientists have to say about the meaningfulness of their measurement data.

Prior research has revealed some limitations in the validity of such calibration models (Vincent, 1999; Atkinson & Nevill, 2001). Firstly, the site location and restrictive range of the anthropometric variables that are used as individual components within a calibration model are problematic (Heyward, 2000; Atkinson & Nevill, 2001). There is no evidence to suggest that the greater the number of variables or the most commonly used variables will result in a model that estimates whole body density with greater precision. Indeed what it does provide is an opportunity to potentially use a wide range of variables which could aid a sports scientist whom is working in the field.

Secondly, a plausible limitation could be the manner in which the anthropometric variables are used interchangeably within the calibration model regression equation. The reason that this is deemed noteworthy is that the regression equation can provide an outcome for male athletes with significant errors in whole body density (g ml^{-1}) (Ball *et al*., 2004; Ishiguro *et al*., 2005; Peeters *et al*., 2013). In some instances, models included variables as either stand-alone outcomes, a combination of summed variables, squared or even logged, indicating a variety of different approaches with the development of such calibration models. Thirdly, the sample size employed when designing a model. Some models have reported to use sample sizes of n = 50 participants or less, which is not considered an adequate basis upon which to develop calibration models due to the restrictive nature of the calibration model and to the resulting wide confidence intervals (normally expressed as standard error of the estimate) (Hawes, 1996; Atkinson, 2005). Finally, that cross-validation of the resulting model has not been undertaken (Vincent, 1999). Ideally, the calibration model should be cross-validated by comparing values in a different sample of participants drawn from the population of interest, than those originally used to develop the calibration model (Vincent, 1999; Atkinson & Nevill, 2001).

A pertinent example of some of these limitations can be seen from the classic paper by Durnin and Womersley (1974). They were amongst the first researchers to consider different populations and various combinations of anthropometric skinfold measurements (Cooper, 1995). Furthermore, their sample of n = 481 participants (209 men and 272 women), drawn from the age ranges of 16-72 years demonstrated a large anthropometric data collection for its time. However, scrutinisation of their methods revealed that Durnin and Womersley (1974) split their sample into male and female groups, and further into age groups (17-19, 20-29, 30-39, 40-49, 50-72 years for men

and 16-19, 20-29, 30-39, 40-49, 50-68 years in women). Division of the overall sample in these ways resulted in some density models being developed from samples as small as n = 24 participants, which is far fewer given the overall sample size. Furthermore, Durnin and Womersley (1974) did not cross-validate their calibration models using a different sample of participants drawn from the population of interest, thereby questioning the validity of such models (Becque *et al.*, 1986; Sheng, 1988; Vincent, 1999; Atkinson & Nevill, 2001).

With these limitations in mind, care must be taken when selecting an appropriate calibration model to use on another population sample, by taking account of the circumstances of initial validation, the nature of the sample used (including sample size and sample characteristics) and procedural factors (Mayhew *et al.*, 1985; Cooper, 1995; Heyward, 2000). With the number of calibration models available, careful examination of the validity of the whole body densities predicted by these models is warranted. However, the primary investigator had to make an informed decision, based on a consistent selection criterion, about which calibration models should be included in study 2. Hence, the aim of the study 2 was to determine the agreement and subsequent validity from a range of previously published calibration models used to predict body density determined from underwater weighing as the criterion measurement method. The data entered into the models were gained from careful measurements with known reliability (Study 1), the sample size was large (n = 206 participants) and the criterion validity was determined with reference to Bland and Altman's 95% limits of agreement approach.

5.2 Methods

5.2.1 Participants and recruitment

Two hundred and six Fédération Internationale de Football Association (FIFA) registered contracted professional football players ($\bar{x} \pm s$; age = 24.1 ± 5.4 years, body mass = 78.8 ± 8.4 kg, stretched stature = 180.1 ± 7.0 cm and whole body density = 1.075 ± 0.010 (g ml^{-1}) were recruited from eight professional football clubs that represented Barclays Premiership, npower Championship, npower League One, npower League Two and Blue Square Premier Leagues during the 2007-2008, 2008-2009 and 2009-2010 playing seasons. Sampling included players who were all over 18 years of age, free from disease or illness and who agreed to act as participants for the study by giving their written informed consent. Signs and symptoms of disease and diagnosed disease were determined through health screening procedure involving completion of a health screening questionnaire. Ethical considerations were carried out using robust operational procedures as previously reported in Section 3.2.

5.2.2 Approach to inclusion of calibration models

As previously discussed a plethora of calibration models exist in the literature that investigate the reliability and validity of skinfold thickness for the estimation of body density specifically on young athletic men (Forsyth & Sinning, 1973; Katch & McArdle, 1973; Wickkiser & Kelly, 1975; White *et al*., 1980). With the number of calibration models available, the primary investigator needed to interrogate the degree to which models could potentially be applied to the present population. A decision was made to consider all potential models, while a consistent selection criterion (*a priori*) was put in place for accepting or rejecting them for future investigation in study 2. Whilst examining the literature for potential models, many authors failed to present sufficient detail to extract the components of the model(s) within their paper, therefore,

those potential model(s) could not be used. Table 5.1 illustrates the calibration models that were considered and where relevant data was able to be extracted from the literature. For instance, (i) year of publication, which illustrates the timespan in which models have been designed; (ii) sample number, to determine the range of participants that were used for each study and subsequent model(s); (iii) sample population, to illustrate the type of population that was used (volunteers, sports enthusiast's etc.); (iv) Country, to establish where the study was carried out; (v) Ethnicity, to indicate the number of Caucasian and non-Caucasian participants that were used; (vi) Skinfold caliper, to determine the type of caliper that was adopted when carrying out the study; (vii) $\bar{x}$ or ranges of the age, body mass and stretched stature of each study's sample.

Of the 18 models identified, four models were rejected on the basis that they required the chest skinfold to be measured, which is considered outdated in relation to International Society for the Advancement of Kinanthropometry (ISAK) accreditations. Subsequently 14 models and via the processes of air displacement plethysmography were accepted to predict whole body density in professional football players in the present study (Table 5.1).

Table 5.1 Calibration Models for consideration in Study 2

Nº	Author(s)	Publication Year	Sample No	Sample Characteristics	Country	Ethnicity	Skinfold Caliper	Age	Body Mass	Stretched Stature	Accept or reject model
1	Pascale *et al*.,	1956	88	Soldiers	America	Caucasian	Medical Nutrition	17.0 – 25.0	49.7 – 109.8	94.0 – 193.0	Reject
2	Brožek & Keys	1951	159	University students	America	Undisclosed	Undisclosed	$\overline{X}$ 20.4	$\overline{X}$ 69.1	$\overline{X}$ 177.8	Reject
3	Durnin & Rahaman	1967	60	Volunteers	Scotland	Undisclosed	Harpenden	18.1 – 33.8	43.6 – 95.6	154.8 – 192.0	Accept
4	Sloan	1967	50	University students	South Africa	Undisclosed	Medical Nutrition	18.0 – 26.0	57.8 – 85.7	163.0 – 191.0	Accept
5	Wilmore & Behnke	1969	133	University students	America	Undisclosed	Lange	16.8 – 36.8	53.2 – 121.2	159.0 – 193.4	Accept
6	Sloan & Weir	1970	50	Volunteers	Scotland	Undisclosed	Medical Nutrition	18.0 – 26.0	Undisclosed	Undisclosed	Accept
7	Forsyth & Sinning	1973a	50	University sports students	America	Undisclosed	Lange	19.0 – 22.0	68.5 – 85.9	178.4 – 179.6	Accept
8	Forsyth & Sinning	1973b	50	University sports students	America	Undisclosed	Lange	19.0 – 22.0	68.5 – 85.9	178.4 – 179.6	Accept
9	Katch & McArdle	1973	53	University sports students	America	Caucasian	Lange	18.0 – 21.0	62.8 – 80.0	169.4 – 183.4	Accept
10	Behnke & Wilmore	1974	54	University students	America	Undisclosed	Undisclosed	Undisclosed	Undisclosed	Undisclosed	Accept
11	Durnin & Womersley	1974	209	Sports enthusiasts	Scotland	Undisclosed	Harpenden	17.0 – 72.0	49.8 – 121.4	150.0 – 193.0	Accept
12	Wickkiser & Kelly	1975	65	American footballers	America	Undisclosed	Lange	$\overline{X}$ 17.2	$\overline{X}$ 88.0	$\overline{X}$ 182.5	Accept
13	Pollock *et al*.,	1976	95	Volunteers	America	Undisclosed	Lange	18.0 – 22.0	74.6 – 82.2	179.6 – 179.8	Reject
14	Jackson & Pollock	1978	403	Volunteers	America	Undisclosed	Lange	18.0 – 61.0	54.0 – 123.0	163.0 – 201.0	Accept
15	White et al.,	1980	58	American footballers	America	Undisclosed	Undisclosed	$\overline{X}$ 19.9	$\overline{X}$ 89.7	$\overline{X}$ 182.0	Accept
16	Lohman	1981	61	University students	America	Undisclosed	Undisclosed	Undisclosed	Undisclosed	Undisclosed	Accept
17	Thorland *et al*.,	1984	141	Athletes of national calibre	America	Undisclosed	Lange	16.5 – 18.4	56.2 – 78.8	167.9 – 185.1	Accept
18	Withers *et al*.,	1987	207	State representatives	Australia	Undisclosed	Harpenden	15.4 – 39.1	53.3 – 117.3	154.1 – 215.1	Reject

The accepted models illustrated from Table 5.1 were varied in terms of both their methodologies, as well as the year of publication which ranged from as far back as 1967 to 1984. No models were available post 1987. Sample numbers ranged from 50 – 403 participants, with 10 studies having less than 100 participants. The populations used mainly consisted of university students or volunteers, but no model was designed specifically for use with professional football players. On 13 occasions the ethnicity of the population was undisclosed, suggesting the study used a Caucasian sample. The most commonly used skinfold caliper was the Lange, Harpenden or Medical Nutrition models, although the type of caliper used was often dependent upon the country where the study took place. For instance the Lange is extremely popular in North America. Seven studies used the Lange and were conducted in America. The Harpenden (the skinfold caliper used in the present study) was used predominately used within the United Kingdom. The $\bar{x}$ or ranges of the age, body mass and stretched stature were provided for illustrative purposes of each study's sample.

Table 5.2 provides the components of the calibration model regression equations for the 14 accepted pre-published calibration models for the prediction of whole body density used in study 2. Furthermore, Table 5.2 exhibits the anthropometric measures that were common within the models, which consisted of the biceps, triceps, subscapular, suprailiac, abdominal, supraspinale, iliac crest, anterior thigh and medial calf skinfolds, stretched stature, waist circumference and biiliocristal breadth.

Table 5.2 Calibration models for the prediction of whole body density (g ml^{-1})

Durnin and Rahaman (1967)

$D_b = 1.1610 – 0.0632$ X

Where X = $\log_{10}$ of the Σ of biceps, triceps, subscapular and suprailiac skinfolds

Sloan (1967)

$D_b = 1.1043 – 0.001327 (X_1) – 0.001310 (X_2)$

Where X_1 = front thigh skinfold, X_2 = subscapular skinfold

Wilmore and Behnke (1969)

$D_b = 1.08543 – 0.000886 (X_1) – 0.00040 (X_2)$

Where X_1 = abdominal skinfold, X_2 = front thigh skinfold

Sloan and Weir (1970)

$D_b = 1.1043 – 0.00133 (X_1) – 0.00131 (X_2)$

Where X_1 = anterior thigh skinfold, X_2 = subscapular skinfold

Forsyth and Sinning (1973a)

$D_b = 1.10647 – 0.00162 (X_1) – 0.00144 (X_2) – 0.00077 (X_3) + 0.00071 (X_4)$

Where X_1 = subscapular skinfold, X_2 = abdominal skinfold, X_3 = triceps skinfold, X_4 = mid-axilla skinfold

Forsyth and Sinning (1973b)

$D_b = 1.03523 – 0.00156 (X_1) + 0.00207 (X_2) – 0.00140 (X_3)$

Where X_1 = subscapular skinfold, X_2 = biiliocristal breadth, X_3 = abdominal skinfold

Katch and McArdle (1973)

$D_b = 1.09665 – 0.00103 (X_1) – 0.00056 (X_2) – 0.00054 (X_3)$

Where X_1 = triceps skinfold, X_2 = subscapular skinfold, X_3 = abdominal skinfold

Behnke and Wilmore (1974)

$D_b = 1.08543 – 0.00086 (X_1) – 0.00040 (X_2)$

Where X_1 = abdominal skinfold, X_2 = anterior thigh skinfold

Durnin and Womersley (1974)

$D_b = 1.1765 – 0.0744 (\log_{10} X_1)$

Where X_1 = Σ 4 skinfolds (triceps, biceps, subscapular and iliac crest)

Wickkiser and Kelly (1975)

$D_b = 1.10148 – 0.00118 (X_1) - 0.00114(X_2) + 0.00044 (X_3)$

Where X_1 = waist circumference, X_2 = triceps skinfold, X_3 = stretched stature

Jackson and Pollock (1978)

$D_b = 1.0982 – 0.000815 (X) + 0.0000084 (X)^2$

Where X = Σ 3 skinfolds (triceps, abdomen and subscapular)

White *et al*., (1980)

$D_b = 1.0958 – 0.00088 (X_1) – 0.00060 (X_2)$

Where X_1 = suprailiac skinfold, X_2 = anterior thigh skinfold

Lohman (1981)

$D_b = 1.1091 – 0.00052 (X_1) + 0.00000032 (X_1)^2$

Where X_1 = Σ 7 skinfolds (triceps, subscapular, mid-axilla, iliac crest, abdominal, front thigh and medial calf)

Thorland *et al*., (1984)

$D_b = 1.0988 – 0.0004 (X_1)$

Where X_1 = Σ 7 skinfolds (triceps, subscapular, biceps, supraspinale, abdominal, front thigh and medial calf)

5.3 Statistical analyses

In order to establish the requisite indices of validity for each calibration model for participants whole body density (g ml^{-1}) there are three major elements that need to be considered and can be investigated by application of Bland and Altman's (1986) 95% limits of agreement method. This method relies on the assumptions that the $\bar{x}$ and *s* of the differences between calibration models and criterion method of hydrostatic weighing are constant (Bland & Altman, 1986; Atkinson & Nevill, 2001). As it is a parametric method, it is also predicated on the assumption that the differences calibration models and criterion method follow a normal distribution in the population from which the samples were drawn (Bland & Altman, 1986; Atkinson & Nevill, 2001). Bland and Altman (1986) recommend that it is possible for the sport scientist to observe and identify three components of agreement plot the respective plots (see Figures 5.1 – 5.4). First, whether there is a systematic bias in the collected data, second, what is the degree of random variation in the observed data and third the degree of heteroscedasticity in the data, which is the condition of un-equal residual variance.

The treatment of validity of each calibration model was determined by applying the 95% limits of agreement method to quantify the bias and the limits of agreements. Bland and Altman (1986) maintain that the great majority of the differences between values should lie between the limits of agreement $\pm$ 1.96 x s_{diff}). For each calibration model, calculated whole body density (g ml^{-1}) was plotted against the criterion value on a scatter plot that included the line of identity to allow a visual overview of the agreement between each calibration model and the criterion (see Figures 5.1 – 5.4).

Calculations involve determining the mean difference ($\bar{x}_{diff}$) between the criterion and calibration model values to establish the bias and to compute the standard deviation of the differences (s_{diff}) between the criterion and calibration model values to establish the random variation.

Quantification first identifies the extent of systematic bias in the whole body density (g ml^{-1}) values from the mean of the differences between each calibration model and criterion method of hydrostatic weighing ($\bar{x}_{diff}$). Random variation between calibration model and criterion method values is related to the standard deviation of the differences and provided the differences are confirmed as being normally distributed in the population form which the sample was drawn can be expressed to a 95% probability – 1.96 x ($s_{diff.}$) The extent to which heteroscedasticity is present in these scores can be quantified by correlating absolute differences against mean scores for calibration model and criterion method values and can be illustrated on a scatter plot of these two variables (see Figures 5.5 – 5.8). The scatter plot included R^2, *r* and *P*-values and the distribution line to allow a visual overview of the relationship between the calibration model and the criterion values (see Table 5.5).

The final part of the treatment of validity values is to identify error for each model and to contextualise and interpret the quantification of agreement, where it would be expected that variability between whole body density (g ml^{-1}) derived from underwater weighing values should lie (Figure 5.7). The issue for the primary investigator is to judge, whether these limits of agreement are narrow enough for the whole body density (g ml^{-1}) to be providing practically valid values. That is, whether a range of error of this magnitude would have any detrimental effect on the practical use of values gathered from this whole body density (g ml^{-1}) with this population of participants. Therefore the

primary investigator established *a priori* consideration for the Bland and Altman 95% LoA method (relative reliability) that presented acceptable tolerable limits within the context of this study. The process of arriving at the acceptable limits is not set to determine whether the agreement is small enough to allow minimal impact on the participant. The acceptance limit may be too broad to detect actual changes in what is being measured, but may have a hierarchical impact. Under review from ISAK and previous literature, Bland and Altman 95% LoA method was set at ± 3.8% ($P <= 0.05$) as acceptable limits (ISAK, 2001; Ludbrook, 2010; Woodman, 2010; Marfell-Jones, 2013 (personal communication – see Appendix X)). For instance, whole body density of 1.075 g ml^{-1} could be considered average within the context of this thesis, therefore ± 3.8% acceptable limit, whole body density ranged from 1.034 to 1.116 g ml^{-1} in the studied population. Too high could impose possible impact on training prescription and possible impact on team selection. Conversely too low could be considered a definite danger to the health and wellbeing of the participant. When illustrated in this manner, it is clear that the acceptable limits can be used interchangeably with the criterion measurement method to assess body density in professional football players.

5.4 Results and discussion

Table 5.3 reveals the general characteristics for hydrostatic weighing, $n = 14$ calibration models plus air displacement to predict whole body density (g ml^{-1}).

Table 5.3 General summary ($\bar{x} \pm s$) characteristics for hydrostatic weighing, $n = 14$ calibration models plus air displacement to predict whole body density (g ml^{-1})

Calibration models	$\bar{x} \pm s$ (g ml^{-1})	**Range** (g ml^{-1})
Durnin and Rahaman (1967)	1.066 ± 0.008	1.047 – 1.083
Sloan (1967)	1.075 ± 0.008	1.047 – 1.090
Wilmore and Behnke (1969)	1.068 ± 0.006	1.045 – 1.079
Sloan and Weir (1970)	1.074 ± 0.001	1.039 – 1.092
Forsyth and Sinning (1973a)	1.070 ± 0.011	1.034 – 1.089
Forsyth and Sinning (1973b)	1.060 ± 0.011	1.025 – 1.081
Katch and McArdle (1973)	1.075 ± 0.007	1.053 – 1.086
Behnke and Wilmore (1974)	1.068 ± 0.006	1.046 – 1.079
Durnin and Womersley (1974)	1.060 ± 0.010	1.037 – 1.082
Wickkiser and Kelly (1975)	1.074 ± 0.007	1.048 – 1.091
Jackson and Pollock (1978)	1.081 ± 0.002	1.078 – 1.086
White *et al*., (1980)	1.080 ± 0.005	1.060 – 1.089
Lohman (1981)	1.071 ± 0.011	1.035 – 1.092
Thorland *et al*., (1984)	1.072 ± 0.008	1.045 – 1.086
Air displacement plethysmography	1.071 ± 0.015	1.050 – 1.090
Hydrostatic weighing	**1.075 ± 0.015**	**1.034 – 1.132**

Bland and Altman 95% limits of agreement approaches were used to determine the bias, random variation and heteroscedasticity. Figures 5.1 – 5.4 exhibit the Bland and Altman plots for whole body density (g ml^{-1}) gained from the criterion method of hydrostatic weighing and each individual calibration models and air displacement method.

Figure 5.1 exhibit the Durnin and Rahaman (1967), Sloan (1967), Wilmore and Behnke (1967) and Sloan and Weir (1970) calibration models (g ml^{-1}) where there is a bias of +0.009 g ml^{-1}, +0.000 g ml^{-1}, +0.008 g ml^{-1} and +0.001 g ml^{-1} and 95% limits of agreement of –0.018 to +0.036 g ml^{-1}, –0.027 to +0.028 g ml^{-1}, –0.019 to +0.034 g ml^{-1} and –0.027 to +0.029 g ml^{-1} respectively. There is some evidence of systematic bias and random variation where there are data plots that lie above and below the zero line, with the distances ranged between -0.027 to +0.036 g ml^{-1}. The differences between the calibration models and the criterion method of hydrostatic weighing were normally distributed. Therefore the study's *a priori* criteria propose that these findings are within acceptable limits, although both Durnin and Rahaman (1967) and Wilmore and Behnke (1967) calibration models were at the upper limits.

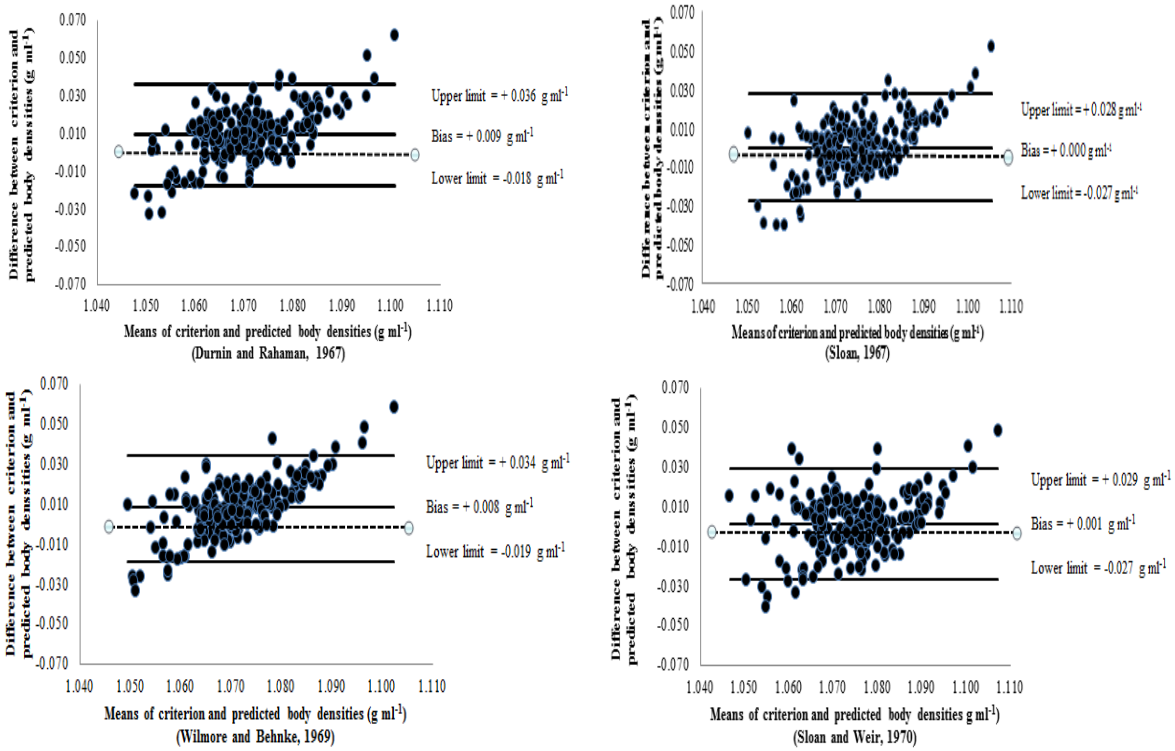

Figure 5.1 Bland and Altman plots summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the Durnin and Rahaman (1967) calibration model; Sloan (1967) calibration model; Wilmore and Behnke (1969) calibration model and Sloan and Weir (1970) calibration model (g ml^{-1})
Note: Direction of bias [hydrostatic weighing – calibration model]

The Forsyth and Sinning (1973a), Forsyth and Sinning (1973b), Katch and McArdle (1973) and Behnke and Wilmore (1974) calibration models (g ml^{-1}) are illustrated in Figure 5.2 where there is a bias of +0.006 g ml^{-1}, +0.015 g ml^{-1}, +0.001 g ml^{-1} and +0.007 g ml^{-1} and 95% limits of agreement of –0.023 to +0.034 g ml^{-1}, –0.015 to +0.045 g ml^{-1}, –0.026 to +0.027 g ml^{-1} and –0.019 to +0.033 g ml^{-1} respectively. Systematic bias and random variation is evident with the distances ranged between -0.015 to +0.045 g ml^{-1} with the differences between the criterion method of hydrostatic weighing and calibration models being normally distributed. According to the study's *a priori* criteria propose that the model proposed by Katch and McArdle (1973) were within acceptable limits, and Forsyth and Sinning (1973a) and Behnke and Wilmore (1974) models were at the upper limits of the criteria. However, the model presented by Forsyth and Sinning (1973b) were not within acceptable limits by 0.007 g ml^{-1}.

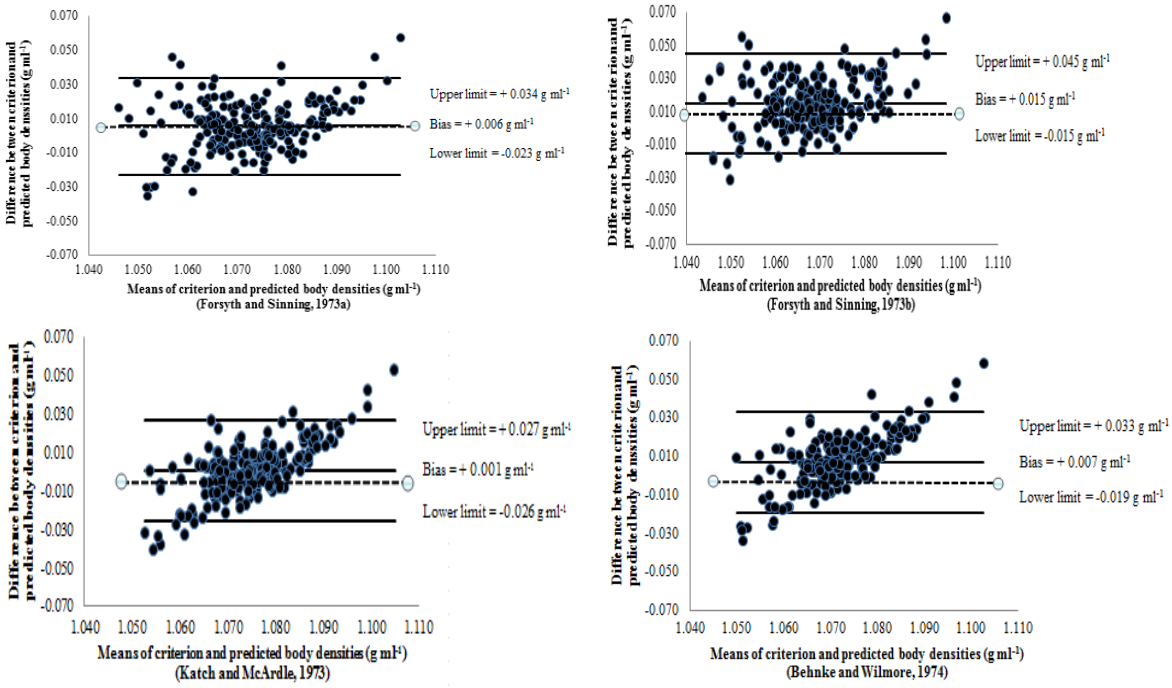

Figure 5.2 Bland and Altman plots summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the Forsyth and Sinning (1973a) calibration model; Forsyth and Sinning (1973b) calibration model; Katch and McArdle (1973) calibration model and Behnke and Wilmore (1974) calibration model (g ml^{-1})
Note: Direction of bias [hydrostatic weighing – calibration model]

Figure 5.3 display the Durnin and Womersley (1974), Wickkiser and Kelly (1975), Jackson and Pollock (1978) and White *et al*., (1980) calibration models (g ml^{-1}) where there is a bias of +0.015 g ml^{-1}, +0.001 g ml^{-1}, -0.006 g ml^{-1} and -0.005 g ml^{-1} and 95% limits of agreement of –0.012 to +0.043 g ml^{-1}, –0.028 to +0.029 g ml^{-1}, –0.033 to +0.021 g ml^{-1} and –0.031 to +0.021 g ml^{-1} respectively. There is evidence of systematic bias and random variation with the distances ranged between -0.012 to +0.043 g ml^{-1} with normal distribution between the criterion method of hydrostatic weighing and the calibration models. The study's *a priori* criteria indicate that the models presented by Jackson and Pollock (1978) and White *et al*., (1980) were at the lower limits of the criteria, yet Durnin and Womersley (1974) findings are not within acceptable limits by 0.005 g ml^{-1}.

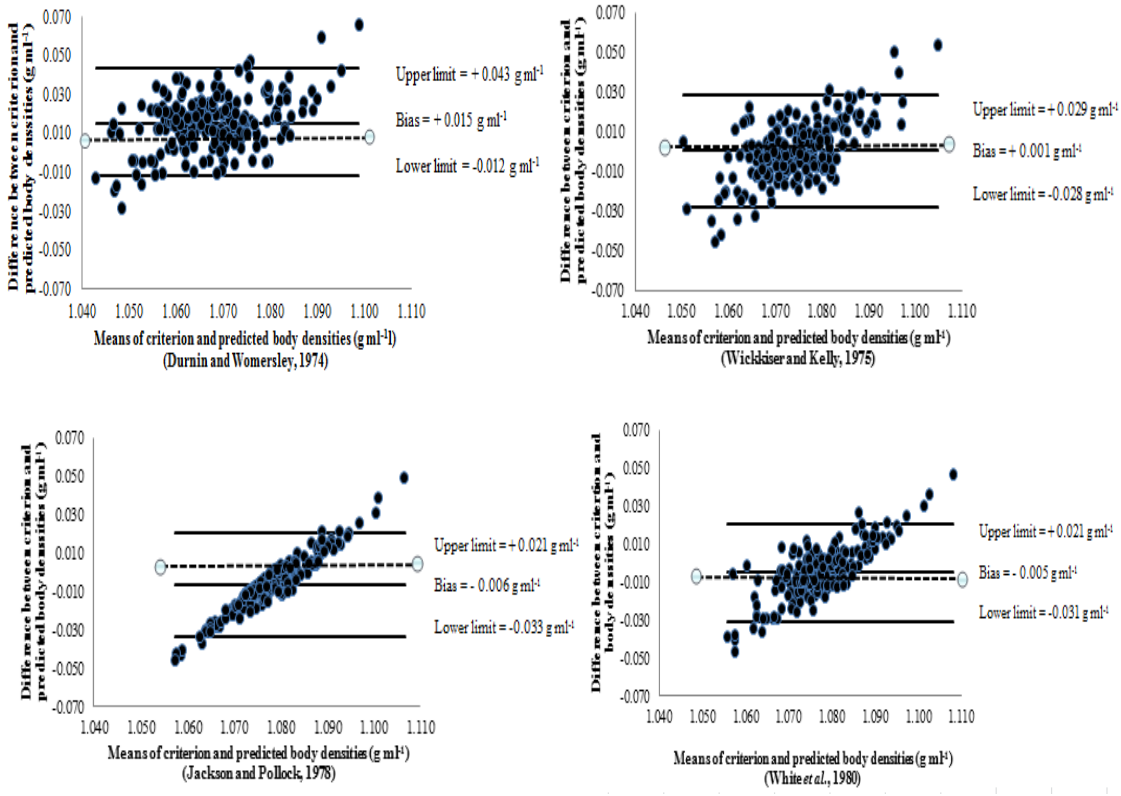

Figure 5.3 Bland and Altman plots summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the Durnin and Womersley (1974) calibration model; Wickkiser and Kelly (1975) calibration model; Jackson and Pollock (1978) calibration model and White *et al*., (1980) calibration model; (g ml^{-1})
Note: Direction of bias [hydrostatic weighing – calibration model]

Lohman (1981), Thorland *et al*., (1984) and air displacement plethysmography calibration models (g ml^{-1}) are shown in Figure 5.4 where there is a bias of +0.004 g ml^{-1}, +0.003 g ml^{-1} and +0.004 g ml^{-1} and 95% limits of agreement of –0.024 to +0.032 g ml^{-1}, –0.024 to +0.030 g ml^{-1} and –0.024 to +0.033 g ml^{-1} respectively. The air displacement plethysmograph demonstrates an ordinal scale visual that discriminates intervals between the range. As this model was based on the BodPod calculating whole body density, and as there was inaccessibility to the raw data to enable intimate calculations, these figures do not reflect visuals like the remaining calibration models. There is some evidence of systematic bias and random variation therefore the *a priori* criteria these findings are within acceptable limits, although Lohman (1981) and the air displacement plethysmography calibration models were found to be at the upper limits.

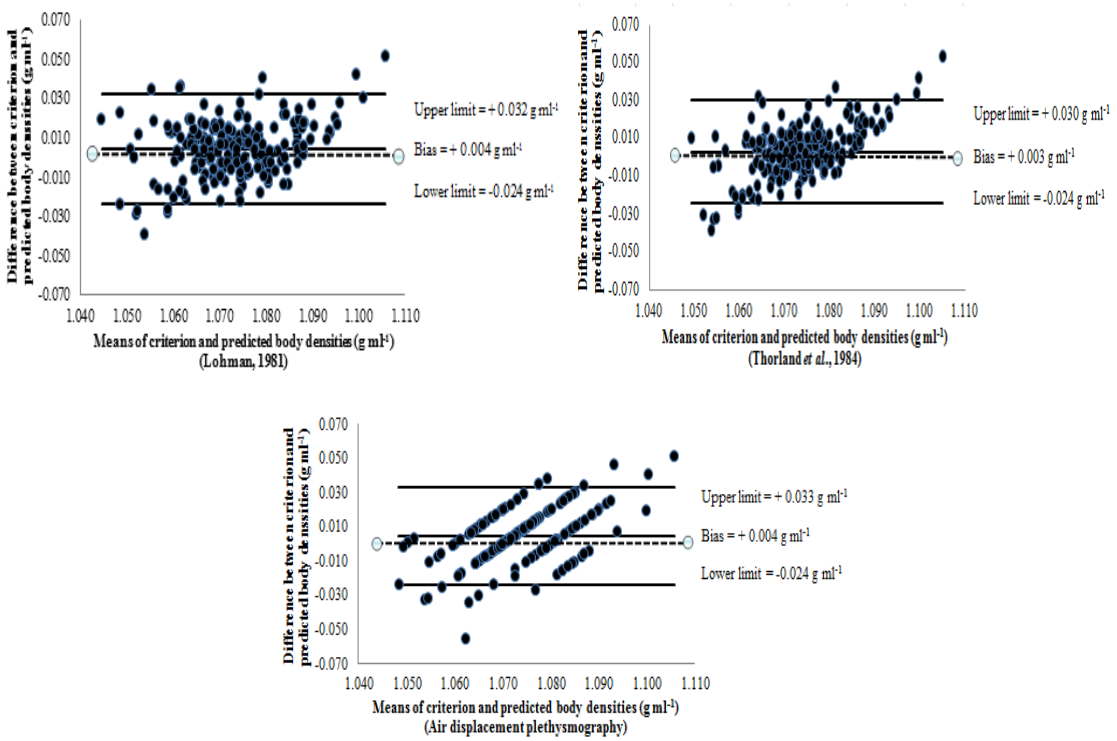

Figure 5.4 Bland and Altman plots summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the Lohman (1981) calibration model; Thorland *et al*., (1984) calibration model and Air displacement plethysmography (BodPod) calibration model (g ml^{-1})
Note: Direction of bias [hydrostatic weighing – calibration model]

For illustrative purposes, Table 5.4 provides an overview of bias, lower and upper limits of 95% limits of agreement for all calibration models displayed from Figures 5.1 – 5.4. Inspection of Table 5.4 indicated that in thirteen of the calibration models (on average) whole body density (g ml^{-1}) derived from hydrostatic weighing was greater than whole body density (g ml^{-1}) derived from the models, so there was a positive bias. Results from the 95% limits of agreement analyses indicated bias (systematic errors) between criterion measured body densities and densities predicted by calibration models ranged from 0.005 to 0.009 g ml^{-1} and random errors ranged from 1.012 to 1.079 g ml^{-1} thus suggesting underestimation of whole body density of professional football players.

Table 5.4 Overview of 95% upper and lower limits of agreement and bias indicators for (n = 14) calibration models plus air displacement method

Calibration models	**Bias** (g ml^{-1})	**(95 LoA) Lower Limit** (g ml^{-1})	**(95 LoA) Upper Limit** (g ml^{-1})
Durnin and Rahaman (1967)	+0.009	-0.018	+0.036
Sloan (1967)	+0.000	-0.027	+0.028
Wilmore and Behnke (1969)	+0.008	-0.019	+0.034
Sloan and Weir (1970)	+0.001	-0.027	+0.029
Forsyth and Sinning (1973a)	+0.006	-0.023	+0.034
Forsyth and Sinning (1973b)	+0.015	-0.015	+0.045
Katch and McArdle (1973)	+0.001	-0.026	+0.027
Behnke and Wilmore (1974)	+0.007	-0.019	+0.033
Durnin and Womersley (1974)	+0.015	-0.012	+0.043
Wickkiser and Kelly (1975)	+0.001	-0.028	+0.029
Jackson and Pollock (1978)	-0.006	-0.033	+0.021
White *et al*., (1980)	-0.005	-0.031	+0.021
Lohman (1981)	+0.004	-0.024	+0.032
Thorland *et al*., (1984)	+0.003	-0.024	+0.030
Air displacement plethysmography	+0.004	-0.024	+0.033

In contrast, two of the fifteen calibration models found that (on average) whole body density derived from hydrostatic weighing was lower than whole body density derived from the models, so had a negative bias. Results from the 95% limits of agreement analyses indicated negative bias (systematic errors) between criterion measured body densities and densities predicted by calibration models ranged from 0.009 to 0.015 g ml^{-1} and random errors ranged from 1.027 to 1.090 g ml^{-1} thereby indicating overestimation of whole body density of professional football players. Similar overestimation was also found in studies by Eston *et al*., (1995) and Rodríguez *et al*., (2005) where the evidence suggested over-prediction of body densities when comparing 47 healthy Chinese male adults and 113 Caucasian adolescent males respectively. According to the study's *a priori* criteria, two models presented by Forsyth and Sinning (1973b) and Durnin and Womersley (1974) were not within acceptable limits by as much as 0.007 g ml^{-1}, and 0.005 g ml^{-1} respectively. Five models were found to be at the upper limits of the criteria and two models found to be at the lower limits of the criteria, indicating a wide spectrum of reported whole body density values for professional football players. As is common place in comparison studies, models systematically underestimated whole body density in professional football players when compared to densities gathered from the criterion underwater weighing method. Of course this is a likely assumption given that the models are based on different populations. These outcomes compared well with those identified by Ball *et al*., (2004) for a similar comparison made on 160 men aged 18 - 62 years and by Jackson *et al*., (2009) made on 423 men aged 17 – 35 years.

Figures 5.5 – 5.8 exhibit the scatter plots for illustrative purposes of heteroscedasticity to demonstrate the relationship between the criterion method of hydrostatic weighing and each calibration model.

Heteroscedasticity for the Durnin and Rahaman (1967), Sloan (1967), Wilmore and Behnke (1969) and Sloan and Weir (1970) calibration models are shown in Figure 5.5 with *r* values of 0.328, 0.056, 0.374 and -0.064 and R^2 (%) coefficients of 0.1077%, 0.0031%, 0.1398% and 0.0041% respectively. These models illustrated heteroscedastic data between criterion method of hydrostatic weighing and calibration models with deviations from the line of identity between the whole body density (g ml^{-1}) values. All models indicated statistical significance of $P = 0.01$ except for Sloan and Weir (1970) $P < = 0.05$ and were normally distributed. Wider deviation from the line of identity was particularly prevalent with the model developed by Sloan and Weir (1970).

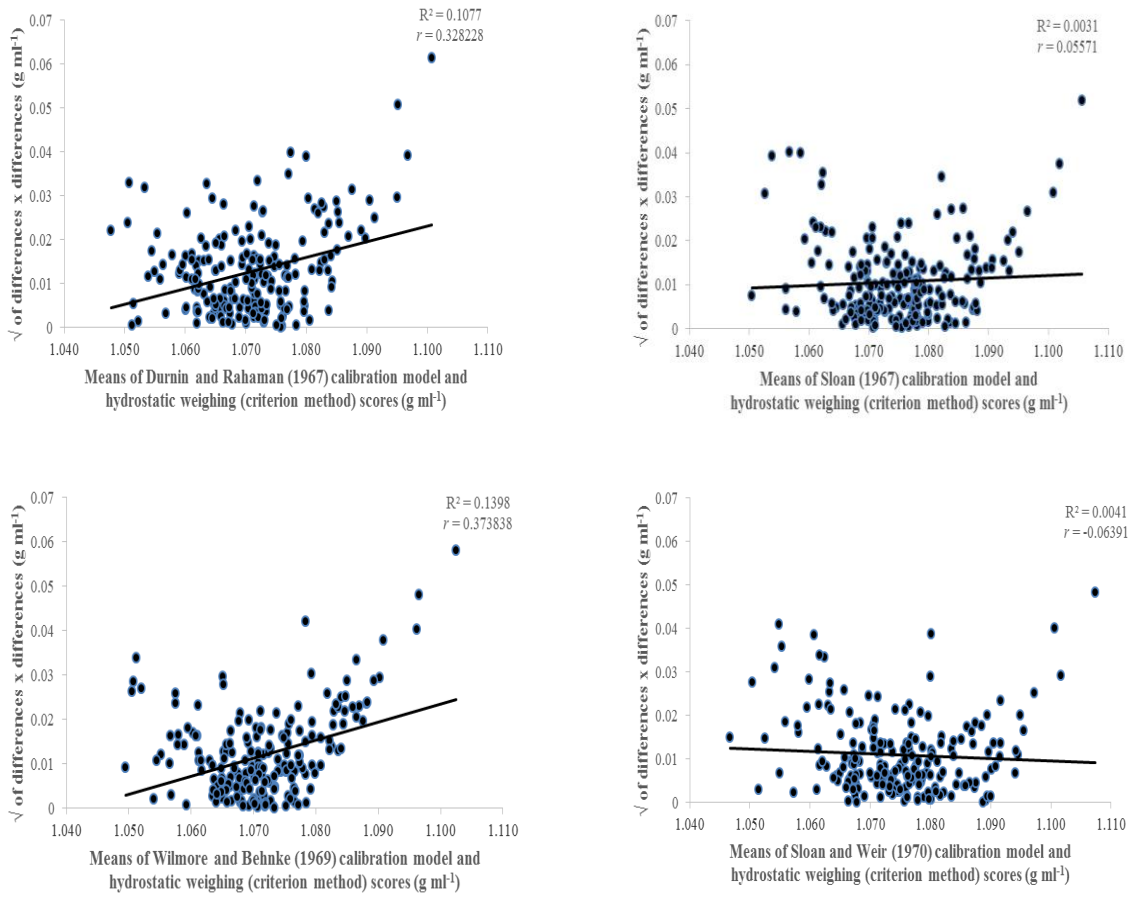

Figure 5.5 Scatter plots for the heteroscedasticity of hydrostatic weighing (criterion method) compared to Durnin and Rahaman (1967) calibration model (means); Sloan (1967) calibration model (means); Wilmore and Behnke (1969) calibration model (means) and Sloan and Weir (1970) calibration model (means) for whole body density (g ml^{-1})

The heteroscedasticity for calibration models of Forsyth and Sinning (1973a), Forsyth and Sinning (1973b), Katch and McArdle (1973) and Behnke and Wilmore (1974) and possible are shown in Figure 5.6 with *r* values of -0.024%, 0.130%, 0.106% and 0.372% and R^2 (%) coefficients of 0.0006, 0.0171, 0.0112 and 0.1387 respectively. There is some evidence of heteroscedasticity and greater error between criterion method of hydrostatic weighing and calibration models with wider deviations from the line of identity evident in the calibration models designed by Forsyth and Sinning (1973a) and Forsyth and Sinning (1973b). All models indicated statistical significance of $P <= 0.05$ except for Katch and McArdle (1973) of $P = < 0.01$ and were normally distributed.

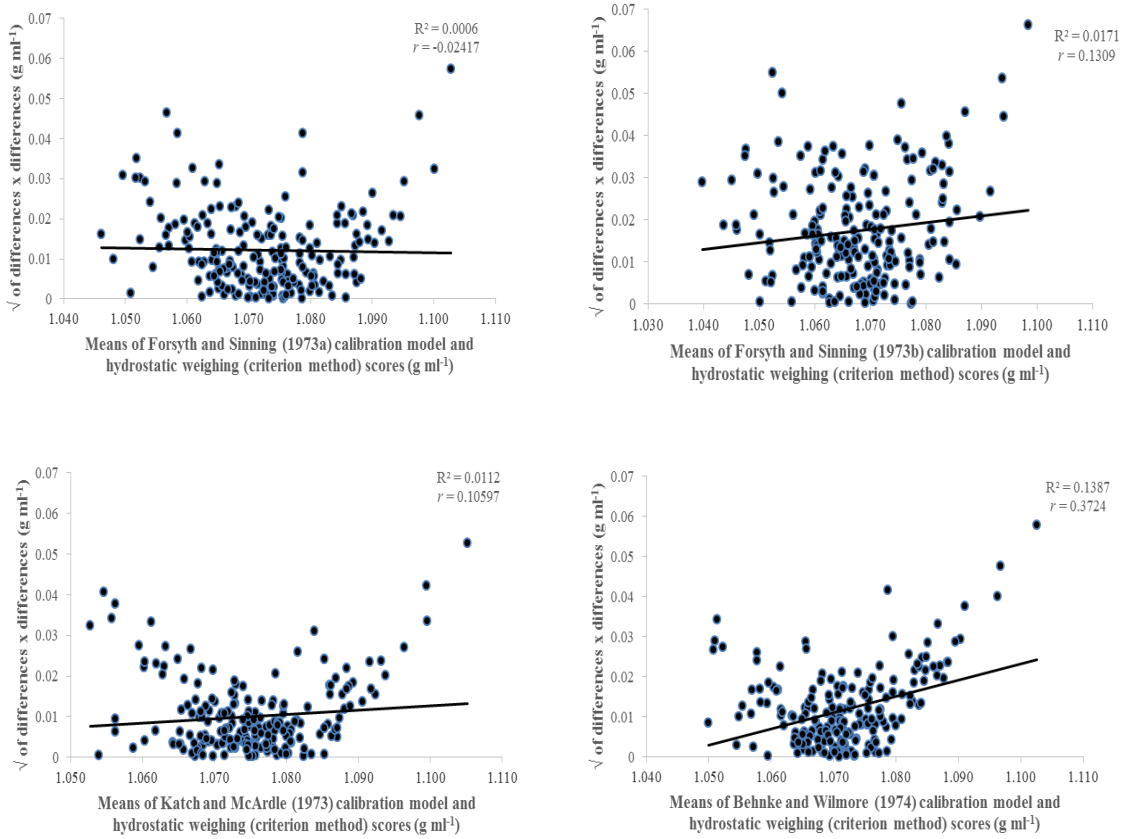

Figure 5.6 Scatter plots for the heteroscedasticity of hydrostatic weighing (criterion method) compared to Forsyth and Sinning (1973a) calibration model (means); Forsyth and Sinning (1973b) calibration model (means); Katch and McArdle (1973) calibration model (means) and Behnke and Wilmore (1974) calibration model (means) for whole body density (g ml^{-1})

Heteroscedasticity for calibration models of Durnin and Womersley (1974), Wickkiser and Kelly (1975), Jackson and Pollock (1978) and White *et al*., (1980) calibration models are shown in Figure 5.7 with *r* values of 0.286, 0.132, -0.323 and -0.185 and R^2 (%) coefficients of 0.082%, 0.0174%, 0.1046% and 0.0341% respectively. Wider deviations from the line of identity in Figure 5.7 were especially prevalent with Durnin and Womersley (1974) model, although the Jackson and Pollock (1978) model provided more controversial deviation from the line of identity and demonstrated heteroscedasticity. Jackson and Pollock (1978) and White *et al*., (1980) indicated statistical significance of $P = < 0.01$, whereas Durnin and Womersley (1974) and Wickkiser and Kelly (1975) indicated statistical significance of $P = < 0.05$ and were all normally distributed.

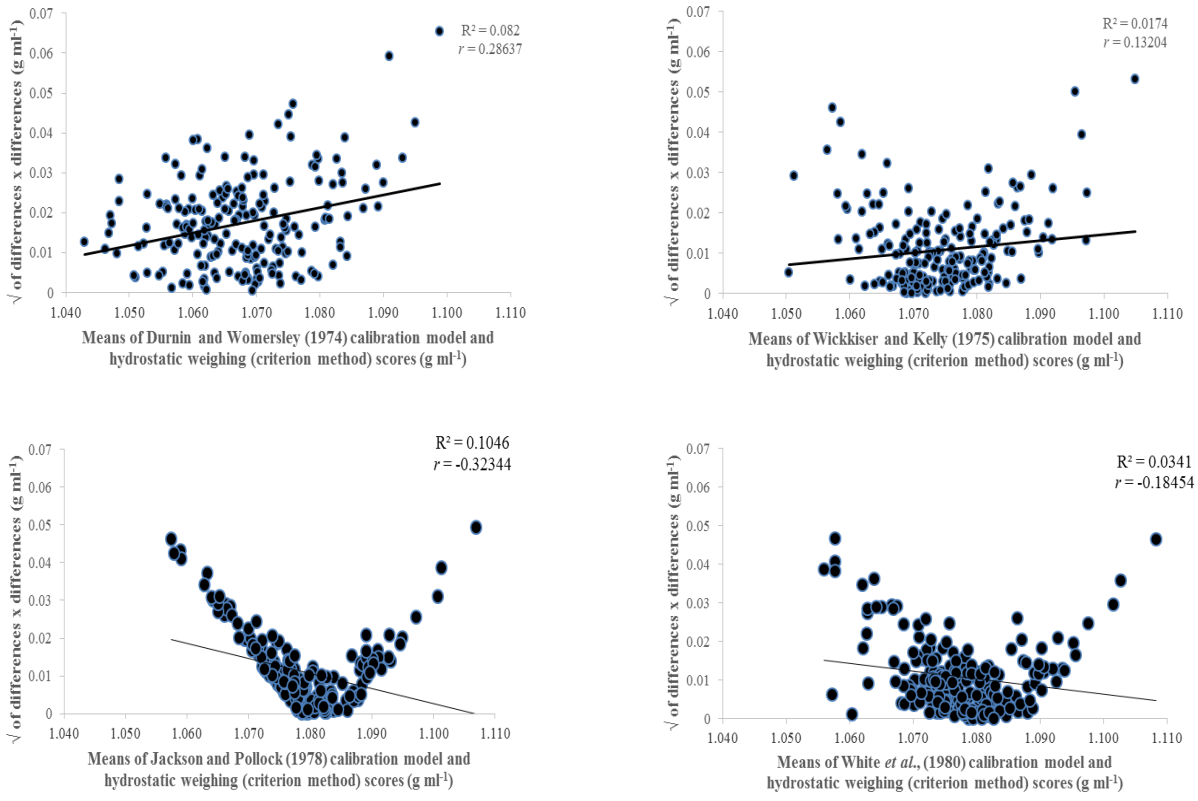

Figure 5.7 Scatter plots for the heteroscedasticity of hydrostatic weighing (criterion method) compared to Durnin and Womersley (1974) calibration model (means); Wickkiser and Kelly (1975) calibration model; Jackson and Pollock (1978) calibration model (means) and White *et al*., (1980) calibration model (means) for whole body density (g ml^{-1})

The heteroscedasticity of calibration models of Lohman (1981), Thorland *et al*., (1984) and Air displacement plethysmography calibration models are shown in Figure 5.5 with *r* values of 0.009, 0.140 and 0.296 and R^2 (%) coefficients of 0.00000005%, 0.0195% and 0.0875% respectively. Inspection of Figure 5.5 suggested there is some heteroscedastic data between whole body density values between the criterion method of hydrostatic weighing and calibration models. As previously reported with the Bland and Altman plot in Figure 5.4, the air displacement plethysmography demonstrates an ordinal scale visual that discriminates intervals between the range, thereby not reflecting visuals like the remaining calibration models and as such can be seen as a controversial deviation. All models exhibited statistical significance of $P = < 0.05$ except for air displacement plethysmography of $P = < 0.01$ and were normally distributed.

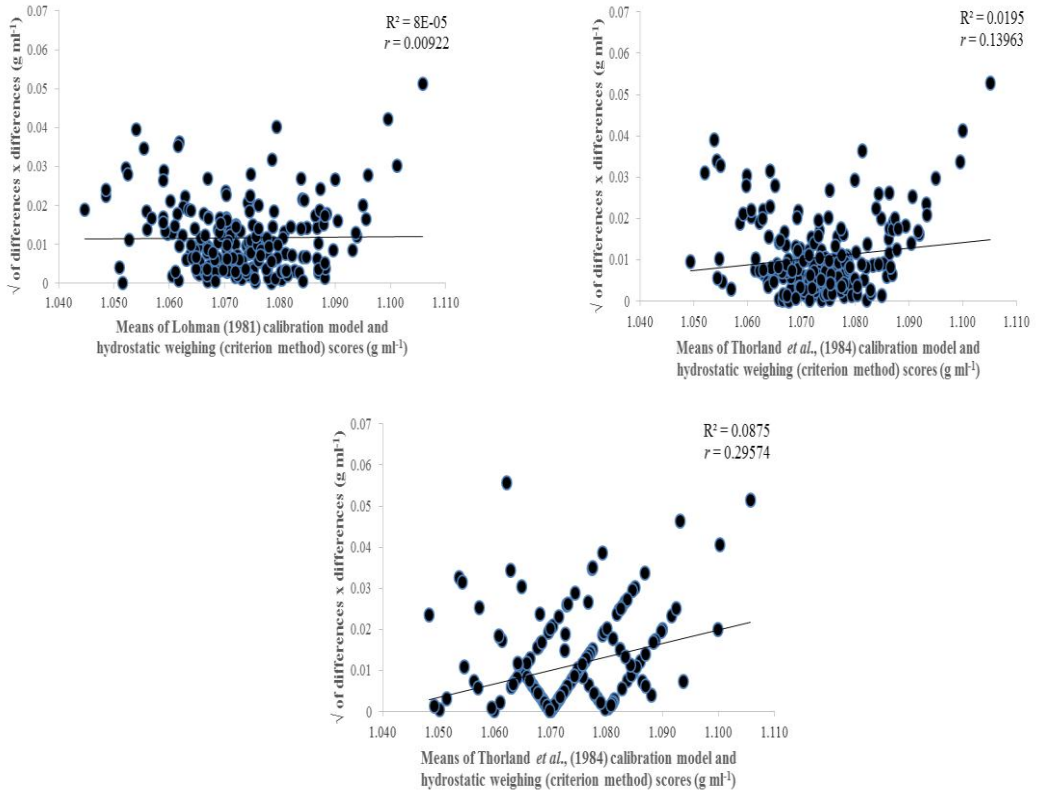

Figure 5.8 Scatter plots for the heteroscedasticity of hydrostatic weighing (criterion method) compared to Lohman (1981) calibration model (means); Thorland *et al*., (1984) calibration model (means) and Air displacement plethysmography calibration model (means) for whole body density (g ml^{-1})

Table 5.5 exhibits an overview of the heteroscedasticity scatter plots (Figures 5.5 – 5.8) R^2 (%) *r* and *P* values for all calibration models.

Table 5.5 Overview of heteroscedasticity scatter plots R^2, *r* and *P* values for calibration models (g ml^{-1})

Calibration model	***r***	***R*²(%)**	***P***
Durnin and Rahaman (1967)	0.328	0.1077	0.01
Sloan (1967)	0.056	0.0031	0.01
Wilmore and Behnke (1969)	0.374	0.1398	0.01
Sloan and Weir (1970)	-0.064	0.0041	0.05
Forsyth and Sinning (1973a)	-0.024	0.0006	0.05
Forsyth and Sinning (1973b)	0.130	0.0171	0.05
Katch and McArdle (1973)	0.106	0.0112	0.01
Behnke and Wilmore (1974)	0.372	0.1387	0.05
Durnin and Womersley (1974)	0.286	0.0820	0.05
Wickkiser and Kelly (1975)	0.132	0.0174	0.05
Jackson and Pollock (1978)	-0.323	0.1046	0.01
White *et al*., (1980)	-0.185	0.0341	0.01
Lohman (1981)	0.009	0.00000005	0.05
Thorland *et al*., (1984)	0.140	0.195	0.05
Air displacement plethysmography	0.296	0.0875	0.01

At this point of statistical analysis it was worth considering the issue of heteroscedasticity and whether there is a need to find the cause and resolve it. By log transforming this could correct for heteroscedasticity, but it only really becomes a real issue if it is severe enough (Jackson & Pollock, 1978). Generally speaking there are two basic reasons for applying log transformation, firstly to accommodate non-linearity and secondly to reduce skewness (Manning & Mullahy, 2001). Given that the Jackson

and Pollock (1978) was the only calibration model which demonstrated heteroscedasticity from Figures 5.5 - 5.8, a decision was needed whether to log transform all data. As there was no measurement error or reliability issues across the variables or calibration models, a judgement was made not to log transform, and keep the data in its present condition.

As there are obvious patterns of distribution within each case it is therefore important to obtain some clarity over the most appropriate calibration model to use. Furthermore, to avoid repetition when reporting outcomes, the primary investigator used the same hypothetical whole body density value of 1.045 g ml^{-1} for each individual calibration model that was used to predict whole body density. Given the study's sample, the hypothetical predictions are summarised in Table 5.6 and presented in rank order from lowest to highest in terms of differences of agreement indicators.

Table 5.6 Rank order of 95% upper and lower limits of agreement and differences indicators for (n = 14) calibration models plus air displacement method for whole body density of 1.045 (g ml^{-1})

Rank	calibration model	Lower limit (g ml^{-1})	Upper limit (g ml^{-1})	Difference (g ml^{-1})
1	Behnke and Wilmore (1974)	1.026	1.078	0.052
2	White *et al*., (1980)	1.014	1.066	0.052
3	Wilmore and Behnke (1969)	1.026	1.079	0.053
4	Katch and McArdle (1973)	1.019	1.072	0.053
5	Durnin and Rahaman (1967)	1.027	1.081	0.054
6	Jackson and Pollock (1978)	1.012	1.066	0.054
7	Thorland *et al*., (1984)	1.021	1.075	0.054
8	Sloan (1967)	1.018	1.073	0.055
9	Durnin and Womersley (1974)	1.033	1.088	0.055
10	Sloan and Weir (1970)	1.018	1.074	0.056
11	Lohman (1981)	1.021	1.077	0.056
12	Air displacement plethysmography	1.021	1.078	0.057
13	Wickkiser and Kelly (1975)	1.017	1.074	0.057
14	Forsyth and Sinning (1973a)	1.022	1.079	0.057
15	Forsyth and Sinning (1973b)	1.030	1.090	0.060

For the Behnke and Wilmore (1974) (lowest) and Forsyth and Sinning (1973b) (highest) models (Figure 5.2) there is a bias of 0.007 g ml^{-1} and 0.015 g ml^{-1} and 95% limits of agreement of 0.019 g ml^{-1} to 0.033 g ml^{-1} and 0.015 g ml^{-1} to 0.045 g ml^{-1} respectively. If a new participant from this population of interest (not one of the n = 206 sample) was measured via hydrostatic weighing with a whole body density of 1.045 g ml^{-1} there is a 95% probability that when measured using the Behnke and Wilmore (1974) and Forsyth and Sinning (1973b) models the whole body density could be estimated as low as 1.045 – 0.019 = 1.260 g ml^{-1} and 1.045 – 0.015 = 1.030 g ml^{-1} to as high as 1.045 + 0.033 = 1.078 g ml^{-1} and 1.045 + 0.045 = 1.090 g ml^{-1}

respectively. When expressed in this way, Atkinson and Nevill (1998) believe that the 95% limits of agreement are actually an estimate of total error (bias + random error). Based on these findings, the issue is whether an error of this magnitude would detrimentally affect anything the primary investigator has to say about the participants' whole body density (g ml^{-1}) derived from the chosen calibration models. In other words could the primary investigator replace hydrostatic weighing method with the calibration model. The statistics provided here cannot answer this question. Indeed the question that the primary investigator needs to ask is, are the 95% limits of agreement narrow enough for measurements to be of practical use.

Examination of the three lowest ranking calibration models by Behnke and Wilmore (1974), White *et al*., (1974) and Wilmore and Behnke (1969) where measured population samples consisted of university students and American footballers, suggesting similarities with the current study sample in that they were also physically active and young men (16.8 – 36.8 y) (Table 5.1). Sample sizes used in these studies were $n = 54$, $n = 58$ and $n = 133$ respectively which are at least 73 participants less than the present study. A maximum of three skinfold measurements were employed within their regression equation component details and all included the anterior thigh and a skinfold within the abdominal area (Table 5.2). Further scrutiny of the next four ranking calibration models of Katch and McArdle (1973), Durnin and Rahaman (1967), Jackson and Pollock (1978) and Thorland *et al*., (1984) found the participants were a range of volunteers, university sports students and athletes of national calibre with sample sizes of $n = 53$, $n = 60$ and $n = 403$, $n = 141$ respectively. The latter two models were developed using large samples, but when investigated further the age ranged from 18.0 to 61.0 years with the Jackson and Pollock (1978) model which is a difference of 23 years compared to the present study and from 16.5 to 18.4 years for the Thorland *et*

al., (1984) compared to the present study of 18.0 to 38.0 years. These samples are not similar to the present study sample, and as such could significantly influence judgements of whole body density decisions made (Table 5.1). These four models included the triceps and subscapular skinfolds and with the exception of the Durnin and Rahaman (1967) model, all used the abdominal skinfold in their regression equation components, suggesting the impact this skinfold can have a positive impact on the estimation of whole body density (Table 5.2). The higher ranking calibration models from the work of Sloan (1967), Durnin and Womersley (1974), Sloan and Weir (1970) and Lohman (1981) had participants' that were university students, volunteers or sports enthusiasts and sample sizes were n = 50, n = 209, n = 50 and n = 61 respectively. Sloan (1967) and Sloan and Weir (1970) used only the anterior thigh and subscapular skinfolds as components in their regression equation, whereas, Durnin and Womersley (1974) used four skinfolds from the upper body and Lohman (1981) used seven from different regions of the body.

The three highest ranked calibration models of Wickkiser and Kelly (1975), Forsyth and Sinning (1973a) and Forsyth and Sinning (1973b) employed participants that were closely related to those used in the present study – university sports students and university American football players. Wickkiser and Kelly (1975) reported body mass and stretched stature values ($\bar{x} \pm s$) of 88.0 ± 12.1 kg and 182.5 ± 5.8 cm compared to those in the present study of 78.8 ± 8.4 kg and 180.1 ± 7.0 cm, suggesting similarities between the samples, although age was 17.2 years compared to the present 24.1 years, indicating a younger age group. A maximum of four variables were used in the work of Wickkiser and Kelly (1975) calibration model, and included alternative measures to skinfolds such as waist circumference, stretched stature and biliocristal breadth. All used the subscapular skinfold, but Forsyth and Sinning (1973a) and Forsyth and Sinning

(1973b) also used the abdominal skinfold, whereas Wickkiser and Kelly (1975) used waist circumference and the triceps skinfold. The sample measured by Forsyth and Sinning (1973b) in their study did provide some similarities with the present study sample, in that the participants' had a body mass range of 68.5 – 85.9 kg compared to the present 59.4 – 104.2 kg and stretched stature of 178.4 – 179.6 cm compared to the present 162.7 – 201.2 cm. A maximum of three anthropometric measures were used in designing of the Forsyth and Sinning (1973b) model, using the subscapular and abdominal skinfolds and biacromial breadth, however, there were significant limitations to the model's design. For instance, the Forsyth and Sinning (1973b) model was developed on a sample of only n = 50 university sports students, with an age range from 19.0 – 22.0 years compared to 18.0 – 38.0 years, and more importantly found that whole body density derived from underwater weighing (1.075 ± 0.015 g ml^{-1}) was higher than whole body density derived from Forsyth and Sinning (1973b) model (1.060 ± 0.011 g ml^{-1}) so in essence, had a negative bias, thereby raising doubt over its validity.

It is important to stress that it is unlikely that the calibration models will agree exactly for estimated whole body density amongst themselves, but these findings suggest a need to provide an explanation as to why 13 calibration models (on average) under-reported and two calibration models (on average) over-reported body density for a group of professional footballers. Whilst reviewing the literature, it became apparent that the researchers cited, had various limitations with the design and development of their calibration models. Five main limitations were identified: The first possible limitation could be due to the variation of measures that were used as individual components of each model. Of the all the possible anthropometric sites that could be measured, as illustrated in Table 5.7, the most frequently used, as part of the components of the calibration models, included the subscapular skinfold, triceps skinfold, iliac crest,

anterior thigh, abdominal skinfold, biacromial breadth, biiliocristal breadth, chest girth, waist girth and supraspinale skinfold. What is evident from closer inspection of Table 5.7 is that on every occasion the subscapular was measured within study design, and in 79% of cases was utilised as one of the components within the calibration model(s). In stark contrast, sitting height, buttocks skinfold, chin skinfold, knee skinfold and buttocks girth, were measured in at least one study, but never included in the development of the calibration model. This observation fails to support evidence from previous research that indicates the value of including skinfold thicknesses measured at lower body sites when estimating body composition parameters (Eston, 2003).

With the exception of two of the models, a maximum of four anthropometric measurement sites were used and seven of the models failed to take into account of any limb measures in the development of these models. With evidence that there are higher concentrations of body fat in the waist and iliac crest region of males (see Figure 2.1) (Garn, 1954 cited Lohman, 1981; Lamb, 1984), this assumption appears to be overlooked when developing calibration models in young adult men. Scrutiny of previous authors' research papers found that they did not mention why variables did not make it into their models, or indeed hypothesise why. However, most provided a rationale for selecting the variables to use, which was based on the statistical analysis regression method.

Table 5.7 Anthropometric variables measured taken and/or used for the development of calibration models for the prediction of whole body density (g ml^{-1})

	Anthropometric variables																																								
	Stretched stature	Sitting height	Body mass	Triceps skinfold	Subscapular skinfold	Biceps skinfold	Iliac crest skinfold	Supraspinale skinfold	Chest skinfold	Buttocks skinfold	Chin skinfold	Abdominal skinfold	Anterior thigh skinfold	Knee skinfold	Medial calf skinfold	Head girth	Neck girth	Shoulders girth	Arm (relaxed) girth	Arm (flexed) girth	Forearm girth	Elbow girth	Wrist girth	Chest girth	Waist girth	Buttocks girth	Hips girth	Thigh girth	Knees girth	Calf girth	Ankle girth	Biacromial breadth	Biiliocristal breadth	Transverse chest depth	Anterior-posterior chest depth	Humerus width	Wrist width	Femur width
Durnin & Rahaman (1967)	✓	✓		☑	☑	☑	☑												✓									✓		✓		✓	✓					
Sloan (1967)				✓	☑		✓			✓		✓	☑																									
Wilmore & Behnke (1969)				✓	✓		✓	✓				☑	☑	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	✓		✓		✓
Sloan & Weir (1970)					☑								☑																									
Forsyth & Sinning (1973a)	✓		✓	☑	☑			☑	✓			☑	✓									✓	✓	✓				✓		✓	✓	✓					
Forsyth & Sinning (1973b)	✓		✓	✓	☑				✓			☑	✓									✓	✓	✓				✓		✓	✓	☑					
Katch & McArdle (1973)	✓		✓	☑	☑		✓					☑	✓			✓		✓		✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Behnke & Wilmore (1974)												☑	☑																									
Durnin & Womersley (1974)			✓	☑	☑	☑	☑												✓								✓	✓		✓							
Wickkiser & Kelly (1975)	☑			☑	✓		✓		✓			✓	✓										✓		☑													
Jackson & Pollock (1978)				☑	☑		✓	☑	✓			✓	✓								✓				✓													
White *et al*., (1980)				✓	✓		☑		✓			✓	☑		✓		✓	✓		✓	✓			✓	✓		✓	✓		✓		✓	✓			✓	✓	✓
Lohman (1981)				☑	☑	✓	☑	☑	✓		✓	☑	☑		☑																							
Thorland *et al*., (1984)				☑	☑	☑	✓	✓	☑			☑	☑		☑		✓		✓	✓	✓		✓	✓	✓		✓	✓				✓	✓					✓

KEY: ✓ anthropometric measure taken during study ☑ anthropometric measure used during development of calibration model

A second possible limitation alludes to the emphasis placed on individual anthropometric variables and the manner in which the variables are used interchangeably within the calibration model regression equations. In some instances some variables were provided as stand-alone outcomes, some as a combination of summed variables, some squared or even logged (see Table 5.2), thereby providing the outcome with a different bias. Research by Guo *et al.,* (2000) and Hawes and Martin (2001) revealed that if used indiscriminately, the strength of the outcome is lost and thereby can accommodate significant whole body density errors in male athletes.

Thirdly, the sample size that was employed to develop the calibration models could be another possible limitation. Ten studies investigated had less than 100 participants in their sample and in some instances as low as 50 participants. Two of the top three ranked models, Forsyth and Sinning (1973a) and Forsyth and Sinning (1973b) only used n = 50 participants respectively, as opposed to the model designed by Jackson and Pollock (1978) who used n = 403 participants. Mayhew *et al*., (1981), Hawes (1996) and Atkinson (2005) have considered the sample sizes employed in developing calibration models and suggested that if the sample is relatively small, it is not an adequate basis to develop calibration models. Too frequently the sample sizes have been too restrictive to be effective indicators of the predictive nature of the existing calibration model and therefore raises concern over its practical use with the given population.

The fourth limitation surrounds cross-validation. Interrogation of the 14 published calibration models found that 10 failed to cross-validate their data with another sample from the population of interest in order to test the prediction results. Three cross-

validated but with other published calibration models and not their newly developed one. Jackson and Pollock (1978) was the only calibration model that used cross-validation on their data. It is therefore to be expected that many questions have been raised relating to models specificity and validity with evidence that cross-validation is either ignored or used on very low restrictive sample numbers which raises doubt over the models validity (Atkinson & Nevill, 2001). What is crucial is that cross-validation yields supportive evidence for the existing calibration models and should therefore be given serious consideration (Mayhew *et al*., 1985; Lohman, 1992).

The fifth limitation discovered the arguably inappropriate analytical methods to develop these models and conduct through cross-validation, such as correlation coefficients and linear regression methods as indices of the equations' validity. Whereas the preferred analysis of choice should involve decisions based upon outcomes generated from employing the 95% limits of agreement analyses. Furthermore, the decision to log transform heteroscedastic data has also become an area of debate, particularly when considering whether there is a need to find the cause and resolve heteroscedasticity (Manning & Mullahy, 2001).

In conclusion, the limits of agreement findings are too wide to state with authority that these calibration models can be used interchangeably with the criterion method to assess whole body density in professional football players. Furthermore, when comparing the criterion whole body density values (1.075 ± 0.01 g ml^{-1}) for the present sample against data reported in the literature, whole body density values were lower than the those reported by Santos de Fonseca *et al*., (2007) [1.083 ± 0.010 g ml^{-1}].

In contrast the present whole body density values were considerably higher than those reported for non-Caucasian and Caucasian professional football players by Adams *et al*., (1981) [1.106 ± 0.020 g $ml^{-1}$and 1.098 ± 0.01 g ml^{-1} respectively]. Thereby raising doubt over the validity of such calibration models for use within the current population, moreover, indicating the need to develop a specific calibration model for use with professional football players.

5.5 Summary of main findings

The aim of the present study was to gain some insight into the validity of estimating whole body density from 15 calibration models that already exist in the public domain by comparing them too those gathered from the criterion hydrostatic weighing method in a large sample of professional footballers.

- Bland and Altman 95% limits of agreement approaches were used to determine the bias and random variation. 13 calibration models found that (on average) estimated whole body density (g ml^{-1}) derived from hydrostatic weighing was greater than whole body density (g ml^{-1}) derived from the models. Bias ranged from - 0.005 to + 0.009 g ml^{-1} and random errors ranged from 1.012 to 1.079 g ml^{-1}. Two calibration models found that (on average) whole body density (g ml^{-1}) derived from hydrostatic weighing was lower than whole body density (g ml^{-1}) derived from the models. Bias ranged from + 0.009 to + 0.015 g ml^{-1} and random errors ranged from 1.027 to 1.090 g ml^{-1}.

- The study's *a priori* criterion was set at ± 3.8% as acceptable limits for the Bland and Altman 95% limits of agreement method (Bland & Altman, 1986; ISAK, 2001; Marfell-Jones, 2013). Calibration models presented by Forsyth and Sinning (1973b) and Durnin and Womersley (1974) were not within acceptable limits by as much as 0.007 g ml^{-1}, and 0.005 g ml^{-1} respectively. Five models were found to be at the upper limits of the criteria and two models found to be at the lower limits of the criteria, indicating a wide spectrum of reported whole body density (g ml^{-1}) values for professional football players.

- Bland and Altman 95% limits of agreement approaches were used to determine heteroscedasticity. Of the 15 calibration models used within this study only Jackson and Pollock (1978) model illustrated heteroscedasticity with *r* values of -0.323 and R^2 (%) coefficients of 0.1046% and $P = 0.01$. An important consideration at this point was needed to determine whether to find the cause of heteroscedasticity and resolve it by log transforming. As there was insignificant measurement error or reliability issues in relation to the variables used, and given there was only one calibration model that illustrated heteroscedasticity, a decision was made not to log transform and keep the data in its present condition.

- Due to the obvious patterns of distribution for whole body density (g ml^{-1}) from 15 calibration models, a hypothetical whole body density value of 1.045 g ml^{-1} was applied for each individual calibration model via limits of agreement. A rank order of 95% upper and lower limits was determined to

provide an overview that would best identify the best model to use for the current population of professional footballers. The model developed by Forsyth and Sinning (1973b) was considered the best where bias ranged from -0.015 to +0.045 g ml^{-1} with whole body density values ranging from 1.025 to 1.081 g ml^{-1}. A maximum of three anthropometric measures were used in designing of the Forsyth and Sinning (1973b) model, using the subscapular and abdominal skinfolds and biacromial breadth. However, there were significant limitations to the model's design. For instance, the Forsyth and Sinning (1973b) model was developed on a sample of only n = 50 university sports students, with an age range from 19.0 – 22.0 years compared to 18.0 – 38.0 years, and more importantly found that whole body density derived from hydrostatic weighing (1.075 ± 0.015 g ml^{-1}) was higher than whole body density derived from Forsyth and Sinning (1973b) model (1.060 ± 0.011 g ml^{-1}) so in essence, had a negative bias, thereby raising doubt over its validity. It is important then for coaches and sport scientists to take due care and consideration when selecting calibration models to use when seeking to estimate whole body density in a professional football context by considering the most appropriate criteria about what constitutes practical significance.

- Research has proven that calibration models will infrequently agree with one another for estimated whole body density (g ml^{-1}). For instance, results from the *a priori* criteria (set at ± 3.8%, P = < 0.05 (g ml^{-1})) indicated that most calibration models where within an acceptable range, but there was disagreement between the criterion of hydrostatic weighing against each of the calibration models interrogated through the limits of agreement method.

Thirteen calibration models (on average) systematically underestimated and two calibration models (on average) overestimated whole body density (g ml^{-1}) in professional football players when compared to densities gathered from the criterion hydrostatic weighing method. Of course this is a likely assumption given that the models are based on different populations. Based on these findings, the 95% limits of agreement were not narrow enough for measurements to be of practical use. In most instances, the error (the disagreement) was too great, and as such it would be detrimental to what the primary investigator can conclude about professional players' whole body density.

- Whilst reviewing the literature, it became apparent that the researchers cited have various limitations with the design and development of their calibration models. Scrutiny found various limitations with the design and development of their calibration models; (i) the number of individual anthropometric measured variables that were used as individual components of each model; (ii) the emphasis on individual anthropometric measured variables and the manner in which the variables are used interchangeably; (iii) the sample size employed and (iv) lack of cross-validation and finally (v) the authors have used arguably inappropriate analytical methods to develop these models and conduct through cross-validation, as indices of the equations' validity.

- Future research should include cross-validation of previously developed calibration models as well as the development of new sport specific models. New models should ideally be based on measures from large sample sizes and these should also include the entire playing spectrum of football players.

Above all, decisions about whether existing calibration models are valid and fit for purpose or new models have specificity should be established with reference to sound research principles such as cross-validation procedures.

Chapter 6

Study 3

Development of calibration models to predict whole body density in professional football players

6.1 Introduction

There are a plethora of calibration models that exist in the literature to estimate various components of body composition, although questions have been raised about the validity of such models (Vincent, 1999; Atkinson & Nevill, 2001). Since publication, researchers have identified limitations (as previously discussed in Chapter 5) that can have an impact on whole body density (g ml^{-1}) values when applied to a specific professional football population (Cooper, 1995; Atkinson & Nevill, 1998). Indeed, for male athletes with a higher than average body density, these models will not accurately estimate whole body density (Southwick *et al*., 1984; Bell, 1985; Guo *et al.*, 2000; Heyward, 2000).

Pertinent literature and findings from study two of this thesis (see Chapter 5) have indicated that published calibration models had significant differences of under estimation of whole body density in professional footballers (Sloan, 1967; Wilmore & Behnke, 1969; Sloan & Weir, 1970; Forsyth & Sinning, 1973a; Katch & McArdle, 1973; Behnke & Wilmore (1974); Wickkiser & Kelly, 1975; Jackson & Pollock, 1978; White *et al*., 1980; Lohman, 1981; Thorland *et al*., 1984) and over estimation of whole body density (Durnin & Rahaman, 1967; Forsyth & Sinning, 1973b; Durnin & Womersley, 1974). One such example of underestimation of whole body density is the model derived by Durnin and Womersley (1974) which is arguably the most frequently used for the assessment of body composition parameters in many accredited laboratories throughout the UK (Eston, 2003). This is a serious oversight and might be one reason why different calibration models produce different body densities on the same participant (Becque *et al.*, 1986; Sheng, 1988).

Attempts have been made to cross validate previously published calibration models for the estimation of body composition parameters specifically on football populations (Sinning & Wilson, 1984; Ramadan & Byrd, 1987; Withers *et al*., 1987; Thomas, 1991; Reilly *et al*., 2000). Results indicated that although these models have high measurement reliability, exploitation of whole body density values with severe underestimation (as previously mentioned) will not provide for accurate monitoring of professional football players body composition changes during training (Roche, 1984; Guo *et al.,* 2000). It is no surprise that research has been on the increase to develop population specific calibration models for various populations, ages, sports and levels of activity (Lohman, 1992; Guo *et al*., 2000). These population specific approaches have helped to contribute to increasing understanding of body composition in relation to health, fitness, sport, exercise, growth and the ageing process (Lohman, 1984).

The newly developed calibration model(s) should then be cross-validated by establishing how well the predicted values agree with measured criterion values in a different sample of participants from that used to develop the calibration model. Yet, evidence has found that fourteen of the fifteen pre-published calibration models from study 2 are strictly speaking only calibration studies. Controversially, the original authors did not cross-validate values generated by their calibration models with those from a different sample of participants that were used to develop the model (Vincent, 1999; Atkinson & Nevill, 2001). Furthermore in some cases, authors such as Mayhew *et al*., (1981), Jackson and Pollock (1982), Hawes (1996) and Atkinson (2005) suggested that if the participant sample sizes for cross-validation and the range of measures have been too restrictive, it can limit the validity of the calibration models. Indeed, some authors have even called for a halt to the development of new calibration

models unless they are cross-validated in order to test the validity of the prediction results (Sheng, 1988; Vincent, 1995; Atkinson & Nevill, 2001). Issues surrounding which statistical methods to use have been an area of renewed interest within the sport science community in recent years (Hopkins, 2000; Atkinson, 2003).

The sheer variety of statistical methods employed by sport scientists to appraise these measurement issues was highlighted some years ago in a review paper by Atkinson and Nevill (1998). By design, calibration models are multiple regressions models and are developed using linear regression techniques. One of the major benefits of this process might be to determine whether there is a strong correlation or indeed if the coefficient is high enough between criterion values and predictor values (usually ≥ 0.8) (Atkinson & Nevill, 1998). These values can be reasonably accurate predictions of the criterion that can be made from the predictor(s) (Thomas *et al*., 2005). Many designers of calibration models would conclude that if the validity coefficient (r) is close to ± 1, the model(s) is measuring similarly to the criterion, and would consider it to be relevant. When r is closer to 0, the model(s) would have little relevance (Thomas *et al*., 2005). Here a calibration model can be developed between the two sets of data by correlating the values and (providing r_{XY} is sufficiently high) computing a linear regression model that predicts the criterion test values. It is important to note that correlations are unique to the sample, when calibration models are applied to different samples, the original relationships do not hold (Thomas *et al*., 2005). Oppliger and Cassady (1994) stressed that the homogeneity of body composition in specific sports present statistical problems for the development of a new model(s). This problem relates in large part to the small inter-individual variability between the participants. As such, there are generally poor correlations between the predictor and criterion variables and large standard errors.

Given that there are no specific calibration models that exist in the literature to estimate whole body density in professional football players, evidence suggests that the development of a model(s) with cross-validation techniques can provide sport scientists with an essential mechanism for making sound body composition judgements for the football profession (Sheng, 1988; Casajús, 2001; Hencken, 2004). The development of such calibration models to estimate whole body density in professional football players was underpinned by the organic nature of three studies within this thesis. Firstly to identify and quantify intra-rater measurement reliability of anthropometric measures, and to establish the reliability and precision of these measures when used to estimate whole body density to professional football players. The reliability of these measures was crucial by which the second and third study could not be practically based with confidence. Secondly to compare pre-published calibration models for the estimation of whole body density when compared to values derived from the criterion method of hydrostatic weighing, furthermore, to investigate the agreement when applied to professional football players. This comparison increases confidence in the ability to make assumptions on the development of calibration models.

Therefore the aim of study 3 was to develop two separate calibration models to estimate whole body density (g ml^{-1}) in professional football players and to cross-validate the models to determine validity. The first would be a 'best fit' calibration model which could be used within an academic environment (research, sports science and teaching) where there is a high level of expertise and understanding within the area of body composition. The second would be a 'practical' calibration model which could be used within a football environment (field testing monitoring and sports science) where it could be used for regular monitoring of a player(s) and/or squad(s) and provide

informative insight into body composition and thus contributing towards the optimisation of performance potential. The data entered into the design of these models were gained from careful measurements with known reliability (Study 1), the sample size was large (n = 140 participants) for the development of the calibration model(s) using an ordinary least squares backward stepwise regression analysis approach and the measurements taken from n = 66 participants were used for cross-validation purposes to determine the validity and the relevance of the calibration model(s) using Bland and Altman's 95% limits of agreement approach.

6.2 Methods

6.2.1 Participants

Two hundred and six Fédération Internationale de Football Association (FIFA) registered contracted professional football players ($\bar{x} \pm s$; age = 24.1 ± 5.4 years, body mass = 78.8 ± 8.4 kg, stretched stature = 180.1 ± 7.0 cm and whole body density = 1.075 ± 0.010 g ml^{-1}) were recruited from eight professional football clubs that represented Barclays Premiership, npower Championship, npower League One, npower League Two and Blue Square Premier Leagues during the 2007-2008, 2008-2009 and 2009-2010 playing seasons. Sampling included players who were all over 18 years of age, free from disease or illness and who agreed to act as participants for the study by giving their written informed consent. Signs and symptoms of disease and diagnosed disease were determined through health screening procedure involving completion of a health screening questionnaire. Ethical considerations were carried out using robust operational procedures as previously reported in Section 3.2.

6.2.2 Data collection procedures

Two groups were constructed: CM (calibration model group; *n* = 140) and CV (cross-validation group; *n* = 66). Due to low numbers and potentially contentious issues relating to the estimation of whole body density, non-Caucasians and goalkeepers were positively assigned into the two separate groups. The CM group had *n* = 13 non-Caucasians whereas the CV group had *n* = 12 non-Caucasians, whilst both groups had *n* = 7 goalkeepers. Remaining participants were randomly assigned into each group. The sample size for the CM and CV groups has been regarded as large enough to be representative of the population for whom the calibration model was to be developed (Oppliger & Cassady, 1994; Heyward & Wagner, 2004). Generally speaking the larger the sample size, the more statistical power can be achieved (Sun & Chumlea, 2005). In this instance *n* = 140 participants will provide a significant statistical power of 1% (Sun & Chumlea, 2005). It is also worth noting that there is a recommended maximum of nine variables given the sample number. This ratio accounts for 15.5 participants per variable which Cohen (1988), Atkinson (2005) and Sun and Chumlea (2005) agree would provide more stability. Although failure to reach these participant numbers per variable ratio for regression analyses can be treated as suspect and ultimately question its validity (Sun & Chumlea, 2005).

6.3 Statistical analyses

Phase one

A total of *n* = 28 anthropometric variables from study 1 were used to establish a correlation matrix on *n* = 206 participants using SPSS (see Appendix Y). The correlation matrix provided Pearson's correlation coefficients (*r*) and *P* values between the dependent variable (*Y* = whole body density) and independent variable (*X*s). Those

variables that had a level of significance (*P* value) at 0.01 or below were considered potential candidates for the development of the calibration models. The remainder of the matrix was interrogated for collinearity - linear relationships between the independent variables. Regression analyses for whole body density (*Y*) and each potential predictor (*X*) was conducted to determine the standard error of estimate (SEE), coefficient of determination (R^2) and R^2 - adjusted values for each variable. The SEE was used to establish the error related to the *Y* value, and R^2 and R^2 adjusted values used to determine the correlation between *Y* and *X* values, which is the percentage of common variance between these variables (see Table 6.1).

A cut-off correlation coefficient was set at 0.950 because this would give a corresponding coefficient of determination ($R^2 \times 100$) of 90% (Vincent, 1995; Bryman & Cramer, 1996; Atkinson & Nevill, 1998). Those variables that were above 0.950 and 90% R^2 were rejected and those that were below were used in the next phase of analyses (see Table 6.1). This coefficient indicates that 90% of the variance in the criterion method values is due to the variance in the predictor values (Bryman & Cramer, 1996). One might question the interpretation that is given to the variance that is unaccounted for, i.e. 100 - 90 = 10%. This indicates that an amount of the variance in the criterion method values is not being accounted for by the variance in the predictor values, but by something else that was not measured. One of the purposes of R^2 might be to predict if the variables are significantly related, linearity is assumed and it is possible to predict values on one variable from values on the other. Therefore, the higher the relationship (higher R^2) the more accurately a sport scientist can predict one value from another value, if for instance R^2 = 100%, then one can predict with complete accuracy (Bland & Altman, 1986; Bryman & Cramer, 1996).

A further consideration at this stage was to see whether groups of *X* variables could improve the correlation matrix. There is of course mileage in aggregating these values to improve the prediction, but the question is to what extent and whether it is good enough to make the choices practically useful. The correlation matrix was further investigated by allocating variables into groups of measures that included skinfold thicknesses, girths and other variables (body mass, stretched stature, sitting height, transverse chest depth and biiliocristal breadth).

Phase two

All remaining potential variables gathered from phase one were standardised (*z*-scores, $\bar{x}$ = 0.0, SD = ± 1.0) thereby converting them into one unit of measurement to help reduce heteroscedasticity. Beta weight (β) (or standardised regression coefficient), *r*, *t*, significance of *t* and *P*-values were calculated via SPSS on the CM group of *n* = 140 participants (see Table 6.2). The beta weight is particularly important within this phase of analyses as the beta weight can be compared to determine which of two or more independent variables (*X*) is the more important in relation to the dependent variable (*Y*) (Bryman & Cramer, 2009). Essentially the beta weight (β) can inform how many standard deviation units the dependent variable will change for a one standard deviation change in the independent variable (Bryman & Cramer, 2009). In this instance, it is important to ensure that the independent variables are not too highly related to each other and should not exceed *r* = 0.80, otherwise the independent variables that show a relationship might be exhibiting multicollinearity (Bryman & Cramer, 2009). Multicollinearity is regarded as a problem as it could imply that the beta weight may be unstable and suggests that they are likely to be subjected to variability from population to population (Bryman & Cramer, 2009).

Phase three

Forced regression analysis using an ordinary least squares stepwise approach was conducted from the values obtained from phase two on the CM group of n = 140 participants. Whilst using the stepwise approach, a 'best fit' calibration model, where all potential variables (those that did not exceed r = 0.80 or a negative beta (β) weight, from phase two) were used within the development of such a model and secondly a 'practical' model where the primary investigator pre-selected variables that were considered most applicable within a practical sports science setting. Pre-selection of the most applicable and worthy anthropometric variables are exhibited in Figure 6.1.

As part of the model development process, the stepwise analysis procedure involved the elimination of one variable at each stage. Obviously the number of steps taken was dependent on the number of potential variables available. This elimination was determined by the t value and P value. At each stage analysis of variance (ANOVA) values such as F and P values were obtained to determine significance, and testing for heteroscedastic (multiplicative) residual errors were calculated including r and P values. Finally, establishing the most practical and statistically sound calibration models were determined by having the lowest SEE and the highest R^2 values (Lohman, 1992).

Phase four

Cross-validation on n = 66 of the sample was conducted to test the veracity of the two newly developed calibration models using Bland and Altman 95% Limits of Agreement (LoA) method. Predicted whole body density was plotted on a Bland and Altman scatter plot to identify agreement between each calibration models and the criterion (see Figures 6.2 – 6.3). Quantification of agreement involved determining the mean

difference ($\bar{x}_{diff}$) between the criterion and calibration model(s) values to establish the bias and to compute the standard deviation of the differences (s_{diff}) between the criterion and calibration model values to establish the random variation. Quantification first identifies the extent of systematic bias in the whole body density (g ml^{-1}) values from the mean of the differences between both calibration models and criterion method of hydrostatic weighing ($\bar{x}_{diff}$). Random variation between calibration model and criterion method values is related to the standard deviation of the differences and provided the differences are confirmed as being normally distributed in the population from which the sample was drawn can be expressed to a 95% probability: 1.96 x (s_{diff}). The extent to which heteroscedasticity is present in these values can be quantified by correlating absolute differences against mean scores for calibration model and criterion method values and can be illustrated on a scatter plot of these two variables (see Figures 6.2 – 6.3). The scatter plot included R^2, *r* and *P*-values and the distribution line to allow a visual overview of the relationship between the calibration model and the criterion values.

The final part of the treatment of validity is to identify error and to contextualise and interpret the quantification of agreement where it would be expected to lie for both models ('best fit' and 'practical') for the estimation of whole body density. Whether these limits of agreement are narrow enough for whole body density to be providing practically valid values was an issue for the primary investigator to judge. In other words, whether the error encountered would have any detrimental practical impact for this sample of participants. The judgement could be made against an existing evidence base, and might be related to training based changes, but in the context of this thesis *a priori* consideration for the Bland and Altman 95% LoA method was established to

provide acceptable tolerable limits within the context of this particular study. Using research from pertinent literature and advice from the International Society for the Advancement of Kinanthropometry (ISAK), the primary investigator set *a priori* of acceptable limits at ± 3.8%, $P \leq 0.05$ (g ml^{-1}) (Bland & Altman, 1986; ISAK, 2001; Ludbrook, 2010; Woodman, 2010; Marfell-Jones, 2013 (personal communication – see Appendix X)). These limits were set to determine whether the agreement had minimal impact on the determination of whole body density. For instance, if too high it could have an impact on training prescription, thus a possible impact on team selection, whereas if too low it could be considered a definite danger to the health and wellbeing of the participant. Thus acceptable limits can be used interchangeably with the criterion measurement method to estimate whole body density in professional football players.

6.4 Results and discussion

Phase one

The correlation matrix provided outcomes for calculating *r*, R^2 (%), R^2 - adjusted, SEE and *P*-values for all variables measured in study one ($n = 28$) and is illustrated in Table 6.1. Results found that of the 28 variables used, 17 variables were statistically significant ($P = < 0.01$) and considered potential candidates for use in the development of the calibration models, whereas 11 variables did not achieve an alpha level of 0.01 and were therefore rejected and subsequently not used for further statistical analyses (see Table 6.1).

Table 6.1 Overview of *r*, R^2 (%), R^2 - adjusted, SEE and *P* values for *n* = 28 variables

Variables	*r*	R^2 (%)	R^2 adjusted	SEE	*P*	Accept / reject
Skinfolds (mm)						
Triceps	-0.249	6.2	5.8	0.014	0.001	Accept
Subscapular	-0.302	9.1	8.7	0.014	0.001	Accept
Biceps	-0.129	1.7	1.2	0.014	0.066	Reject
Iliac crest	-0.378	14.3	13.9	0.013	0.001	Accept
Supraspinale	-0.337	11.3	10.9	0.014	0.001	Accept
Abdominal	-0.354	12.5	12.1	0.013	0.001	Accept
Anterior thigh	-0.271	7.3	6.9	0.014	0.001	Accept
Medial calf	-0.203	4.1	3.7	0.014	0.001	Accept
Girths (cm)						
Neck	-0.269	7.2	6.8	0.014	0.001	Accept
Arm (relaxed)	-0.233	5.4	5.0	0.014	0.001	Accept
Arm (flexed)	-0.191	3.7	3.2	0.014	0.006	Accept
Forearm	-0.079	0.6	0.1	0.014	0.260	Reject
Wrist	-0.022	0.0	0.0	0.014	0.756	Reject
Chest	-0.163	2.7	2.2	0.014	0.019	Reject
Waist	-0.235	5.5	5.1	0.014	0.001	Accept
Hip	-0.283	8.0	7.5	0.014	0.001	Accept
Thigh	-0.138	1.9	1.4	0.014	0.048	Reject
Calf	-0.173	3.0	2.5	0.014	0.013	Reject
Ankle	-0.117	1.4	0.9	0.014	0.094	Reject
Breadths (cm)						
Biacromial	-0.135	1.8	1.3	0.014	0.054	Reject
Biiliocristal	-0.240	5.8	5.3	0.014	0.001	Accept
Depths (cm)						
Transverse chest	-0.201	4.0	3.6	0.014	0.004	Accept
Anterior-posterior chest	-0.177	3.1	2.7	0.014	0.011	Reject
Widths (cm)						
Humerus	-0.100	1.0	0.5	0.014	0.155	Reject
Femur	0.004	0.0	0.0	0.014	0.956	Reject
Other variables						
Body mass (kg)	-0.439	19.2	18.8	0.013	0.001	Accept
Stretched stature (cm)	-0.271	7.3	6.9	0.014	0.001	Accept
Sitting height (cm)	-0.188	3.5	3.1	0.014	0.001	Accept

All but one of the skinfold thicknesses were used except for the biceps. Five of the eleven girths measured was accepted, with two from the upper limb, two from the core body and none from the lower limb. At least one breadth and one depth were accepted thereby providing a wide range of upper limb, lower limb and core body variables (see Table 6.1).

Examination of the correlation matrix (Appendix Y) for collinearity – linear relationships between the independent variables resulted in the cut-off correlation coefficient being set at 0.950 which would give a coefficient of determination (R^2) of 90%. Of the 17 potential variables, none had a correlation coefficient with any other variable of 0.950 or R^2 of 90% or above. Therefore, all variables were subsequently accepted and used in the next phase of the analyses.

Further examination of the correlation matrix (Appendix Y) led to the grouping of the 17 variables accepted to help improve the prediction. Three groups were considered (skinfold thicknesses, girths and other variables (body mass, stretched stature, sitting height, transverse chest depth and biiliocristal breadth) and re-entered into another correlation matrix. The predictions did improve, for instance the medial calf skinfold rose from an original value of r = -0.203 to r = -0.211. Results from these recalculations found that improvements in grouped predictions were so minimal that it was thought sufficient enough to continue with values from the original correlation matrix.

Phase two

Seventeen variables from phase one were standardised into *z*-scores to help reduce heteroscedasticity. β weight, *r*, *t*, significance of *t* and *P*-values on the CM group of *n* = 140 participants are shown in Table 6.2.

Table 6.2 Overview of *r*, beta, *t*, significance of *t* and *P*-values for *n* = 17 variables

Variables	*r*	β	*t*	Sig of *t*	*P*
Skinfolds (mm)					
Triceps	0.019	-0.111	-0.772	0.442	0.410
Subscapular	0.078	0.070	0.471	0.638	0.179
Iliac crest	0.067	0.112	0.730	0.467	0.215
Supraspinale	0.001	-0.107	-0.785	0.434	0.496
Abdominal	0.071	0.015	0.099	0.921	0.204
Anterior thigh	0.144	0.188	1.454	0.148	0.045
Medial calf	0.065	-0.056	-0.438	0.662	0.222
Girths (cm)					
Neck	0.079	0.104	0.769	0.443	0.176
Arm (relaxed)	0.001	0.130	0.694	0.489	0.495
Arm (flexed)	-0.048	-0.188	-1.072	0.286	0.288
Waist	-0.078	-0.201	-1.082	0.072	0.180
Hip	0.148	0.210	1.772	0.079	0.040
Breadths (cm)					
Biiliocristal	-0.043	-0.143	-1.246	0.215	0.305
Depths (cm)					
Transverse chest	-0.091	-0.171	-1.539	0.126	0.142
Other variables					
Body mass (kg)	0.171	0.107	0.667	0.506	0.022
Stretched stature (cm)	0.188	0.198	1.314	0.191	0.013
Sitting height (cm)	0.103	-0.027	-0.206	0.837	0.114

When interrogating the *r*-values for relationships between independent variables and multicollinearity illustrated in Table 6.2, no measures exceeded the recommended *r* = 0.80. The highest *r*-values however were recorded for the anterior thigh skinfold (0.144), hip girth (0148), body mass (0.171), stretched stature (0.188) and sitting height (0.103). Both the supraspinale skinfold and arm (relaxed) girth having the lowest *r*-values of 0.001. However, results summarised in Table 6.2 indicate that of the 17 potential predictor variables, the hip girth provided the highest β weight (0.210) and thereby the greatest impact on whole body density. Sitting height had the lowest β weight (-0.027) with eight other variables having negative values (triceps skinfold, supraspinale skinfold, medial calf skinfold, arm (flexed) girth, waist girth, biiliocristal breadth and transverse chest depth), indicating that these variables had the smallest impact on whole body density and therefore not fulfilling the acceptance criteria as explained in section 6.3. Therefore, nine variables: subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, neck girth, arm (relaxed) girth, hip girth, body mass and stretched stature were chosen to be used in the next phase of analyses with the development of the calibration models.

Phase three [the 'best fit' calibration model]

The next phase of analyses was to construct two separate calibration models (a 'best fit' calibration model and a 'practical calibration model) using data from the CM group (*n* = 140). Summary results for general characteristics of the CM group and a summary of all the participants' anthropometric measures can be seen in Table 6.3 and Table 6.4.

Table 6.3 General summary ($\bar{x} \pm s$) of characteristics for the calibration model Group (n = 140) of football players

Variables	$\bar{x} \pm s$	Range
Age (yr)	24.0 ± 5.1	18.0 – 37.0
Body mass (kg)	78.1 ± 8.5	59.3 – 104.3
Stretched stature (cm)	179.7 ± 7.0	162.7 – 201.2
Sitting height (cm)	93.2 ± 4.9	79.5 – 109.4

Results from Table 6.3 indicated that participants were within an age range between 18 and 37 years, with body mass, stretched stature and sitting height ranging between 59.3 – 104.3 kg, 162.7 – 201.2 cm and 79.5 – 109.4 cm respectively.

Table 6.4 provides an summary of anthropometric measures of the CM group. Findings indicated the iliac crest 14.8 ± 5.7 mm, had the largest values, with the chest, hip and waist having the greatest mean range of values with 98.8 ± 4.9 cm, 93.5 ± 4.6 cm and 81.9 ± 4.9 cm respectively.

Table 6.4 Anthropometric summary ($\bar{x} \pm s$) measures for the calibration model group (n = 140) of football players

Variables	$\bar{x} \pm s$	Range
Skinfolds (mm)		
Triceps	7.9 ± 3.0	3.7 – 18.1
Subscapular	10.0 ± 2.4	6.1 – 17.5
Biceps	4.4 ± 2.0	2.1 – 11.5
Iliac crest	14.8 ± 5.7	3.8 – 34.0
Supraspinale	9.4 ± 3.5	4.3 – 26.5
Abdominal	14.2 ± 5.8	5.1 – 34.4
Anterior thigh	12.1 ± 4.1	4.5 – 24.0
Medial calf	6.9 ± 2.4	3.0 – 15.7
Girths (cm)		
Neck	38.3 ± 1.6	34.4 – 44.0
Arm (relaxed)	31.9 ± 2.2	27.1 – 37.7
Arm (flexed)	34.2 ± 2.4	29.4 – 40.2
Forearm	28.2 ± 1.9	24.1 – 39.4
Wrist	17.4 ± 0.8	15.4 – 19.9
Chest	98.8 ± 4.9	82.5 – 109.7
Waist	81.9 ± 4.9	70.8 – 98.6
Hip	93.5 ± 4.6	75.0 – 106.4
Thigh	55.5 ± 2.9	47.8 – 63.0
Calf	38.0 ± 2.1	29.7 – 42.3
Ankle	23.1 ± 1.3	19.7 – 26.0
Breadths (cm)		
Biacromial	43.4 ± 2.1	33.8 – 49.9
Biiliocristal	29.6 ± 1.7	25.0 – 33.8
Depths (cm)		
Transverse chest	30.8 ± 1.8	26.2 – 36.3
Anterior-posterior chest	20.6 ± 1.8	16.4 – 31.3
Widths (cm)		
Humerus	7.2 ± 0.6	6.2 – 10.3
Femur	9.6 ± 0.5	6.6 – 10.9

For the CM group of *n* = 140 participants ordinary least squares forced regression analysis employing a backward stepwise approach was conducted using the remaining nine variables to establish the 'best fit' calibration model. The variables were: subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, neck girth, arm (relaxed) girth, hip girth, body mass and stretched stature.

Table 6.5 summarises the nine 'best fit' calibration models for the estimation of whole body density developed using measurements from the CM group of *n* = 140 participants. The order in which elimination of variables occurred was as follows: 1) iliac crest skinfold, 2) abdominal skinfold, 3) subscapular skinfold, 4) body mass, 5) neck girth, 6) arm (relaxed) girth, 7) hips girth and 8) anterior thigh skinfold.

Table 6.5 'Best fit' calibration models for the estimation of whole body density using anthropometric measures as predictors in professional football players (n = 140)

Variable included	Calibration model (D_b = g ml^{-1})	SEE	R^2
BM, StS, SS, IC, Ab, AT, Nek, Armr, Hip	D_b = 1.01 + (0.000070 x BM) + (0.000214 x StS) – (0.000054 x SS) – (0.000008 x IC) + (0.000007 x Ab) + (0.000405 x AT) + (0.000358 x Nek) – (0.000599 x Armr) + (0.000159 x Hip)	0.012	6.6
BM, StS, SS, Ab, AT, Nek, Armr, Hip	D_b = 1.01 + (0.000070 x BM) + (0.000214 x StS) – (0.000059 x SS) + (0.000003 x Ab) + (0.000404 x AT) + (0.000365 x Nek) – (0.000601 x Armr) + (0.000158 x Hip)	0.012	6.6
BM, StS, SS, AT, Nek, Armr, Hip	D_b = 1.01 + (0.000071 x BM) + (0.000214 x StS) – (0.000056 x SS) + (0.000405 x AT) + (0.000364 x Nek) – (0.000602 x Armr) + (0.000158 x Hip)	0.012	6.6
BM, StS, AT, Nek, Armr, Hip	D_b = 1.01 + (0.000066 x BM) + (0.000220 x SS) + (0.000393 x AT) + (0.000336 x Nek) – (0.000587 x Armr) + (0.000154 x Hip)	0.012	6.6
StS, AT, Nek, Armr, Hip	D_b = 0.997 + (0.000258 x StS) + (0.000409 x AT) + (0.000429 x Nek) – (0.000551 x Armr) + (0.000180 x Hip)	0.011	6.5
StS, AT, Armr, Hip	D_b = 1.00 + (0.000270 x StS) + (0.000384 x AT) – (0.000409 x Armr) + (0.000224 x Hip)	0.011	6.3
StS, AT, Hip	D_b = 0.997 + (0.000263 x StS) + (0.000375 x AT) + (0.000160 x Hip)	0.011	5.8
StS, AT	D_b = 1.00 + (0.000309 x StS) + (0.000394 x AT)	0.011	5.5
StS	D_b = 1.01 + (0.000314 x StS)	0.012	3.5

KEY:
(skinfolds): SS = subscapular; IC = iliac crest; Ab = abdominal; AT = anterior thigh. (girths): Nec = neck; Armr = arm (relaxed); Hip = hip. (other variables) BM = body mass. StS = stretched stature. D_b = estimate of whole body density (g ml^{-1}); SEE = standard error of the estimate; R^2 = coefficient of determination (%)

Examination of the regression analyses summarised in Table 6.5 revealed four potential variables for the most practical 'best fit' calibration model. Further examination found that the most statistically robust calibration model considering the 'best fit' criteria was that which used six independent variables: body mass, stretched stature, anterior thigh skinfold, neck girth, arm (relaxed) girth and hip girth. This model had the lowest SEE (0.115 g ml^{-1}) and highest R^2 (6.6%) of the nine 'best fit' potential calibration models. Furthermore, from the ANOVA analysis *Fdf*-value = 1.56 and *P* = 0.164, and with a heteroscedastic coefficient (multiplicative) residual errors at this stage of *r* = -0.213 and *P* = 0.011. This model was statistically significant (*P* = < 0.005).

Phase three – the 'practical' calibration model

The 'practical' calibration model was primarily designed to be used within a football environment of field testing monitoring and sport science support. However, given the practical nature of this intended design, there was an assumption that professional football club might not be the anthropometric equipment available or the technical support available to collect the anthropometric values in these practical environments compared to the 'best fit' model intended for research and academia. Therefore it was vital to select variables where there was likely to be equipment and technical ability available to enable measures to be made from specific locations of the body. Consideration was also needed about which variables around the body to use.

Evidence from pertinent research, ISAK accreditation processes and results from study 1 suggested that given the physiological demands of the game, variables from the lower limb and core body had to be included. Finally, due regard had to given to the total number of variables to be used in this model, which would help to reduce the overall

time taken to measure each participant. For instance, all variables measured for study 1 (n = 28) took ≈ 15 mins per participant (see Figure 3.1), whereas, a maximum of nine variables could take ≈ 5 mins per participant to measure, which could have a profound impact on overall measurement time required for an entire playing squad and consequently reduce the time needed to provide regular monitoring of a player(s) body composition profile. The primary investigator made a judgement call about which variables could potentially be used in the development of the 'practical' calibration model. Moreover, being mindful of this model was to be as practical as possible.

Twenty eight of the potential variables are shown in Figure 6.1. For illustrative purposes the primary investigator's judgements are shaded green, the elimination of variables from the phase one analyses are shaded red and the elimination of variables from phase two analyses are shaded blue.

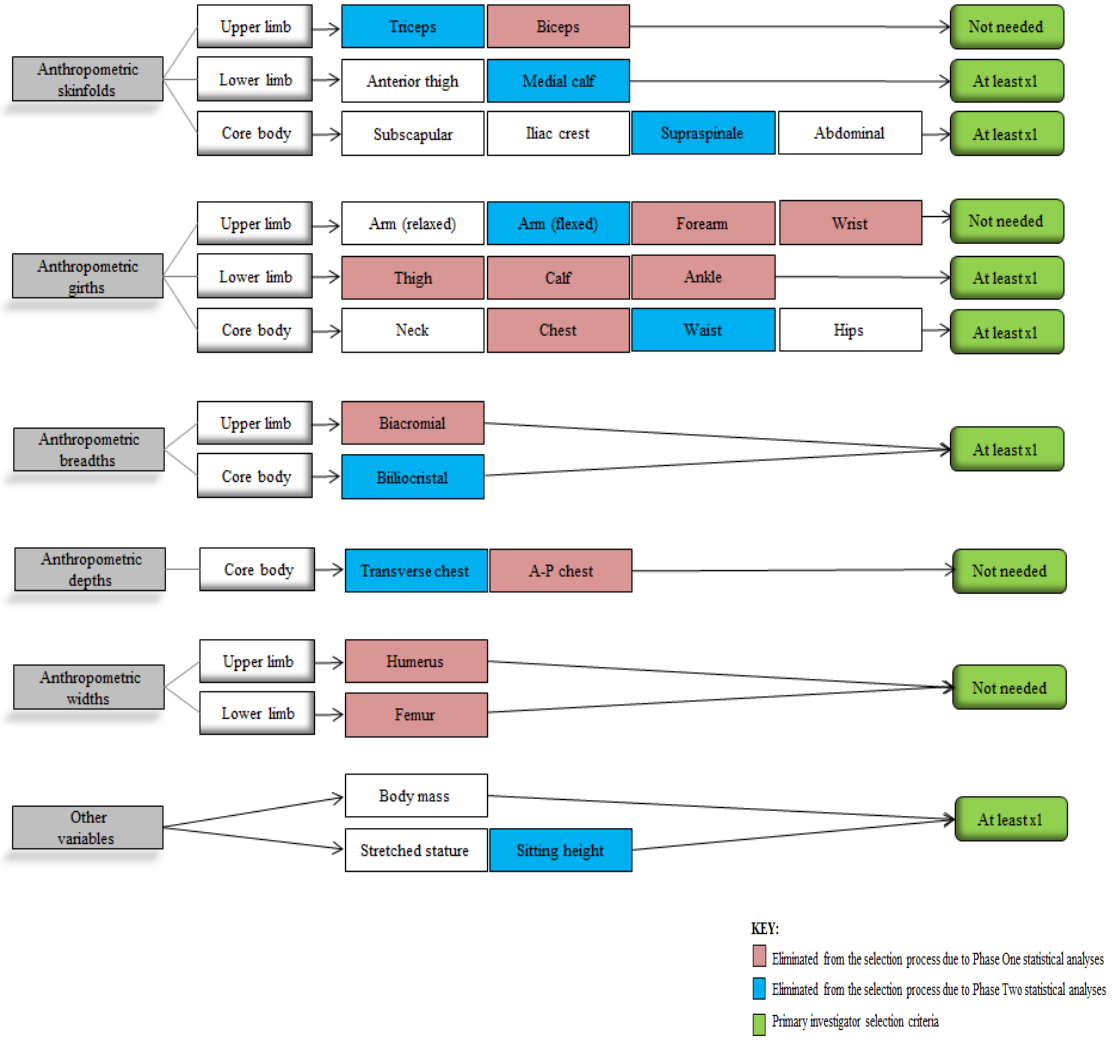

Figure 6.1 Flow chart to illustrate the variables (n = 9) available for selection for the 'practical' calibration model

Of the nine potential skinfold thicknesses, the primary investigator decided that at least one should be taken from the lower limb, and one from the core body corresponding with the research recommendations as previously discussed (Eston *et al*., 2001; Bellisari & Roche, 2005; Stewart, 2006). Although it was not deemed necessary to use a skinfold thickness from the upper limb, the decision not to use a variable from this area, could potentially be suspect, particularly given its location and accessibility, and the number of studies from the literature that have used upper limb skinfold sites. Conversely, to select variables just because other researchers have done so would be

considered erroneous. Therefore the primary investigator remained confident that these variables are non-essential, mainly due to the nature of the game. This judgement was further supported by the outcomes of phase one and two analyses of the present study, where both upper limb skinfold sites at the triceps and biceps were eliminated, due to their low impact on the estimation of whole body density, as were the medial calf and supraspinale skinfolds. The remaining potential variables to be used in the development of the 'practical' calibration model were the subscapular, iliac crest and abdominal skinfolds from the core body and the anterior thigh skinfold of the lower limb.

Eleven potential girths were available, and a judgement was made that the variables of the upper limb were not needed. At least one variable was needed from the lower limb and one from the core body. Following the primary investigator's judgement, one issue was raised: at least one girth from the lower limb was needed, but due to the analyses from phase one and phase two, all three potential variables were eliminated due to their low impact on the estimation of whole body density. On reflection there could have been collinearity issues, in that there is very little justification for selecting variables that are potentially providing the primary investigator with the same information. Indeed the primary investigator was confident in the selection of the anterior thigh skinfold as a high impact variable on the estimation of whole body density rather than the girths from the thigh, calf and ankle. The two breadths of the biacromial and biiliocristal were considered as important variable(s), whereas, the two depths and two widths were considered non-essential in the practical model because they are generally associated with growth and maturation (Ruff, 2003; Rauch, 2005). Analyses from phase one and phase two, eliminated the breadths, depths and widths due to their low impact on the estimation of whole body density (g ml^{-1}). From a theoretical point of

view, the developed calibration models are developed to be specific to a male professional football population, and could be considered as narrow. Although regardless of the population sample, the judgement in what anthropometric variables to use is paramount. Conversely from a practical point of view, the elimination of the two breadths can be considered problematic as these variable(s) as they are an important measure of body frame and size (Frisancho, 2004). Furthermore, specialised equipment is required to measure these features, which potentially can be more technically challenging to administer when in the field. Although it is important to stress that this technical challenge should not impact the outcome of developing the best possible calibration model, therefore, the primary investigator was left with a decision whether to force the breadths into the development of the 'practical' model, given its importance. As the primary investigator followed a rigorous statistical approach with the three distinct phases, the judgement was made therefore that the biacromial breadth, biiliocristal breadth, transverse chest depth, anterior-posterior chest depth, humerus width and femur width were not to be used in the development of the 'practical' calibration model.

Finally, at least one potential variable was needed from either body mass, stretched stature or sitting height. It was unlikely that specialised equipment would be available in a practical context to measure sitting height, and therefore it was rejected. Analyses from phase one and phase two eliminated the sitting height due to its low impact on the estimation of whole body density. Moreover, there might be questions raised over the inclusion of stretched stature as a potential variable. It could be argued that stretched stature is unlikely to change significantly with the present population and that it is unlikely to have an influence on the estimation of whole body density. However,

previous research by Wickkiser and Kelly (1975) used stretched stature in their calibration model, and analyses from phase one and phase two indicated that stretched stature provided a high impact on the estimation of whole body density. Consequently the primary investigator was left with nine potential variables for inclusion in the practical model (subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, arm (relaxed) girth, neck girth, hips girth, body mass and stretched stature). Given the recommendations gleamed from literature and the analyses from this study, the arm (relaxed) girth, neck girth and stretched stature were rejected. In so doing, the following five variables were used in the next phase of analyses (subscapular skinfold, iliac crest skinfold, anterior thigh skinfold, hips girth and body mass) as independent variables in a forced ordinary least squares backward stepwise regression analysis approach to develop the 'practical' calibration model. These variables consisted of a variation of upper, lower and trunk locations that according to Bellisari and Roche (2005) and Stewart (2006) provide an excellent subset of measuring total subcutaneous fat levels to estimate whole body density.

Table 6.6 illustrates the 'practical' calibration models generated for the estimation of whole body density using various combinations of anthropometric measures on the CM group of n = 140 participants. The order in which elimination of variables occurred was as follows: 1) subscapular skinfold, 2) iliac crest skinfold, 3), hips girth and, 4) anterior thigh skinfold.

Table 6.6 'Practical' calibration models for the estimation of whole body density (g ml^{-1}) from anthropometric measures in professional football players (n = 140)

Variable included	Calibration model (D_b = g ml^{-1})	SEE	R^2
BM, SS, IC, AT, Hip	D_b = 1.03 + (0.000161 x BM) – (0.000037 x SS) – (0.000063 x IC) + (0.000384 x AT) + (0.000175 x Hip)	0.012	4.7
BM, IC, AT, Hip	D_b = 1.03 + (0.000160 x BM) – (0.000072 x IC) + (0.000382 x AT) + (0.000173 x Hip)	0.012	4.7
BM, AT, Hip	D_b = 1.03 + (0.000160 x BM) – (0.000072 x IC) + (0.000382 x AT) + (0.000173 x Hip)	0.012	4.7
BM, AT	D_b = 1.04 + (0.000210 x BM) + (0.000343 x AT)	0.011	4.4
BM	D_b = 1.05 + (0.000234 x BM)	0.012	2.9

KEY:
(skinfolds): SS = subscapular; IC = iliac crest; AT = anterior thigh. (girths): Hip = hip. (other variables) BM = body mass. SS = stretched stature. D_b = estimate of whole body density (g.ml^{-1}); SEE = standard error of the estimate; R^2 = Coefficient of Determination (%)

Examination of the calibration model summarised in Table 6.6 identified three potential variables for the most practical calibration model. Further examination found that the most statistically robust model was that which used four independent variables: body mass, iliac crest skinfold, anterior thigh skinfold and hip girth. This model exhibited the lowest SEE (0.115 g ml^{-1}) and highest R^2 (4.7%) of the five potential calibration models. ANOVA components included Fdf-value = 1.68 and P-value of 0.159. Testing for residual errors heteroscedastic (multiplicative) found r = -0.176 and P = 0.038, with the overall practical calibration model indicating P = < 0.005.

Table 6.7 is a duplication of Table 5.7 from study 2 where the anthropometric variables measured taken and/or used for the development of calibration models for the prediction of body density are exhibited. Except in this instance, the primary investigator has illustrated all n = 28 anthropometric variables that were measured in study 1 and indicated which variables were used for both 'best fit' and 'practical' calibration models to help provide an overview.

Table 6.7 Anthropometric variables measured taken and/or used for the development of calibration models for the prediction of whole body density

	Anthropometric variables																																									
	Stretched stature	Sitting height	Body mass	Triceps skinfold	Subscapular skinfold	Biceps skinfold	Iliac crest skinfold	Supraspinale skinfold	Chest skinfold	Buttocks skinfold	Chin skinfold	Abdominal skinfold	Anterior thigh skinfold	Knee skinfold	Medial calf skinfold	Head girth	Neck girth	Shoulders girth	Arm (relaxed) girth	Arm (flexed) girth	Forearm girth	Elbow girth	Wrist girth	Chest girth	Waist girth	Buttocks girth	Hips girth	Thigh girth	Knees girth	Calf girth	Ankle girth	Biacromial breadth	Biiliocristal breadth	Transverse chest depth	Anterior-posterior chest depth	Humerus width	Wrist width	Femur width
Durnin & Rahaman (1967)	✓	✓		☑	☑	☑	☑												✓									✓		✓		✓	✓					
Sloan (1967)				✓	☑		✓			✓		✓	☑																									
Wilmore & Behnke (1969)				✓	✓		✓	✓				☑	☑	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓		✓	✓		✓	✓	✓	✓	✓		✓		✓
Sloan & Weir (1970)					☑								☑																									
Forsyth & Sinning (1973a)	✓		✓	☑	☑			☑	✓			☑	✓									✓	✓	✓				✓		✓	✓	✓					
Forsyth & Sinning (1973b)	✓		✓	✓	☑				✓			☑	✓									✓	✓	✓				✓		✓	✓	☑					
Katch & McArdle (1973)	✓		✓	☑	☑		✓					☑	✓			✓		✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Behnke & Wilmore (1974)												☑	☑																									
Durnin & Womersley (1974)			✓	☑	☑	☑	☑												✓								✓	✓		✓							
Wickkiser & Kelly (1975)	☑			☑	✓		✓		✓			✓	✓										✓		☑													
Jackson & Pollock (1978)				☑	☑		✓	☑	✓			✓	✓								✓				✓													
White *et al*., (1980)				✓	✓		☑		✓			✓	☑		✓		✓	✓		✓	✓			✓	✓		✓	✓		✓		✓	✓			✓	✓	✓
Lohman (1981)				☑	☑	✓	☑	☑	✓		✓	☑	☑		☑																							
Thorland *et al*., (1984)				☑	☑	☑	✓	✓	☑			☑	☑		☑		✓		✓	✓	✓		✓	✓	✓		✓	✓			✓	✓					✓
'Best fit' calibration model	☑	✓	☑	✓	✓	✓	✓	✓				✓	☑	✓	✓		☑		☑	✓	✓		✓	✓	✓		☑	✓		✓	✓	✓	✓	✓	✓	✓		✓
'Practical' calibration model	✓	✓	☑	✓	✓	✓	☑	✓				✓	☑		✓		✓		✓	✓	✓		✓	✓	✓		☑	✓		✓	✓	✓	✓	✓	✓	✓		✓

KEY: ✓anthropometric measure taken during study ☑ anthropometric measure used during development of calibration model

Closer inspection of Table 6.7 indicated that the most common anthropometric measures used in published calibration models, were those variables of the subscapular skinfold, triceps skinfold, iliac crest skinfold, supraspinale skinfold, abdominal skinfold and anterior thigh skinfold. Yet when comparing the three highest ranked calibration models of Wickkiser and Kelly (1975), Forsyth and Sinning (1973a) and Forsyth and Sinning (1973b) from study 2, what became apparent was that no previously published models had included any variables from the lower limb. Only Wickkiser and Kelly (1975) used a girth (waist) and stretched stature, and Forsyth's and Sinning's (1973b) was the only model to use a breadth (biiliocristal). It was to be expected that the models presented by Forsyth and Sinning (1973a and 1973b) would have similarities, because both models used the same sample and the same independent variables.

When considering the 'best fit' calibration model developed in the present study, six independent variables were used which is comparable to the models developed by Lohman (1981) and Thorland *et al*., (1984). Importantly the present study had a large sample size, with a larger range of variables to choose from and conducted more appropriate step-by-step statistical analyses, to determine the most reliable variables to use in the development of calibration models when compared to the Lohman (1981) and the Thorland *et al*., (1984) models. The present 'best fit' calibration model used one skinfold from the lower body, two girths from the core and one girth from the upper limb as well as body mass and stretched stature which conflicts with other comparable models in the literature where there is a tendency to use predominately skinfold thicknesses. Moreover, the present model provided a wide range of anthropometric variables which could potentially reduce the time needed to take six measurements per participant, where there is generally less time needed to locate landmarks and skinfold sites.

In contrast the present 'practical' model used only four independent variables, which is comparable with those use in the Forsyth and Sinning (1973a), Durnin and Rahaman (1967), and Durnin and Womersley (1974) models. These variables – body mass, iliac crest skinfold, anterior thigh skinfold and hip girth, and correspond with previous research which recommends that variables from the core body and lower limb are used to help estimate whole body density (Bellisari & Roche, 2005; Stewart, 2006). Indeed these variables from the core body and lower limb are particularly related to the nature and physiological demands of the game of football.

When comparing the variables used for both the 'best fit' calibration model and the 'practical' calibration model in the present study, both had body mass, anterior thigh skinfold and hip girth, suggesting a range of measures. What is clear, is that both calibration models included few variables (n = 6 and n = 4), a range of variables (skinfolds, girths, body mass and stretched stature) which ultimately provided reliable mechanism to estimate whole body density in professional football players.

Phase four

Phase four of this analyses required the consideration of the cross-validation of the newly developed calibration models on n = 66 of the sample. Summary results for general characteristics of these football players within the CV group are summarised in Table 6.8 and Table 6.9.

Table 6.8 General summary ($\bar{x} \pm s$) of the characteristics for the cross-validation group (n = 66) of football players

Variables	$\bar{x} \pm s$	Range
Age (yr)	24.5 ± 5.7	18.0 – 38.0
Body mass (kg)	80.3 ± 7.8	60.1 – 94.6
Stretched stature (cm)	180.9 ± 6.9	163.8 – 195.0
Sitting height (cm)	94.0 ± 4.6	82.1 – 104.0

The CV group were within an age range of 24.5 ± 5.7 years, body mass 80.3 ± 7.8 kg, stretched stature 180.9 ± 6.9 cm and sitting height 94.0 ± 4.6 cm. Key findings indicate that as previously reported in Table 4.3 and in Table 6.9 that the iliac crest, abdominal and anterior thigh skinfolds had large ranges from 5.7 – 39.2 mm, 6.6 – 32.5 mm and 5.2 – 29.5 mm respectively and were as anticipated, the largest values, with the chest, hip and waist had the greatest range of values of 86.4 – 109.1 cm, 85.2 – 106.9 cm and 71.3 – 98.2 cm respectively.

Table 6.9 Anthropometric summary ($\bar{x} \pm s$) of measures for the cross-validation group (n = 66) of football players

Variables	$\bar{x} \pm s$	Range
Skinfolds (mm)		
Triceps	9.0 ± 3.2	4.1 – 17.1
Subscapular	10.6 ± 2.6	6.1 – 17.7
Biceps	4.5 ± 1.9	2.7 – 10.1
Iliac crest	17.0 ± 7.0	5.7 – 39.2
Supraspinale	10.3 ± 4.5	4.1 – 24.4
Abdominal	15.3 ± 6.3	6.6 – 32.5
Anterior thigh	12.0 ± 4.9	5.2 – 29.5
Medial calf	7.2 ± 2.7	3.1 – 14.3
Girths (cm)		
Neck	38.4 ± 1.7	35.4 – 43.0
Arm (relaxed)	32.0 ± 1.9	28.1 – 36.1
Arm (flexed)	34.4 ± 1.9	30.5 – 38.0
Forearm	28.5 ± 1.5	25.7 – 31.2
Wrist	17.6 ± 0.8	15.8 – 19.1
Chest	99.6 ± 4.7	86.4 – 109.1
Waist	82.8 ± 4.9	71.3 – 98.2
Hip	95.0 ± 4.2	85.2 – 106.9
Thigh	56.7 ± 2.7	50.2 – 63.3
Calf	38.2 ± 2.1	29.9 – 42.3
Ankle	23.0 ± 1.4	18.9 – 25.8
Breadths (cm)		
Biacromial	43.3 ± 1.8	40.4 – 47.1
Biiliocristal	29.7 ± 1.6	26.1 – 32.4
Depths (cm)		
Transverse chest	31.0 ± 1.8	27.1 – 38.1
Anterior-posterior chest	20.7 ± 1.7	16.0 – 25.5
Widths (cm)		
Humerus	7.4 ± 0.9	6.3 – 10.2
Femur	9.6 ± 0.8	6.9 – 10.9

For illustrative purposes, Table 6.10 summarises the nine 'best fit' and five 'practical' calibration models to predict whole body density (g ml^{-1}) on the CV group of n = 66 participants.

Table 6.10 General summary ($\bar{x} \pm s$) of characteristics for the 'best fit' and 'practical' calibration models on the cross validation (CV) group of n = 66 participants to predict whole body density (g ml^{-1})

Calibration models	$\bar{x} \pm s$	Range
'best fit'[9]	1.068 ± 0.003	1.061 – 1.075
'best fit'[8]	1.068 ± 0.003	1.061 – 1.075
'best fit'[7]	1.068 ± 0.003	1.061 – 1.075
'best fit'[6]	1.069 ± 0.003	1.062 – 1.075
'best fit'[5]	1.065 ± 0.003	1.056 – 1.072
'best fit'[4]	1.062 ± 0.003	1.054 – 1.069
'best fit'[3]	1.064 ± 0.003	1.057 – 1.071
'best fit'[2]	1.061 ± 0.003	1.053 – 1.067
'best fit'[1]	1.067 ± 0.002	1.061 – 1.071
'practical'[5]	1.063 ± 0.003	1.059 – 1.069
'practical'[4]	1.063 ± 0.003	1.059 – 1.069
'practical'[3]	1.062 ± 0.003	1.058 – 1.068
'practical'[2]	1.061 ± 0.003	1.056 – 1.068
'practical'[1]	1.069 ± 0.002	1.064 – 1.072
Hydrostatic weighing	**1.075 ± 0.015**	**1.034 – 1.132**

To test the veracity of the newly developed calibration models a cross-validation was conducted on the values from the *n* = 66 CV sample. This involved using the Bland and Altman 95% limits of agreement approach to determine the bias, random variation and heteroscedasticity between whole body density values measured using the criterion method of hydrostatic weighing against both the for both 'best fit' (Figure 6.2) and 'practical' calibration models (Figure 6.3).

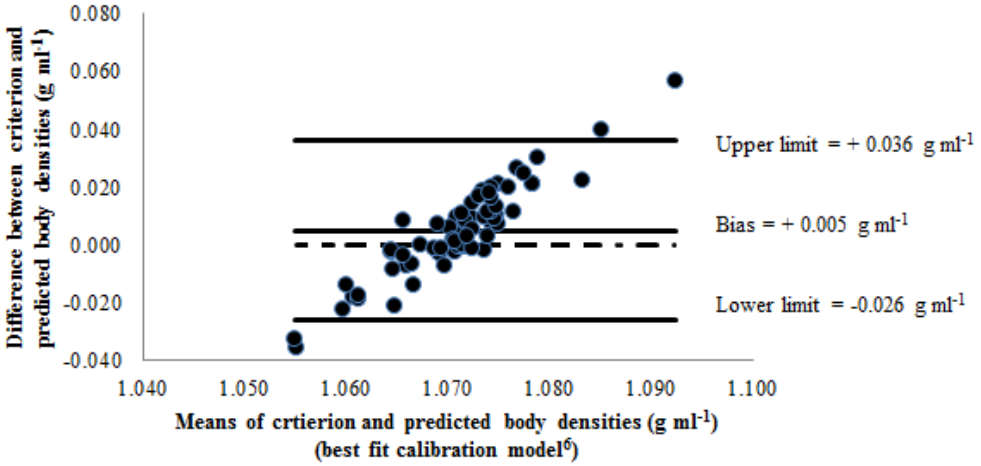

Figure 6.2 Bland and Altman plot summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the 'best fit' calibration model
Note: Direction of bias [hydrostatic weighing – calibration model]

The Bland and Altman plot for the 'best fit' calibration model, shown in Figure 6.2 identifies a positive bias of +0.005 g ml^{-1} and 95% limits of agreement of –0.026 to +0.036 g ml^{-1}. There is some evidence of systematic bias and random variation, with some data clusters around the bias line, and some outliers. Body densities differences between those predicted by the 'best fit' calibration model and those measured using the criterion method of hydrostatic weighing were normally distributed. A decision about the practical significance of the effect of these limits is a scientific decision and not a statistical one. Further criteria about whether these limits are narrow enough to allow the 'best fit'

calibration model to be used to replace the criterion method of measurement in estimating whole body density in this population of participants should be determined by the study's *a priori* criteria. When illustrated in this manner, it is clear that these limits of agreement are within acceptable limits, which in itself, indicates that there are minimal issues for sport scientists to consider with respect to the predictions from the 'best fit' calibration model.

The Bland and Altman plot for the 'practical' calibration model, shown in Figure 6.3 identified a positive bias of +0.011 g ml^{-1} and 95% limits of agreement of –0.019 to +0.041 g ml^{-1}. There is some evidence of systematic bias and random variation, with some data clusters around the bias line, and some outliers**.** The differences in whole body density between the values from the 'best fit' calibration model and those measured by the criterion method of hydrostatic weighing were normally distributed. These limits of agreement are within acceptable limits according to the study's *a priori* criteria and suggest that there are minimal issues for sports scientists when using this 'practical' model to estimate whole body density (g ml^{-1}) in professional football players.

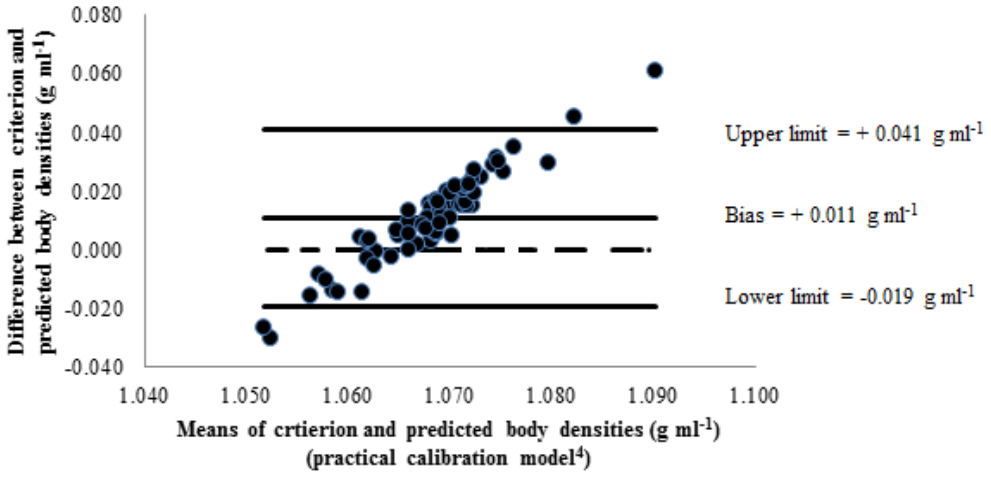

Figure 6.3 Bland and Altman plot summarising the 95% limits of agreement for comparisons between criterion body densities and those predicted from the 'practical' calibration model
Note: Direction of bias [hydrostatic weighing – calibration model]

For illustrative purposes, Table 6.11 provides an overview of bias, lower and upper limits of 95% limits of agreement for both calibration models displayed from Figures 6.2 – 6.3. Inspection of Table 6.11 indicated that the 'best fit' calibration model and the 'practical' calibration model (on average) with whole body density (g ml^{-1}) derived from hydrostatic weighing was greater than whole body density (g ml^{-1}) derived from the models, so there was a positive bias.

Results from the 95% limits of agreement analyses indicated bias (systematic errors) between criterion measured body densities and densities predicted by the 'best fit' and 'practical' calibration models ranged from 0.005 to 0.013 g ml^{-1} and random errors ranged from 1.053 to 1.075 g ml^{-1}. Thus suggesting the ranges are narrow enough to be of practical use to estimate whole body density (g ml^{-1}) of professional football players.

Table 6.11 Overview of 95% upper and lower limits of agreement and bias indicators for 'best fit' and 'practical' calibration models

Calibration models	**Bias** (g ml^{-1})	**(95 LoA) Lower limit** (g ml^{-1})	**(95 LoA) Upper limit** (g ml^{-1})
'best fit'[6]	+0.005	-0.026	+0.036
'practical'[4]	+0.011	-0.019	+0.041

For the 'best fit' calibration model there was a bias of 0.005 g ml^{-1} and limits of agreement of -0.026 g ml^{-1} to +0.036 g ml^{-1}. When determining whether a new participant from this population of interest (not one of the n = 206 sample) was predicted whole body density from the 'best fit' calibration model at 1.000 g ml^{-1} at this time of the test there is a 95% probability that if they were measured using the criterion method of hydrostatic weighing

the whole body density could be as low as 1.000 – 0.026 = 0.974 g ml^{-1} or as high as 1.000 + 0.036 = 1.036 g ml^{-1}. For the 'practical' calibration model there was a bias of 0.011 g ml^{-1} and limits of agreement of -0.026 g ml^{-1} to +0.036 g ml^{-1}. When determining whether a new participant from this population of interest predicted whole body density from the 'practical' calibration model at 1.000 g ml^{-1} at this time of the test, there is a 95% probability that if they were measured using the criterion method of hydrostatic weighing the whole body density could be as low as 1.000 – 0.019 = 0.981 g ml^{-1} or as high as 1.000 + 0.041 = 1.041 g ml^{-1}.

Based on these findings, the issue is whether these whole body density estimations would detrimentally affect anything the primary investigator has to say about the participants' whole body density derived from the developed calibration models. In other words, question whether the primary investigator could replace hydrostatic weighing method with the new calibration models. The statistics provided here cannot answer this question. Indeed the question that the primary investigator needs to ask is are the 95% limits of agreement narrow enough for the measurements to be of use for (i) academia, research and sports science and (ii) field testing monitoring and sports science. Considerations therefore need to be made whether these whole body density estimations are good enough for academia, research and sports science. Results from the *a priori* criteria established that both calibration models are within the acceptable limits and would be of practical use to the population of professional footballers.

For illustrative purposes, Figures 6.4 shows a scatter plot of heteroscedasticity to demonstrate the relationship between the criterion method of whole body density (g ml^{-1}) for 'best fit' calibration model and in Figure 6.5 the 'practical' calibration model. The

heteroscedasticity scatter plot for the 'best fit' calibration model shown in Figure 6.4 provide *r* values = 0.271 and R^2 (%) coefficients = 0.3526. There was some deviation from the line of identity, demonstrating some heteroscedasticity between the criterion method of hydrostatic weighing and the 'best fit' calibration model. This plot illustrated data cluster around 1.070 g ml^{-1}, and provided normal distribution and statistical significance of *P* = 0.01.

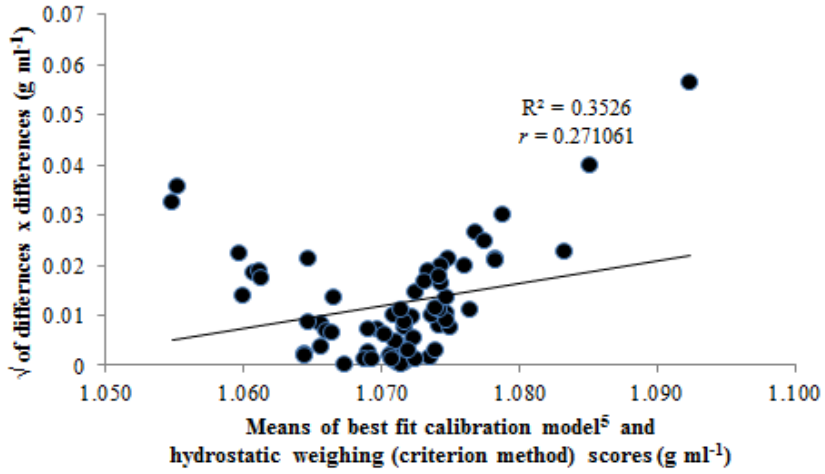

Figure 6.4 Scatter plots for heteroscedasticity of hydrostatic weighing (criterion method) compared to 'best fit'calibration model (means) for whole body density

Figure 6.5 illustrates the heteroscedasticity for 'practical' calibration model with *r* values = 0.596 and R^2 (%) coefficients = 0.3526. There is some evidence of heteroscedasticity and deviations from the line of identity. This particular model indicated statistical significance of *P* = < 0.01 and was normally distributed.

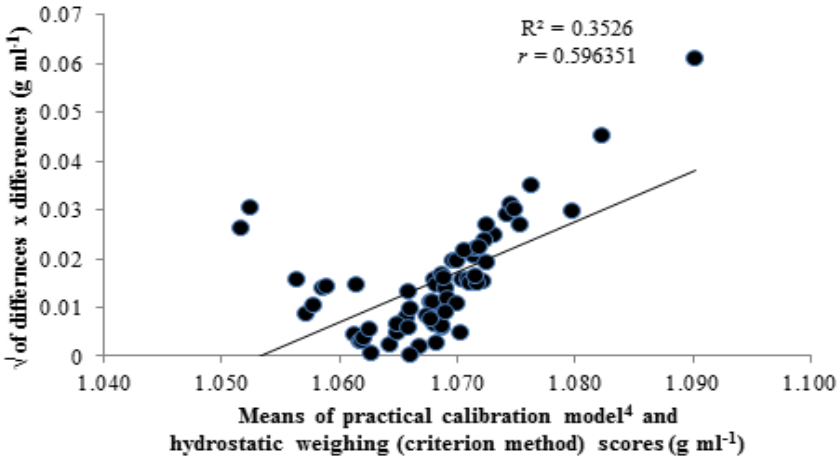

Figure 6.5 Scatter plots for heteroscedasticity of hydrostatic weighing (criterion method) compared to 'practical' calibration model (means) for whole body density

Table 6.12 illustrates an overview of the heteroscedasticity scatter plots R^2 (%), *r* and *P*-values for all nine 'best fit' and five 'practical' calibration models.

Table 6.12 Overview of heteroscedasticity scatter plots R^2, *r* and *P* values for calibration models

Calibration model	*r*	R^2 (%)	*P*
'best fit'[6]	0.271	0.3526	0.01
'practical'[4]	0.596	0.3526	0.01

6.5 Summary of main findings

The aim of the present study was to develop two separate calibration models on a large sample of *n* = 140 participants using a forced ordinary least squares backward stepwise regression method approach. The purpose of the 'best fit' model could be used within an environment that includes research, academia and/or sports science, where there is an expectation of expertise and understanding within the area of body composition analysis. Secondly a 'practical' model which could be used within a football environment including

field testing monitoring and/or sports science, but can be used for regular monitoring of a player(s) and/or squad(s) and providing informative insight into body composition and possible performance potential. Furthermore an aim was to cross-validate the two calibration models on n = 66 participants to determine the validity and relevance by using Bland and Altman's 95% limits of agreement approach.

Phase one

- Initial statistical analyses from the correlation matrix found that of the n = 28 predictor/independent variables available, 17 variables were statistically significant (P = < 0.01) and considered potential candidates for the development of calibration models. However 11 variables did not meet an alpha level of 0.01 and were therefore rejected for further development. In summary chosen independent variables included seven skinfold thicknesses, five girths, one breadth, one depth, body mass, stretched stature and sitting height

- Interrogation of the correlation matrix for collinearity – linear relationships between the independent variables had a cut-off correlation coefficient set at 0.950 which would give a coefficient of determination (R^2) of 90%. Of the 17 potential independent variables, more showed collinearity and therefore all were used in the next phase of analyses. Further examination of the correlation matrix led to the grouping of the 17 accepted independent variables to help improve the prediction equation into three subset groups of skinfold thicknesses, girths and other variables and recalculated into another correlation matrix. The predictions did improve, but improvements were so minimal that it was considered not substantial enough to continue to use these subsets in future model development.

Phase two

- Standardisation (z scores) of the 17 variables provided β weights, *r*, *t*, significance of *t* and *P*-values on the CM group of *n* = 140 participants. When interrogating *r*-values for relationships between the 17 independent potential variables, the hip girth provided the highest β weight (0.210) suggesting a high impact on whole body density (g ml^{-1}), whereas sitting height (-0.027) and seven other variables indicated the smallest impact on whole body density. The 17 independent variables did not exceed *r* = 0.80 (the acceptance criteria).

- Of the 17 potential independent variables, eight of them illustrated negative β weights values, with sitting height providing the lowest beta weight (-0.027) which suggested a negative impact on whole body density as opposed to the highest β weight of the anterior thigh skinfold (0.188). As a consequence, nine variables (subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, neck girth, arm (relaxed) girth, hip girth, body mass and stretched stature) fulfilled the criteria for acceptance and were used in the next phase of analyses in the development of the two calibration models.

Phase three – the 'best fit' calibration model

- A 'best fit' calibration model was developed using the forced regression analysis stepwise – backwards approach on a sample of *n* = 140 participants with nine potential independent variables (subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, neck girth, arm (relaxed) girth, hip girth, body mass and stretched stature). The intention for this calibration model was so that it could be used in an environment (research, academia, sports science)

where there is a high level of expertise and understanding within the area of body composition. The stepwise – backward approach eliminated one variable at each stage which was determined by their *t* and *P*-values, thereby producing nine potential calibration models.

- Results from the regression analysis approach found that the 'best fit'[6] calibration model had the lowest SEE (0.115 g ml^{-1}) and highest R^2 (6.6%) of the nine calibration models to predict whole body density. Furthermore, ANOVA analysis *Fdf*-value = 1.56 and *P*-value = 0.164, and with testing for heteroscedastic (multiplicative) residual errors at this stage revealed *r* = -0.213 and *P* = 0.011. This model was statistically significant (*P* = <0.005).

- The 'best fit' predictive regression equation developed model was:

  Whole body density (g ml^{-1}) = 1.01 + (0.000066 x body mass) + (0.000220 x stretched stature) + (0.000393 x anterior thigh skinfold) + (0.000336 x neck girth) – (0.000587 x arm (relaxed)) + (0.000154 x hip girth)

Phase three – the 'practical' calibration model

- A 'practical' calibration model was also developed using the forced regression analysis stepwise – backwards approach on the sample of *n* = 140 participants which could be used within a practical football environment (field testing, sports science). The primary investigator preselected the most applicable and practical anthropometric variables and made a judgement related to (i) an assumed technical ability to take measures from specific anatomical locations (ii) a range of variables taken from around the body, in particular from the lower limb and core, and,

finally, (iii) the total number of variables to be used. The stepwise – backward regression used five independent variables from a possible nine variables, (subscapular skinfold, iliac crest skinfold, anterior thigh skinfold, hip girth and body mass) and eliminated one variable at each stage. Elimination was determined using *t* and *P*-values, thereby producing five potential calibration models.

- Results from the regression analysis approach found that the 'practical'[4] calibration model had the lowest SEE (0.115 g ml^{-1}) and highest R^2 (4.7%) of the five potential calibration models to predict whole body density. Furthermore, ANOVA analysis *Fdf*-value = 1.68 and *P*-value = 0.159, and with testing for heteroscedastic (multiplicative) residual errors at this stage discovered *r* = -0.176 and *P* = 0.038. This model was statistically significant (*P* = <0.005).

- The 'practical' predictive regression equation developed model was:
  Whole body density (g ml^{-1}) = 1.03 + (0.000160 x body mass) – (0.000072 x iliac crest) + (0.000382 x anterior thigh skinfold) + (0.000173 x hip girth)

Phase four

- Bland and Altman's 95% limits of agreement approach was used to determine the bias, random variation and heteroscedasticity in whole body density from the criterion method of hydrostatic weighing with those predicted from both the 'best fit' and the 'practical' calibration models on a sample of *n* = 66 participants. Bland and Altman plots indicated a positive bias of +0.005 g ml^{-1} and +0.011 g ml^{-1} and 95% limits of agreement of -0.026 to +0.036 g ml^{-1} and -0.019 to +0.041 g ml^{-1} respectively. Residuals from criterion and calibration models were normally

distributed and findings were within acceptable limits compared to the study's *a priori* criteria. Results from the Bland and Altman analyses indicated that the 95% limits of agreement ranges were narrow enough to be of practical use to estimate whole body density in professional football players.

- Scatter plots of heteroscedasticity provided *r* values = 0.271 and 0.596 and R^2 (%) coefficients = 0.3526 for the 'best fit' and 'practical' calibration models. There was some evidence of heteroscedasticity and deviations from the line of identity between the criterion method of hydrostatic weighing and the calibration models. Both plots provided normal distribution and statistical significance of $P = 0.01$.

In summary, reliability findings from study one had a huge influence on the power of prediction for each calibration model, thereby, providing confidence by which sound judgements on whole body density can be made. In essence, given the developmental nature of this thesis, the two calibration models can provide an ecologically and statistically valid contribution to applied sport science knowledge.

Chapter 7

Summary and practical implications

7.1 Introduction

With interest in health, nutritional status and physical fitness, the evaluation of body composition is a common and important component when estimating body fat and whole body density (Provyn *et al*., 2012). The criterion method for the estimation of whole body density is hydrostatic weighing and is mainly attributed to its validation with cadaver analysis (Pateyjohns *et al*., 2006). Recently however, more sophisticated methods have come to the fore, such as Dual Energy X-ray Absorptiometry (DEXA) and Air Displacement Plethysmography (BodPod) with extensive research spanning across different populations and conditions (Wallace *et al*., 2008; LaForgia *et al*., 2009). Yet to date, they have failed to use human cadaver analysis to verify their validity and as such hydrostatic weighing although traditional in nature, remains the criterion (Shypailo *et al*., 2008; Santos *et al*., 2010). An alternative method that is considered quick, easy and inexpensive and can provide reasonably reproducible values is via the use anthropometric skinfolds (Wang *et al*., 2000).

Early investigations in both cadaver analyses and generalised research have indicated that it is possible to estimate whole body density from these measures with the use of calibration models (Brožek & Keys, 1951; Durnin & Rahaman, 1967; Womersley & Durnin, 1973). The components of these calibration models are generally based on independent variables such as anthropometric measures and based on formulae that estimate the dependent variable of whole body density (Provyn *et al*., 2012). There is an abundance of calibration models in the literature that are designed to provide estimation of body composition information relating to different ages, sex, ethnicity and levels of physical activity. On the whole, the design has raised many questions about the generalised approach and how effective they are in terms of reliability, validity and

consistency of measurement values. For instance, sports science research has continuously indicated that athletes have higher body density levels than that of the general population. Therefore, using these generalised calibration models can indiscriminately underestimate whole body density in an athletic population (Ishiguro *et al*., 2005; Peeters *et al*., (2013). The suggestion that many of these models might be unsuitable for athletes, could be indicative of why there has been an increase in the development of models tailored for specific populations. Even though they might appear to be an ideal notion, the development of such models can be fraught with methodological limitations, many of which have already been addressed within this thesis. The main solution could result in the acknowledgement of some of these limitations by using a large sample with reference to sound research principles such as cross-validation procedures.

A players body composition typically fluctuates over the playing season, therefore the sport scientist must be cognisant of the health and wellbeing of their players (see section 2.1.1) (Gil *et al*., 2005; Demura *et al*., 2007). As professionals, their training intensity would expect to be physically demanding therefore, the physiological stress placed on the players over a long period of time can induce a negative health status (Oppliger & Cassady, 1994; Svensson & Drust, 2005). One way to monitor their health would be to conduct body composition assessments on a regular basis to establish desirable body composition prerequisites required so that consequence of morbidity are reduced and a player can perform at an optimal level (Wallace *et al*., 2008; Stewart, 2012).

7.2 Summary of findings from Study 1

The principle aim of study 1 was to:

> *To identify and quantify intra-rater measurement reliability commonly used body composition measures (n = 29) and to establish sources of error through relative and absolute reliability methods Furthermore to establish the reliability and precision of body composition measures used within calibration models to estimate whole body density when applied to professional football players (n = 206). The aim of this study was to establish reliability in the data collected. Without such confidence in the reliability the comparison of findings is not possible and would not support a sound foundation from which Study 2 and Study 3 in this thesis could be based.*

Generally speaking there are two types of reliability that are frequently encountered, namely relative reliability (consistency) and absolute reliability (accuracy) within sports science (Baumgarter, 1989). When estimating the impact of reliability on the outcomes of a given measurement, the sport scientist has to appreciate what the particular measurement error actually represents in practice (Atkinson, 2003). Within the context of this thesis, two methods of expressing measurement reliabilities were investigated to help improve reproducibility. Firstly, inter-rater reliability was investigated using technical error of measurement (TEM) analyses that are commonly used within kinanthropometry. Measurement targets set by the International Society for the Advancement of Kinanthropometry (ISAK) provided an objective method to evaluate the competency of a rater against that of an ISAK level 4 criterion. Inter-tester analyses against level 1 and level 2/3 targets were conducted by comparing test-retest on n = 28 anthropometric measures using ISAK protocols from 2001. The humerus and femur widths provided some of the lowest differences (0.6%), whereas variables such as the skinfolds of the biceps, triceps, subscapular, iliac crest, supraspinale, abdominal, anterior thigh and the girths of the waist and hips had greater variability (3.8%). However reliable, anthropometric measurements were achieved that were well within acceptable ISAK TEM% targets, indicating measurement precision and competency.

Secondly, intra-observer reliability or test-retest method was investigated using Bland and Altman's 95% limits of agreement analyses (LoA) on n = 27 variables. It was important for the primary investigator to judge from the identification and quantification of the agreement outcomes if LoA were narrow enough for the anthropometric variables to provide practically reliable values, or in other words, whether they could have any detrimental effect on the practical use when applied to a population of participants. Therefore *a priori* criterion were set (± 3.8%, P < = 0.05) to establish acceptable limits for the Bland and Altman method that presented acceptable and tolerable limits within the context of this study (ISAK, 2001; Ludbrook, 2010; Woodman, 2010; Marfell-Jones, 2013 (personal communication – see Appendix X)).

All differences between test-retest were found to be normally distributed with some evidence of systematic bias and random variation. Bias ranged from + 0.01 to + 0.08 mm for skinfolds, - 0.01 to + 0.07 (cm), for girths and 0.1 to + 0.06 (cm) for breadths, depths and widths. Possible heteroscedasticity issues were found some contentious anthropometric variables including iliac crest skinfold, supraspinale skinfold, anterior thigh skinfold, chest girth, hip girth and biiliocristal breadth (P = <0.05) with r values = 0.611 and R^2 (%) coefficients = 37.3%. However, none of the variables illustrate heteroscedasticity due to the equal residual variance about the range of the values. As such there was no need to resolve it by log transformation. Interpretation and quantification LoA and the study's *a priori* criteria all n = 28 anthropometric variables were statistically significant (P = < 0.01) and demonstrated agreement and reliability through the test re-test analyses of inter and intra-test reliability.

7.2.1 Practical implications from Study 1

Within sports science, it has been well documented regarding the importance of reliability and measurement error and therefore not uncommon to encounter reliability issues, ranging from equipment calibration to technical execution and repeatability. Given the developmental and practical focus of this thesis, without establishing the accuracy and reliability of anthropometric measures there could not be a foundation on which to build further studies.

To that end, Study 1 provided the primary investigator with three main practical advantages: (i) established accuracy and reliability of *n* = 28 anthropometric measures and that the criterion of hydrostatic weighing was as error free as possible, (ii) confidence in making sound judgements on whether these anthropometric measures would have any detrimental effect when applying to a population of professional footballers and (iii) confidence in which variables to include in the development of calibration models to estimate whole body density (g ml^{-1}). To summarise, study 1 established reliable measures and provided significant practical implications, which ultimately resulted in these *n* = 28 anthropometric variables being of practical use with the study's population.

7.3 Summary of findings from Study 2

The principle aim of study 2 was to:

> *To investigate the validity recognised of pre-published calibration models (n = 15) for the estimation of whole body density when compared to whole body density values derived using the criterion method of hydrostatic weighing. Additionally to investigate the agreement of the estimation of whole body density when applied to professional football players (n = 206). The aim of this study was to investigate whether these generalised calibration models were suitable for professional football players. Data entered into the models were gained from the reliability investigations from Study 1 and the sample size was large to be able to make an informed decision.*

Numerous calibration models exist in the public domain which purports to estimate whole body density for adult males, many of which have been derived from measurements taken from heterogeneous samples. However, from a sport science research perspective, questions remain about measurement validity and whether they are fit for purpose. For instance, previous studies have indicated that indiscriminate use of calibration models to estimate whole body density on populations that are different to those on which they were originally derived might lead to significant over or under-estimation of whole body density with some been known to report ranges of between 1.027 and 1.090 g ml^{-1} with leaner populations, indicating significant underestimation of whole body density (Guo *et al*., 2000; Provyn *et al*., 2012). Therefore, if these calibration models are to be useful in a football context, their validity must be established, or the sport scientist could risk inaccurately estimating whole body density.

After close scrutiny of the literature and with the study's selection criteria in mind, fifteen models were investigated in terms of their suitability for a sample of professional football players. The intention of this study was to select a range of models that represent a host of different considerations. For instance, year of publication, sample numbers, type of participants, equipment used and the anthropometric variables used within the calibration model regression equation. In general, there was no models available post 1987, indicating a significant lack of research in nearly thirty years. As there was no model specifically designed for use with professional football players, this could suggest that there has been a dependency upon these generalised calibration models, whereas a more effective alternative would be to use a model that is specific for the population. Within the models regression equations, there was a wide range of anthropometric variables used, with commonly used skinfolds, girths, breadths, depths, widths and other variables including

body mass, stretched stature and sitting height, indicating many different approaches to the design of models. The sample numbers ranged from 50 to 403 participants, with 10 studies having less than 100 participants. These studies having low numbers could arguably influence one of the most important considerations, of cross-validation. Potentially if these authors had insufficient numbers, they were therefore unable to carry out cross-validation methods with authority, thereby questioning its validity.

Within the context of this thesis, the agreement and validity of estimating whole body density was investigated by carrying out the Bland and Altman 95% LoA method. Analyses found that (on average) estimated whole body density derived from hydrostatic weighing was greater than whole body density (g ml^{-1}) derived from the models with bias ranged from - 0.005 to + 0.009 g ml^{-1} and random errors ranged from 1.012 to 1.079 g ml^{-1}. Two calibration models found that (on average) whole body density (g ml^{-1}) derived from hydrostatic weighing was lower than whole body density (g ml^{-1}) derived from the models, with bias ranged from + 0.009 to + 0.015 g ml^{-1} and random errors ranged from 1.027 to 1.090 g ml^{-1}. Similarly to study 1, *a priori* criteria was set (± 3.8% $P < 0.05$ (g ml^{-1})) to establish acceptable limits for the LoA method. Models presented by Forsyth and Sinning (1973b) and Durnin and Womersley (1974) were not within acceptable limits by as much as 0.007 g ml^{-1}, and 0.005 g ml^{-1} respectively.

Five models were found to be at the upper limits of the criteria and two models found to be at the lower limits of the criteria, indicating a wide spectrum of reported whole body density (g ml^{-1}) values for professional football players. The model of Jackson and Pollock (1978) was the only one that illustrated heteroscedasticity (r = -0.323, R^2 (%) coefficients = 0.1046%, P = 0.01). Given that there was non-significant measurement error or reliability

issues in relation to the variables used and only one model illustrated heteroscedasticity, there was no need to find the cause and resolve it by log transforming, and to leave the data in its present condition. As models will infrequently agree with one another a rank order of the 95% upper and lower limits was determined to provide an overview that would best identify the best model to use for the current population of professional footballers. The model designed by Forsyth and Sinning (1973b) was considered the most valid with bias ranged from -0.015 to +0.045 g ml^{-1} with whole body density values ranging from 1.025 to 1.081 g ml^{-1}. Overall, results suggested that most published models were within an acceptable range, however, thirteen models (on average) systematically underestimated and two calibration models (on average) overestimated whole body density in the sample of professional football players when compared to densities gathered from the criterion hydrostatic weighing method used in the study.

When critiquing the calibration models there were various methodologies used and when scrutinised, they revealed various limitations with their design and development. These limitations are by no means exhaustive, although individually they could present significant problems to the development of new models and inevitably for the outcome of each participant. There was evidence of numerous anthropometric variables used within each model. Some of which were standalone skinfolds, some skinfolds with combinations of other variables (girths, breadths, widths, depths, body mass, stretched stature and sitting height), or finally as log transformations. Those models that used log transformations, were left with no option, as these model only used the sum of skinfolds, indicating that they did not have alternative variables to use in the development of the model. As previously mentioned the sample size employed, did have (whether it was intentional or not) statistical limitations. Research has repeatedly indicated that a robust sample size is

critical otherwise the model might not be capable of providing sound statistical validity. Furthermore, if sample sizes where restricted, that would not enable the researchers to carry out fundamental analyses of cross-validation as indices of the models validity. Ultimately, the limitations in many of these models highlight the need for sports scientists to be mindful of what models to use when applying them to their specific population, or indeed what to consider when developing their own specific model.

7.3.1 Practical implications from Study 2

There can be indiscriminate use of generalised calibration models to estimate whole body density on populations that are different to those on which they were originally derived (Guo *et al*., 2000; Provyn *et al*., 2012). Results from study 2 suggest that these generalised models produced error (disagreement) that was too great, in other words, would not be of practical use for the current sample of professional footballers. Yet there is a suggestion that there might be a dependency on these generalised models, due to the lack of sports specific calibration models available (Provyn *et al*., 2012). Therefore it is critical that sports scientists either consider an appropriate calibration model that constitutes practical significance, alternatively, develop new models that are based on large sample sizes that includes the entire playing spectrum of football players and above all, established with sound research principles such as cross-validation procedures.

7.4 Summary of findings from Study 3

The principle aim of study 3 was to:

> *To determine the most reliable and accurate body composition measures that can be used as potential predictors for the estimation of whole body density on n = 206 professional football players. The potential predictors would be used to develop two sport specific calibration models on n = 140 professional footballers. Firstly to develop a 'best fit' calibration model where there is a high level of understanding and expertise in the area of body composition, and could be used within an academic and research environment. Secondly to develop a 'practical' calibration model that could be used within a football field testing environment. Validity of the two new calibration models, to be determined through cross-validation methods on n = 66 professional footballers to estimate whole body density. The aim of this study was to develop models that are capable enough to monitor whole body density level of professional football players. Moreover, provide an essential tool for the regular monitoring of players and provide informative insight into the body fat levels needed to determine optimal performance potential. Data entered into the models were gained from the reliability investigations from Study 1 and the sample size was large (n = 140 participants) and cross-validation processes were used to determine validity of newly developed calibration models on n = 66 participants to be able to make an informed decision.*

To date there are no calibration models that exist in the literature to estimate whole body density (g ml^{-1}) in professional football players. From a sport science perspective, there is a significant gap in the literature. As such, there is a need to establish practical models to enable sound body composition judgements to be made. These models could be used for regular monitoring of a player(s) and/or squad(s) and provide informative insight into their body composition and thus contribute towards the optimisation of performance potential. Four distinctive phases of statistical analyses were followed in order to develop the two calibration models in Study 3 and furthermore to cross-validate the newly developed models to estimate whole body density (g ml^{-1}) in professional football players. This has been an important omission in the body composition literature.

Phase one initial statistical analyses found that 11 of the 28 anthropometric predictor (IV) variables did not meet an alpha level of 0.01 and were rejected from further development, whereas the remaining 17 potential predictor variables were statistically significant ($P = < 0.01$). Interrogation of a correlation matrix for collinearity – linear relationships between the independent predictor variables had a cut-off correlation coefficient was at 0.950 which would give a coefficient of determination (R^2) of 90%. Of the 17 potential variables, all were accepted and used in the next phase of analyses. To investigate whether the prediction could be improved, led to the grouping of 17 variables into three separate groups of skinfold thicknesses, girths and other variables and examined in another correlation matrix. The predictions did improve slightly, but this improvement was not significant enough to warrant grouping predictors in the final models.

Phase two involved standardisation (z scores) of the 17 variables into unit less measurements to help reduce heteroscedasticity on the CM group of $n = 140$ participants. At this stage none of the 17 independent variables exceeded the r acceptance criteria ($r = 0.80$). Interrogation of β–weights found that eight variables had negative β–weight values with sitting height providing the lowest β weight (-0.27) suggesting a negative impact on whole body density (g ml^{-1}) as opposed to the highest β–weight of the anterior thigh skinfold (0.188). Nine variables (subscapular skinfold, iliac crest skinfold, abdominal skinfold, anterior thigh skinfold, neck girth, arm (relaxed) girth, hip girth, body mass and stretched stature) fulfilled the acceptance criteria and were used in the next phase of analyses in the development of two calibration models.

Phase three analyses involved forced regression analysis stepwise – backwards approach on a sample of n = 140 participants using the nine potential variables identified to develop a 'best fit' and a 'practical' calibration model. The nature of the stepwise-backward approached eliminated one variable at each stage dependent upon outcomes of their t and P-values, thereby producing nine potential calibration models. Results from the regression analysis found that the 'best fit'[6] calibration model had the lowest SEE (0.115 g ml^{-1}) and highest R^2 (6.6%), of the nine potential calibration models. ANOVA analysis gave Fdf-value = 1.56 and P-value = 0.164, and with testing for heteroscedastic (multiplicative) residual errors at this stage revealed r = -0.213 and P = 0.011. The 'best fit' model was statistically significant (P = <0.005) and expressed as: Whole body density (g ml^{-1}) = 1.01 + (0.000066 x body mass) + (0.000220 x stretched stature) + (0.000393 x anterior thigh skinfold) + (0.000336 x neck girth) – (0.000587 x arm (relaxed)) + (0.000154 x hips girth), where this model could be used in an environment where there is a high level of measuring expertise and theoretical understanding within the area of body composition (research, academia and sports science).

A judgement on the most applicable and worthy anthropometric variables was made for the 'practical' model, according to (i) an assumed technical ability to take measures from specific locations of the body (ii) variables taken from around the body, in particular from the lower limb and core body and finally (iii) the total number of predictor variables to be used. The variables consisted of the subscapular skinfold, iliac crest skinfold, anterior thigh skinfold, hip girth and body mass. Results from the regression analysis found that the 'practical'[4] calibration model had the lowest SEE (0.115 g ml^{-1}) and highest R^2 (4.7%) of the five potential calibration models. ANOVA analysis Fdf-value = 1.68 and P-value = 0.159, and with testing for heteroscedastic (multiplicative) residual errors at this stage

revealed r = -0.176 and P = 0.038. The 'practical' model was statistically significant (P = < 0.005) and expressed as: Whole body density (g ml^{-1}) = 1.03 + (0.000160 x body mass) – (0.000072 x iliac crest) + (0.000382 x anterior thigh skinfold) + (0.000173 x hips girth). It now intended that this model could be used in a football environment (field testing and sports science).

The validity of the two new calibration models was determined through cross-validation methods on a smaller sample of n = 66 professional footballers to estimate whole body density in phase four. Bland and Altman 95% LoA approach were used to determine bias and random variation gained from the criterion method of hydrostatic weighing for both 'best fit' and 'practical' developed calibration models on a population sample of n = 66 participants. Bland and Altman plots indicated a positive bias of +0.005 g ml^{-1} and +0.011 g ml^{-1} and 95% LoA of -0.026 to +0.036 g ml^{-1} and -0.019 to +0.041 g ml^{-1} respectively. Random variation distances ranged between 1.059 – 1.075 g ml^{-1} with evidence of systematic bias. Both calibration models were normally distributed and findings were within acceptable limits of the study's *a priori* criteria (± 3.8% $P \leq 0.05$ (g ml^{-1})). Scatter plots of heteroscedasticity illustrated r values = 0.271 and 0.596 and R^2 (%) coefficients = 0.3526 for the 'best fit' and 'practical' calibration models. Both plots provided normal distribution and statistical significance of P = 0.01. Results from the Bland and Altman analyses indicated that the 95% LoA ranges were narrow enough to be of practical use to estimate whole body density in professional football players. In summary, reliability findings from study one had a huge influence on the power of prediction for each of the two new calibration models. This development and cross-validation of two new calibration models ultimately provided confidence by which sound judgements on whole body density in professional football players can be made.

7.4.1 Practical implications from Study 3

As far as the primary investigator is aware, no calibration models exist in the literature to estimate whole body density in professional football players. It would appear that there is a gap in the literature that could be filled in order to make sound body composition judgements. The development of two separate calibration models potentially could be used in different circumstances and environments. Moreover, adding to the literature by providing reliable and valid models for use with professional football players.

The development of such models however, needed consideration from the limitations identified from study 2 (see section 5.4 and 7.3). Given the varying limitations the primary investigator was in particular mindful of two areas in the development of such models. Firstly a judgement on which anthropometric variables to use in the estimation of whole body density was needed. For instance, anthropometric skinfolds are commonly and frequently used within calibration models that estimate whole body density, whereas, anthropometric girths, breadths and width measures are used, but sparingly (Heyward & Wagner, 2004; Stewart, 2006). With these developments, there have been reported problems associated with the number of skinfold sites to use when developing calibration models, for instance, some colleagues recommend a combination of two skinfold sites, whereas others support four or more and others seven or more (Durnin & Rahaman 1973; Durnin & Womersley, 1974; Jackson & Pollock, 1977). What is evident is that many researchers have used the skinfold sites of the upper trunk, with the biceps and triceps skinfold being the most popular to estimate whole body density (Woolford *et al.,* 1993; Wang *et al.,* 2000). Yet there is a clear contradiction as cadaver analyses discovered that men mainly deposit fat in different proportions and parts of the body that is centralised within the trunk region (Sardinha *et al*., 1999). Whereas Heyward and Wagner (2004) and

Stewart (2006) both claim that athletes body fat deposition generally favours the limb sites, especially the thigh. Indeed, when establishing which anthropometric measures to use when designing their own calibration models, researchers need to be mindful and to use a variety of upper, lower and trunk skinfold sites (Bellisari & Roche, 2005; Stewart, 2006).

Secondly, the application of cross-validation procedures, where authors such as Mayhew *et al*., (1981), Jackson and Pollock (1982), Hawes (1996) and Atkinson (2005) have suggested that if the participant sample sizes for cross-validation and the range of measures used have been too restrictive to be effective indicators of the predictive nature of the existing calibration model(s). For instance, relatively small sample sizes of n = 50 participants or less, is not an adequate basis upon which to develop calibration models due to the resulting wide confidence intervals (Hawes, 1996; Atkinson, 2005). In other words, studies conducted on large sample sizes are therefore warranted (Atkinson & Nevill, 2001).

7.6 Strengths and limitations of the thesis

The major strength of this thesis has been the organic developmental nature with which the estimation of whole body density has been statistically analysed. The thesis contributes to knowledge by firstly recruiting a large number of participants (n = 206), which far exceeded the majority of studies available in the public domain and certainly with a professional football population. Secondly, the thesis established reliability and precision of n = 27 anthropometric measures, from which there would not be a sound foundation to build studies 2 and 3 and is an opulent number of measures, compared to previous research on professional football populations. Thirdly, the thesis identified methodological limitations from pre-published calibration models, and addressed some of these limitations in the development of new models that can be transposed into the sports science arena.

Fourthly, to plug the gap in the literature, the thesis developed two practically applied calibration models that could be applied in different environments to estimate whole body density on professional football players. Fifthly, the thesis applied cross-validation methods on the two newly developed calibration models. This cross-validation procedure ultimately provided an ecological and statistically valid contribution to applied sport science knowledge in relation to professional football players' body composition.

Unfortunately, limitations do exist and in the context of this thesis, the major limitation, and one that has been problematic in a great majority of the studies investigated, has been the sample size. This is particularly the case when the reliability and validity of measurement values was the focus of interest. Although generally speaking the sample size was more than adequate for the purposes of study 1 and study 2, and far exceeded the recommended minimum of n = 40 participants by statisticians (as previously mentioned in section 2.8.4) (Atkinson, 2005). However, even though the sample size for cross-validation in study 3 met the criteria mentioned previously it might be considered by some statisticians to be restrictive.

Finally it is worth noting that all anthropometric outcomes are based on ISAK protocols in 2001. Whether this would have changed some of these anthropometric outcomes when using the ISAK 2011 protocols remains to be investigated. Additionally, there was acknowledgement that the primary investigator had not obtained ISAK level 2 accreditation. As a result the primary investigator could be subject to scrutiny as ISAK measurement training had not taken place for the additional n = 11 variables needed for level 2 accreditation. Nevertheless all n = 28 variables followed strict ISAK (2001) protocols, after which the primary investigator compared carried out TEM% statistical

analyses to ISAK level 2 accreditation level. Results demonstrated that the primary investigator was confident that they were operating within ISAK level 2 standards (see Table 4.7). There was acknowledgement that the primary investigator had not obtained ISAK level 2 accreditation. As a result the primary investigator could be subject to scrutiny as ISAK measurement training had not taken place for the additional n = 11 variables needed for level 2 accreditation. Nevertheless all n = 28 variables followed strict ISAK (2001) protocols, after which the primary investigator compared carried out TEM% statistical analyses to ISAK level 2 accreditation level. Results demonstrated that the primary investigator was confident that they were operating within ISAK level 2 standards (see Table 4.7). Moreover, when inspecting the variables utilised in the development of both calibration models all four variables (body mass, iliac crest skinfold, anterior thigh skinfold and hip girth) included in the 'practical' model were to level 1 ISAK standard. With regards to the 'best fit' model, all but one variable (neck girth) were also to level 1 ISAK standard, suggesting the confidence in the measurement outcomes.

7.7 Implications for future research

This thesis has used rigorous methodologies in the three studies presented, thus demonstrating flowing practical sports science research which have not previously been reported with professional football players. However, there is certainly a need for future research to be mindful of a few implications, many of which have already been previously discussed in depth (see sections 7.2.2, 7.3.2 and 7.3.3). It is important that future research has due regard to observing the rubric, where participant samples should be a minimum of n = 40 for test-retest reliability studies, and a minimum of n = 50 when cross-validating is to be attempted. This is important because the calculated LoA, or any other indices of measurement error, are meant to be extrapolated from a given sample to the wider

population under investigation. By employing a larger sample size of participants could distribute them into four playing zones (goalkeepers, defence, midfield and attack), or ideally into playing positions. The latter could prove problematic to quantify given the positional role within the team and/or the team's particular style of play (Svensson and Drust, 2005). However, this distribution of players into zones (in particular) could increase reliability and validity when applying anthropometric data to a football specific calibration model. It is also important that future researchers appreciate that the indices of measurement error will change when used with a different population. Moreover, those measurement error indices are useful to, and are easily understood by, athletes, their coaches, and the sport scientists that support them.

Finally future research could also consider the application of the two newly developed calibration models from this thesis to youth elite footballers. Arguably there are growth and maturation considerations, nonetheless there is potential to diversify to an age group less than 18 years of age, where they are under the management of a professional football club and have appropriate personnel to support and monitor them. Moreover, the two newly developed calibration models could be applied to female elite footballers. Women's football is considered the most prominent team sport around the world and is played at the professional level in numerous counties and with estimates from the Football Association (2013) of approximately 1.38m women and girls playing the game regularly with the UK. Despite this popularity, there would need to be important sex specific considerations regarding the menstrual cycle, body fat deposits and body fat distribution. Nevertheless, there could be an opportunity to develop research in an area of rapid development.

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Plates

Plate 1 Instrument – Hydrostatic Weighing Tank and Seat

Plate 2 Instrument – Whole Body Densitometer Seat and Suspension system

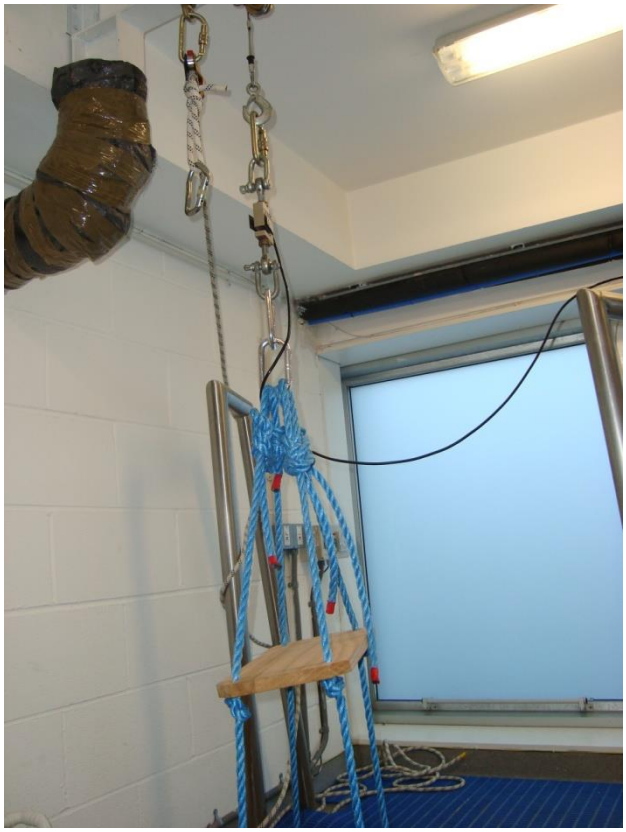


Plate 3 Instrument – Hoist system

Plate 4 Instrument – Wall Mounted Digital Weighing Scale

Plate 5 Instrument – Air Displacement Plethysmograph (BodPod)

Plate 6 Instrument – BodPod (Software)

Plate 7 Instrument – BodPod (swim cap and nose clip)

Plate 8 Instrument – BodPod Weighing Scales

Plate 9 Instrument – Vitalograph Spirometer

Plate 10 Instrument – Holtain Wall Mounted Stadiometer

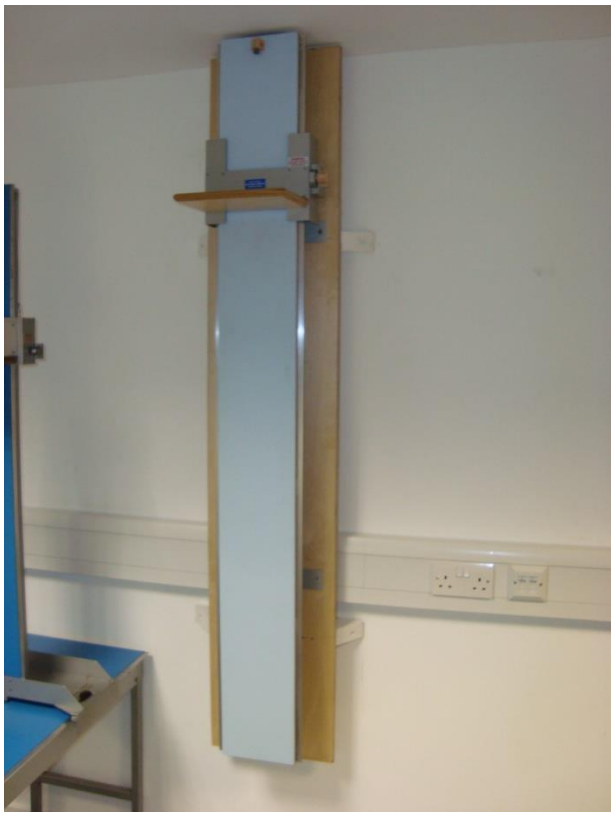


Plate 11 Instrument – Holtain Seated Stadiometer

Plate 12 Instrument – Harpenden Skinfold Caliper

Plate 13 Instrument – Anthropometric Equipment

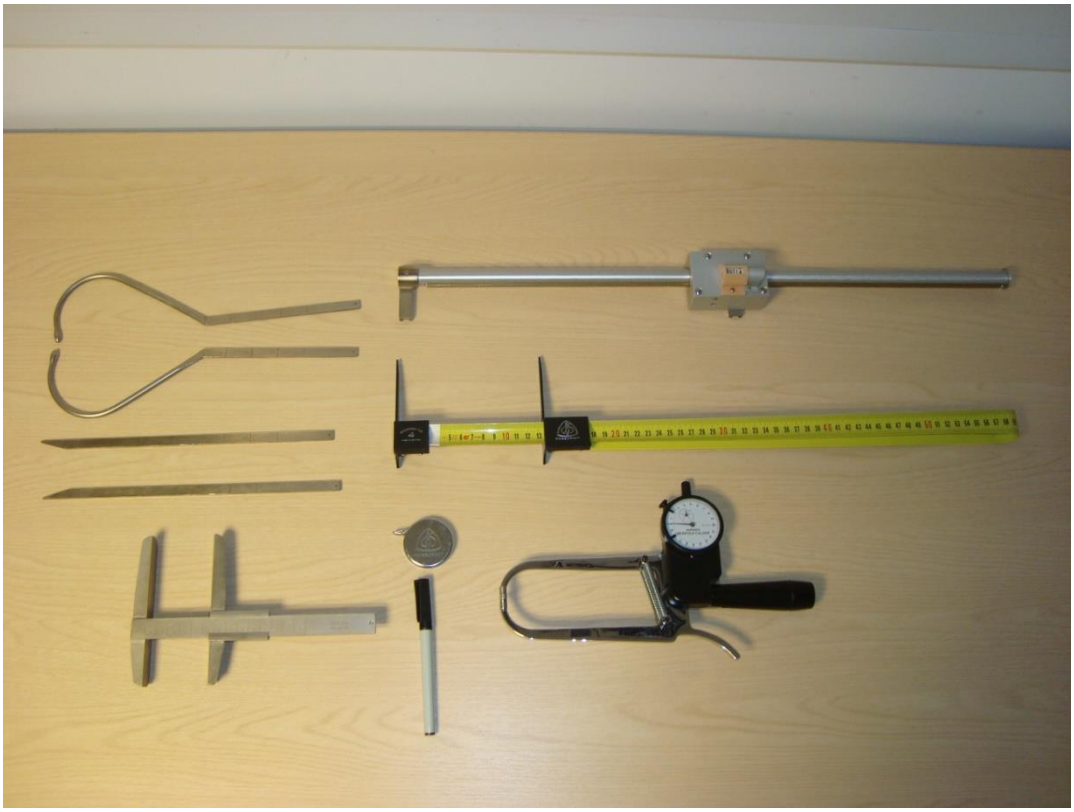


Plate 14 Instrument – Anthropometric Box

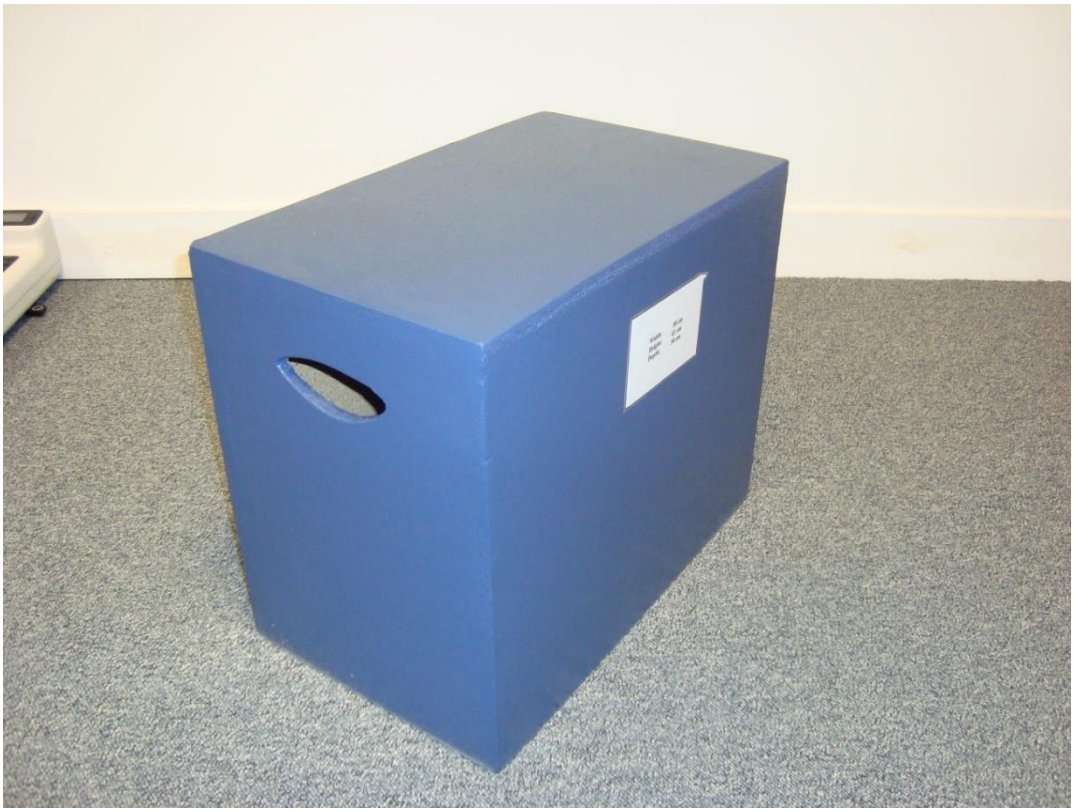


Plate 15 Procedure – Underwater Weighing (g.ml-^{1}) (Suspended)

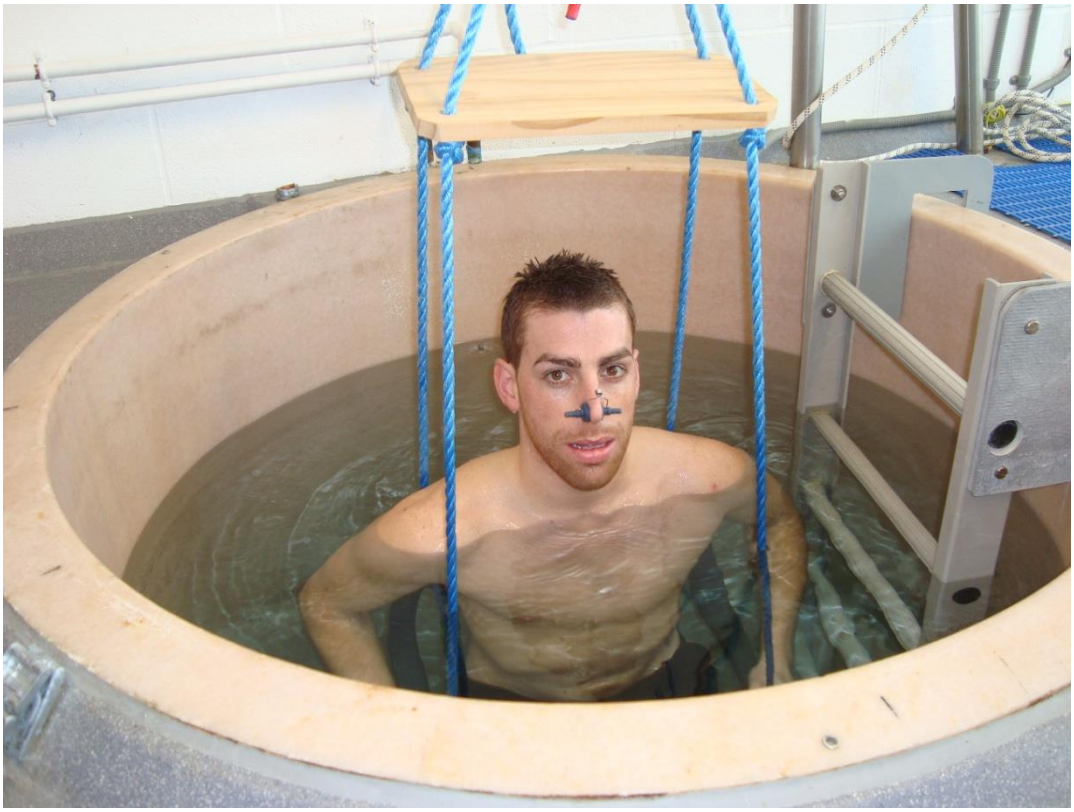


Plate 16 Procedure – Underwater Weighing (g.ml-^{1}) (Maximal Exhalation)

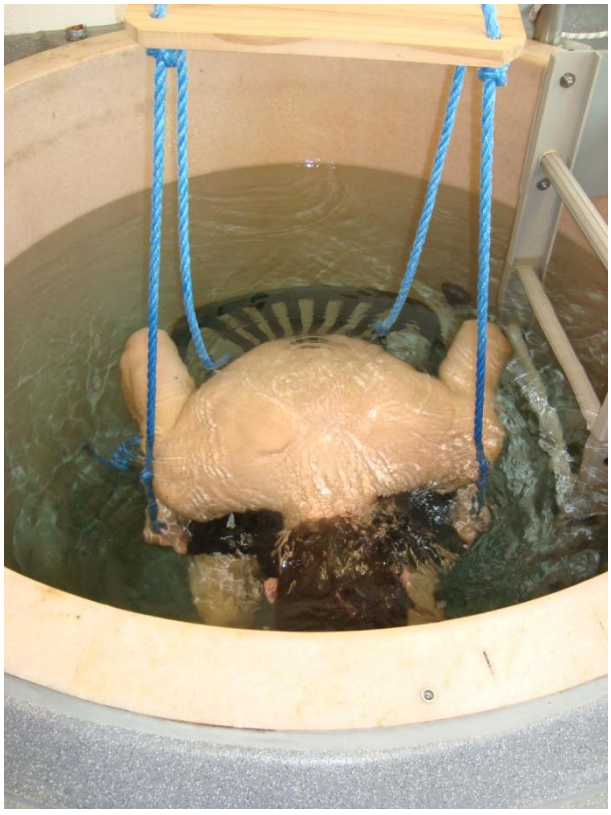


Plate 17 Instrument Verification – BodPod (Mass Weights)

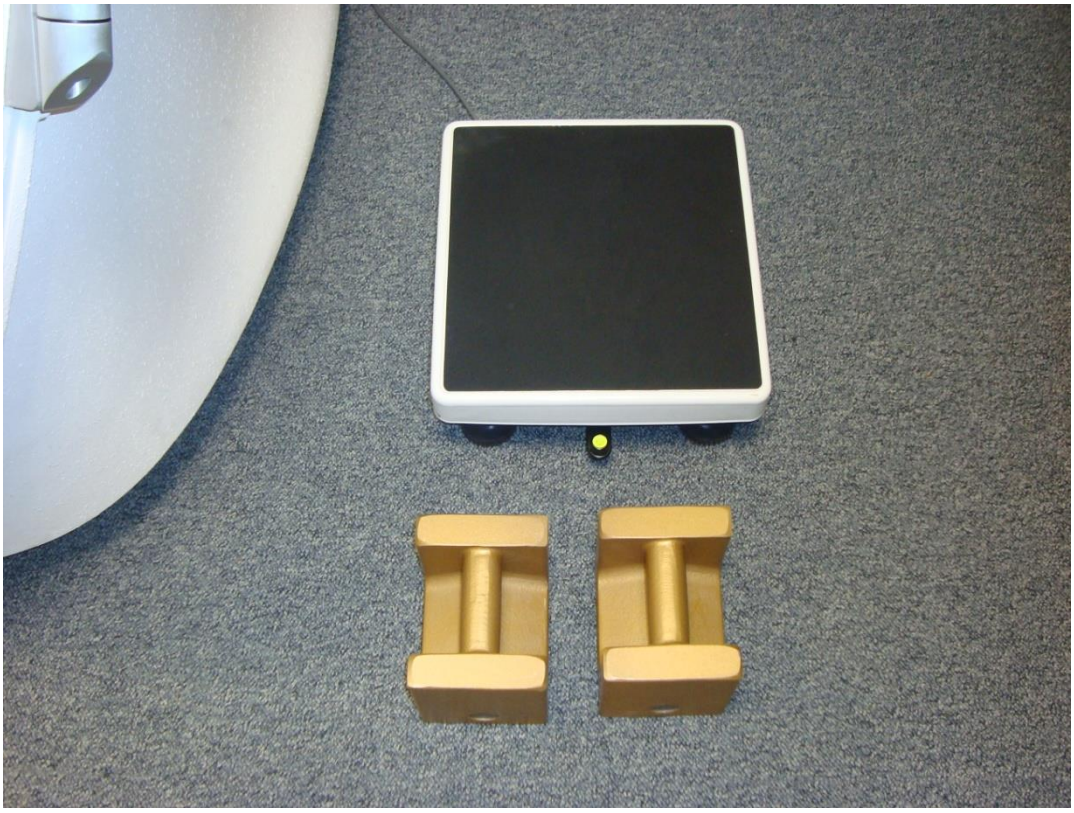


Plate 18 Instrument Verification – BodPod (Mass Weights on Scales)

Plate 19 Instrument Verification – BodPod (Volume Cylinder)

Plate 20 Instrument Verification – BodPod (Volume Cylinder inside BodPod)

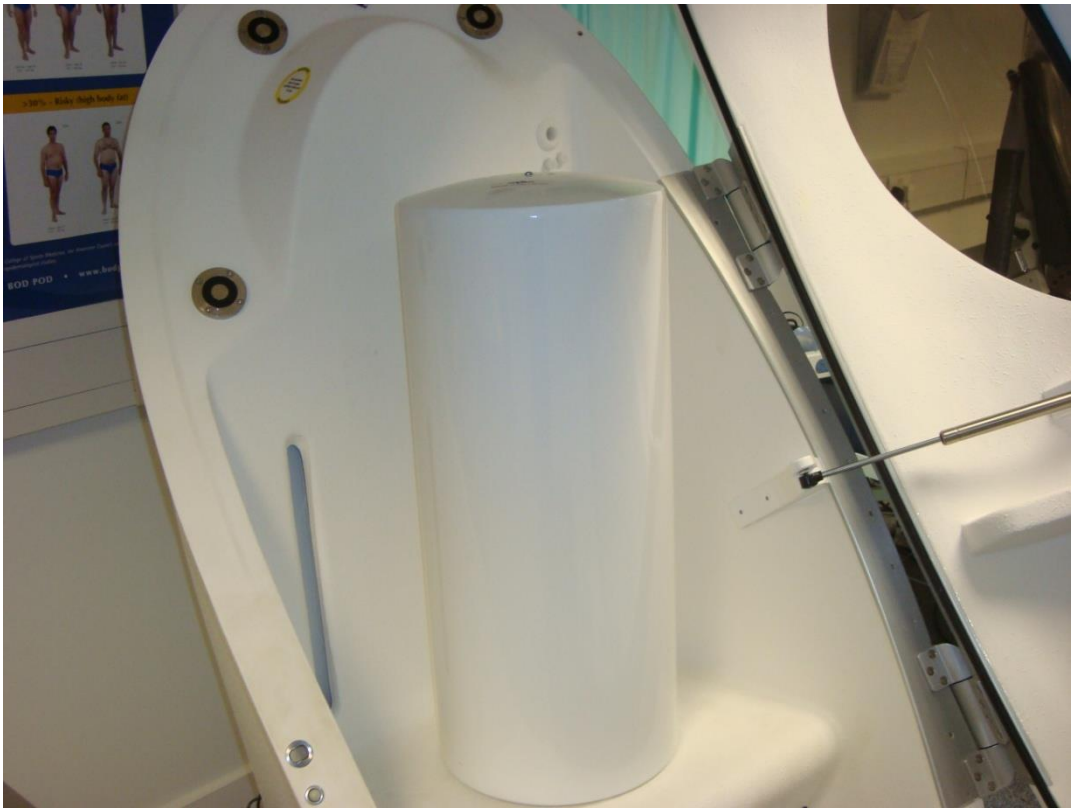


Plate 21 Procedure – Body Mass (kg) Measurement

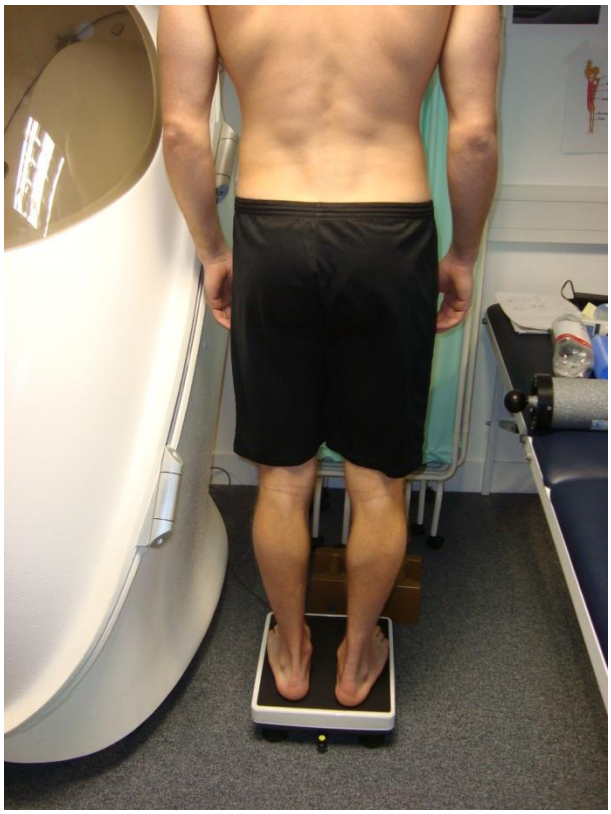


Plate 22 Procedure – BodPod (sitting position)

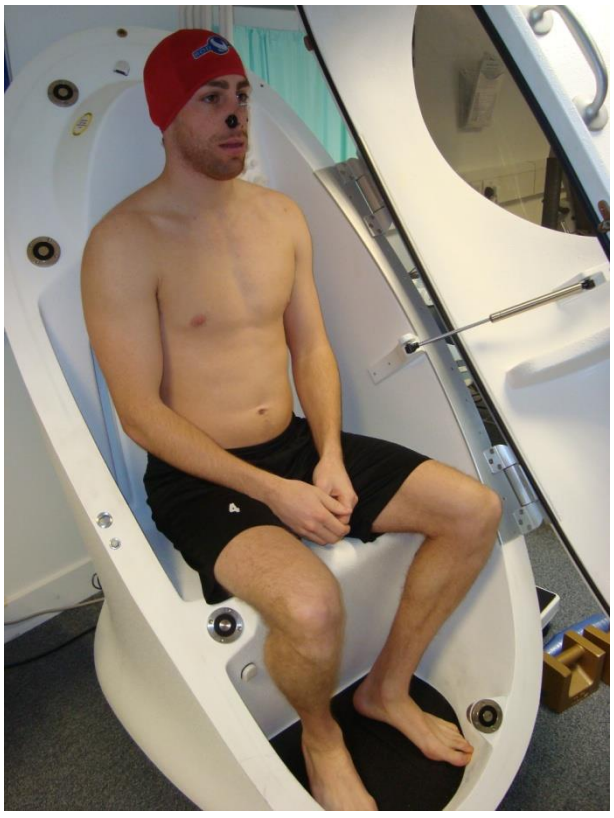


Plate 23 Procedure – BodPod (aluminous panic release button)

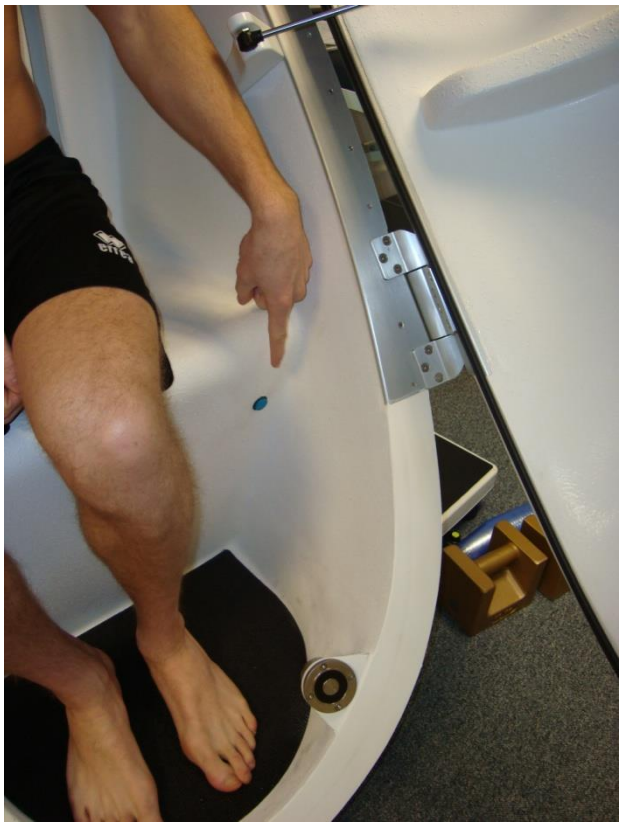


Plate 24 Procedure – BodPod (door sealed)

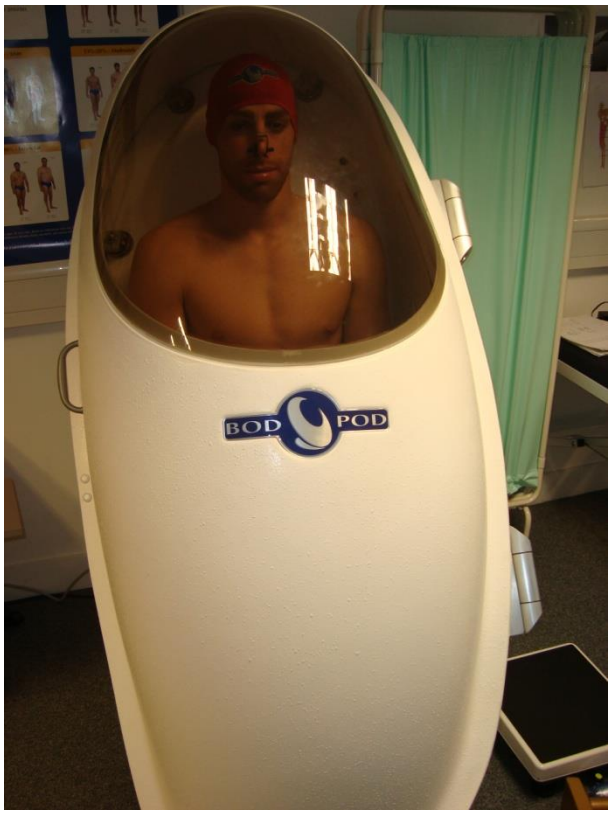


Plate 25 Procedure – Forced Vital Capacity (l) (Relaxed)

Plate 26 Procedure – Forced Vital Capacity (l) (Maximal Exhalation)

Plate 27 Procedure – Stretched Stature (cm) Measurement

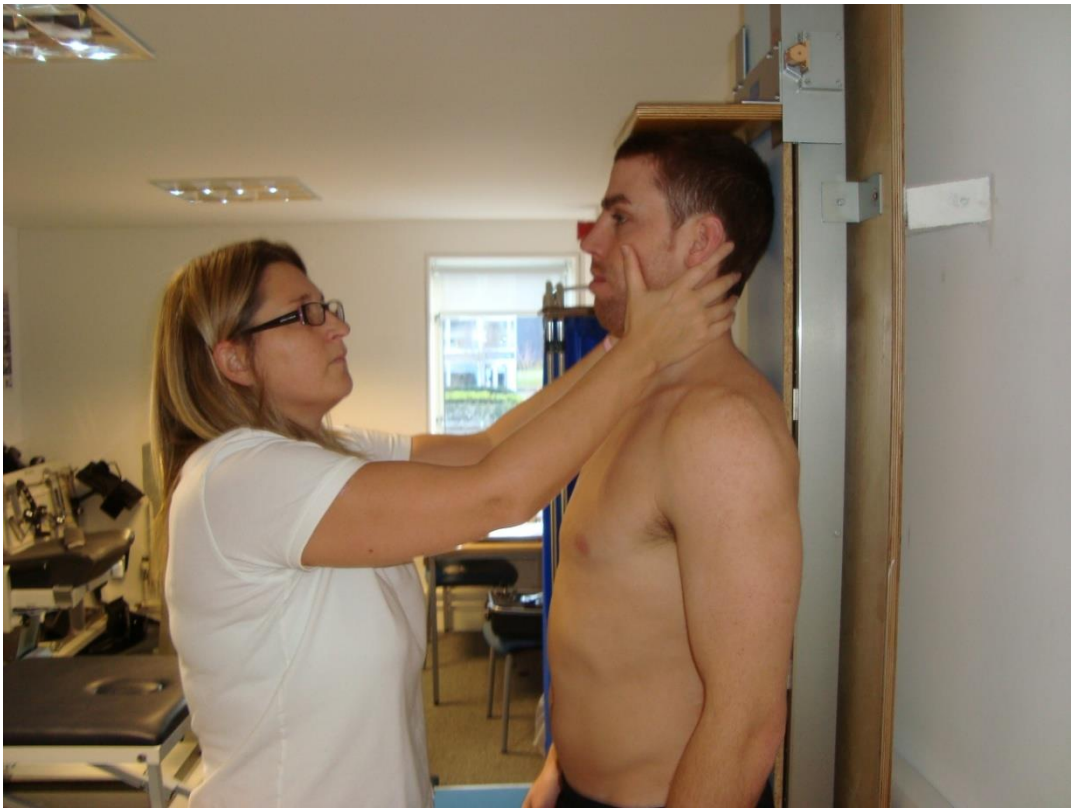


Plate 28 Procedure – Sitting Height (cm) Measurement

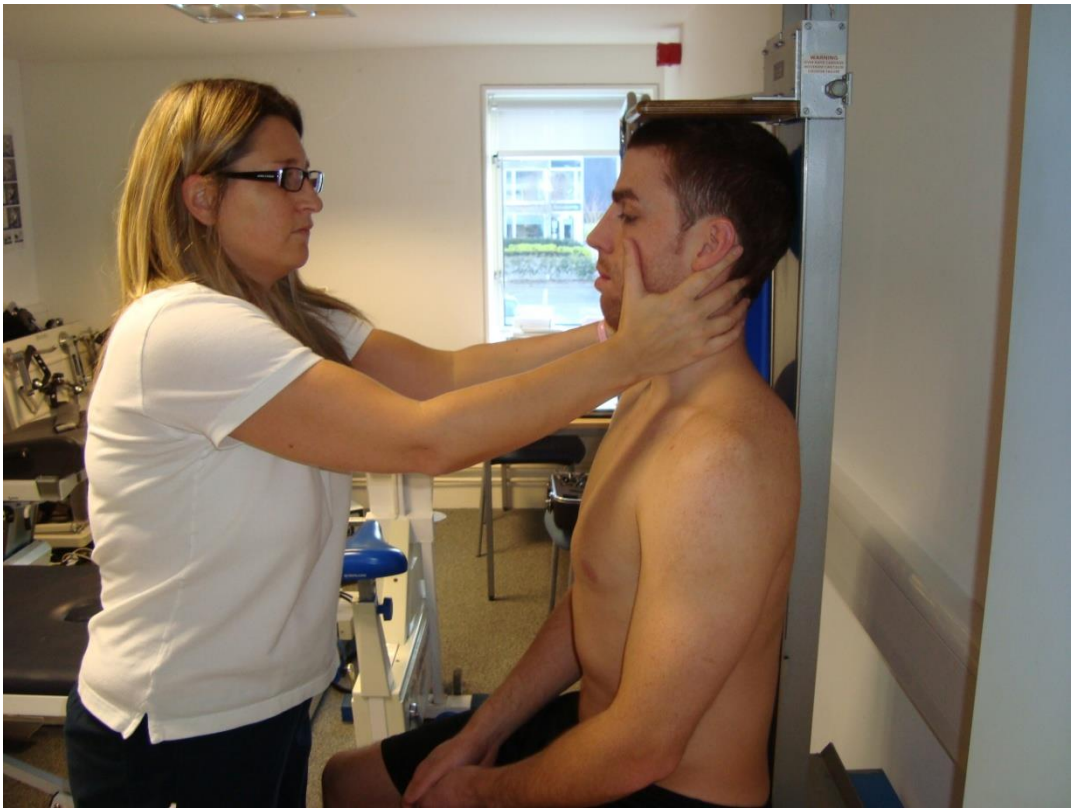


Plate 29 Anthropometry – Universal Anatomical Position (Anterior Position)

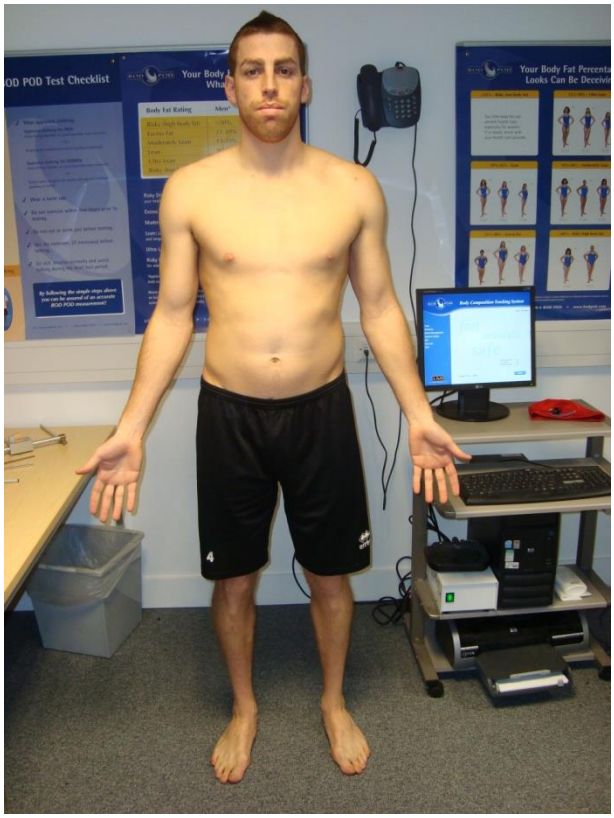


Plate 30 Anthropometry – Universal Anatomical Position (Posterior Position)

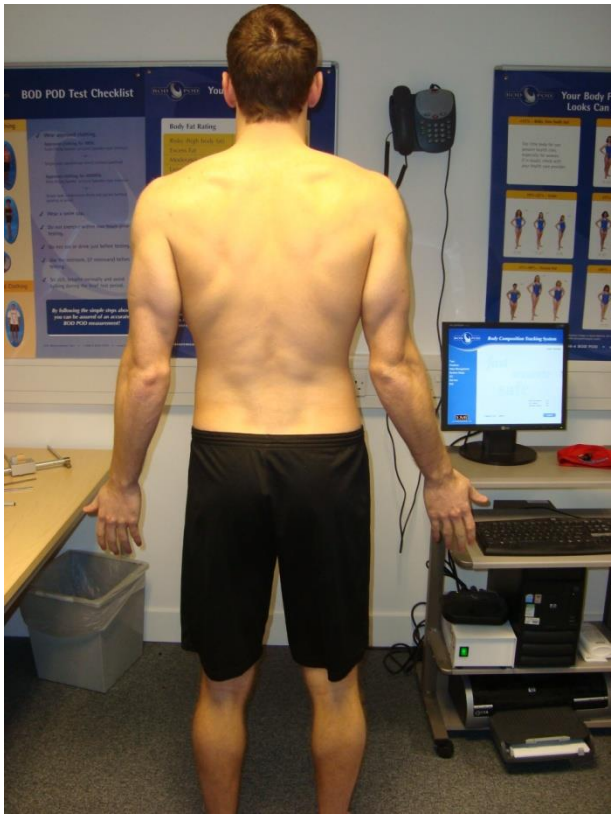


Plate 31 Anthropometric Landmark – Acromiale

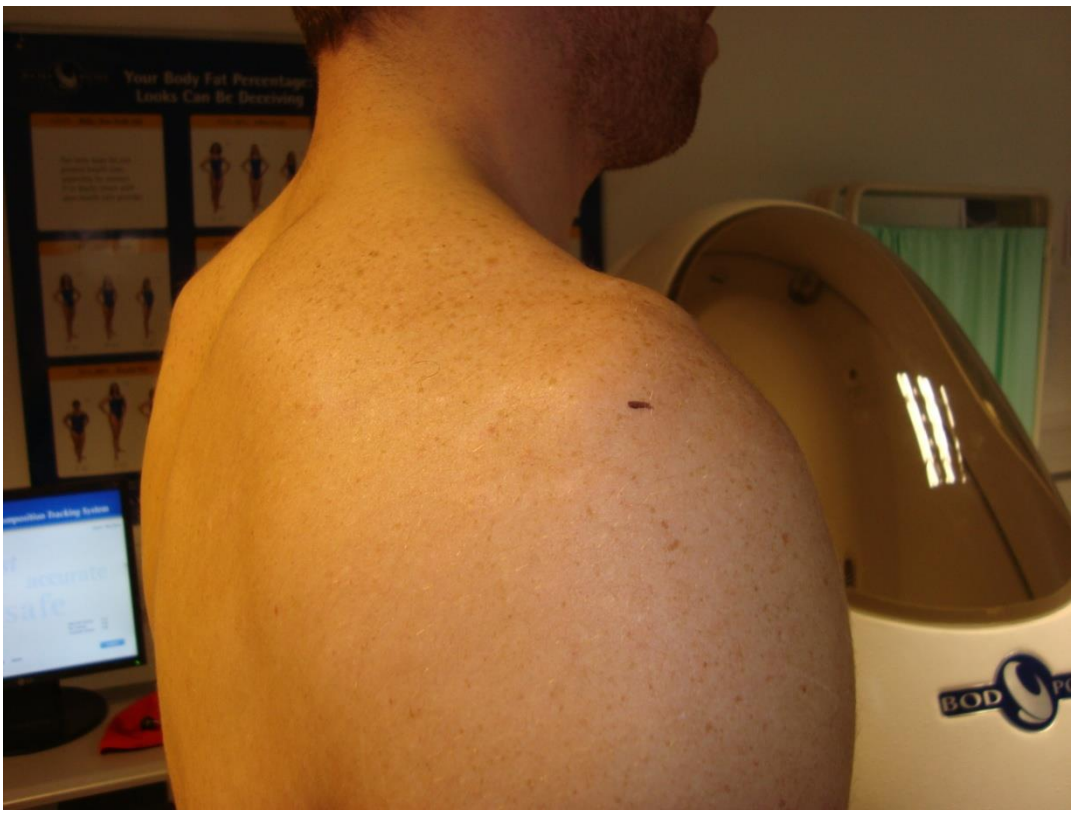


Plate 32 Anthropometric Landmark – Radiale

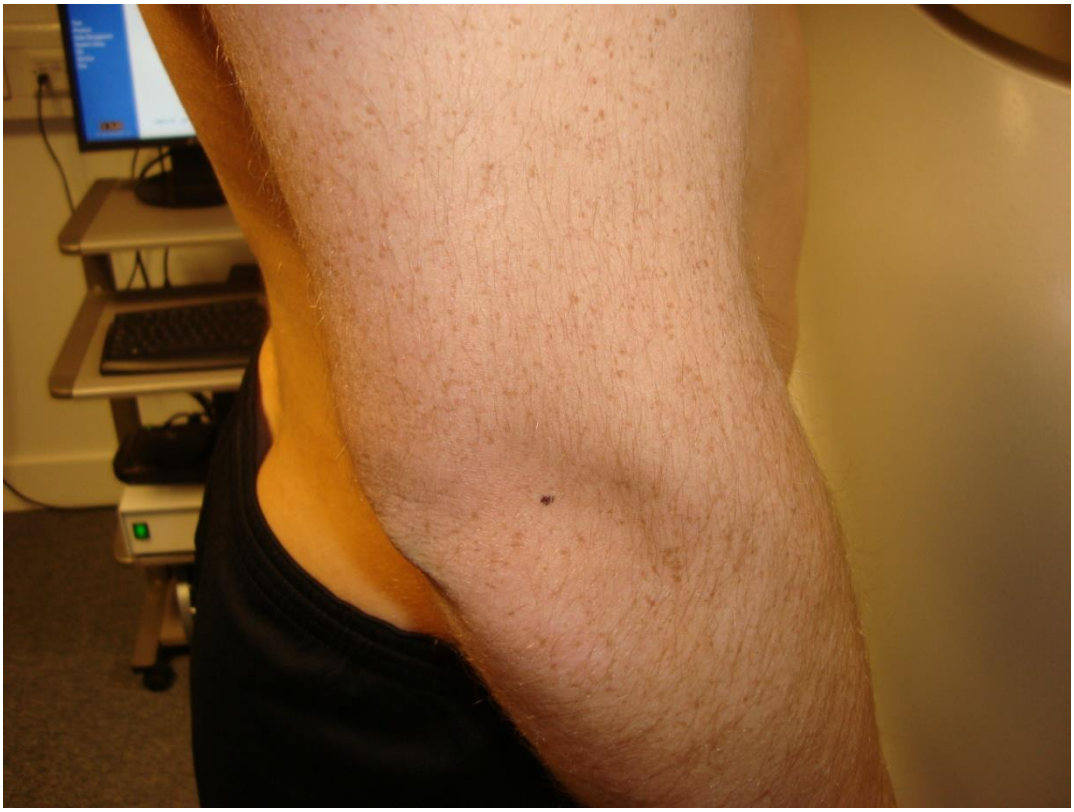


Plate 33 Anthropometric Landmark – Iliocristale

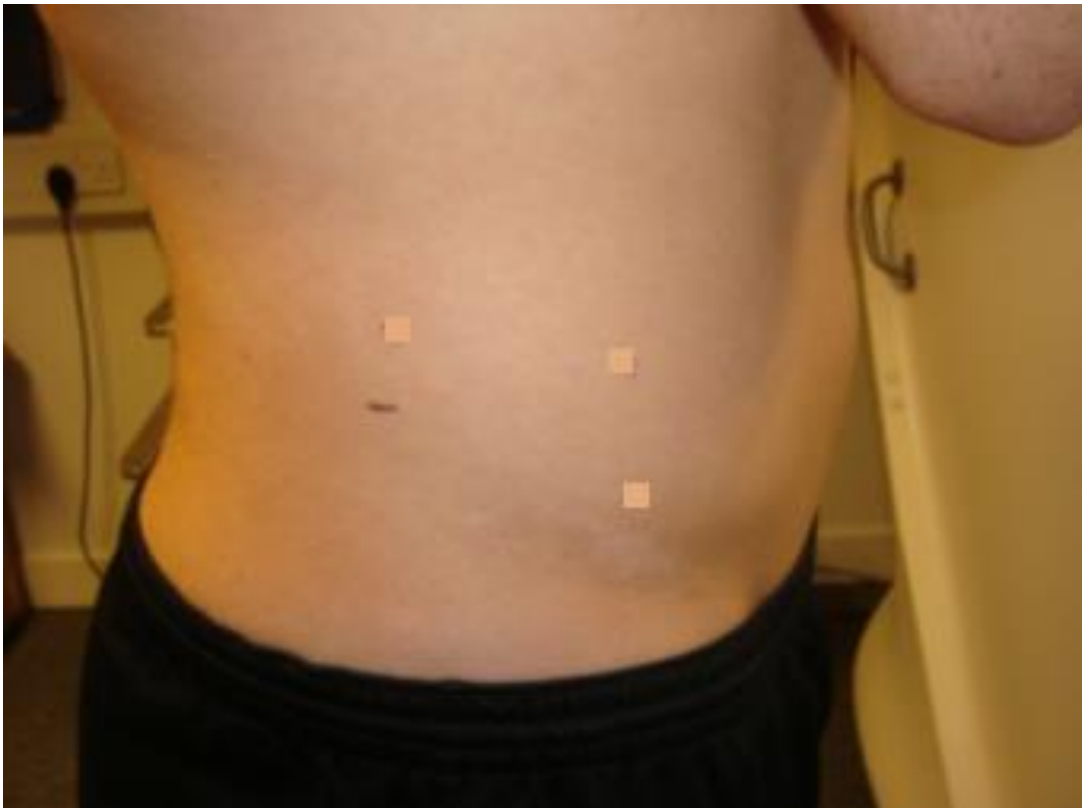


Plate 34 Anthropometric Landmark – Iliospinale

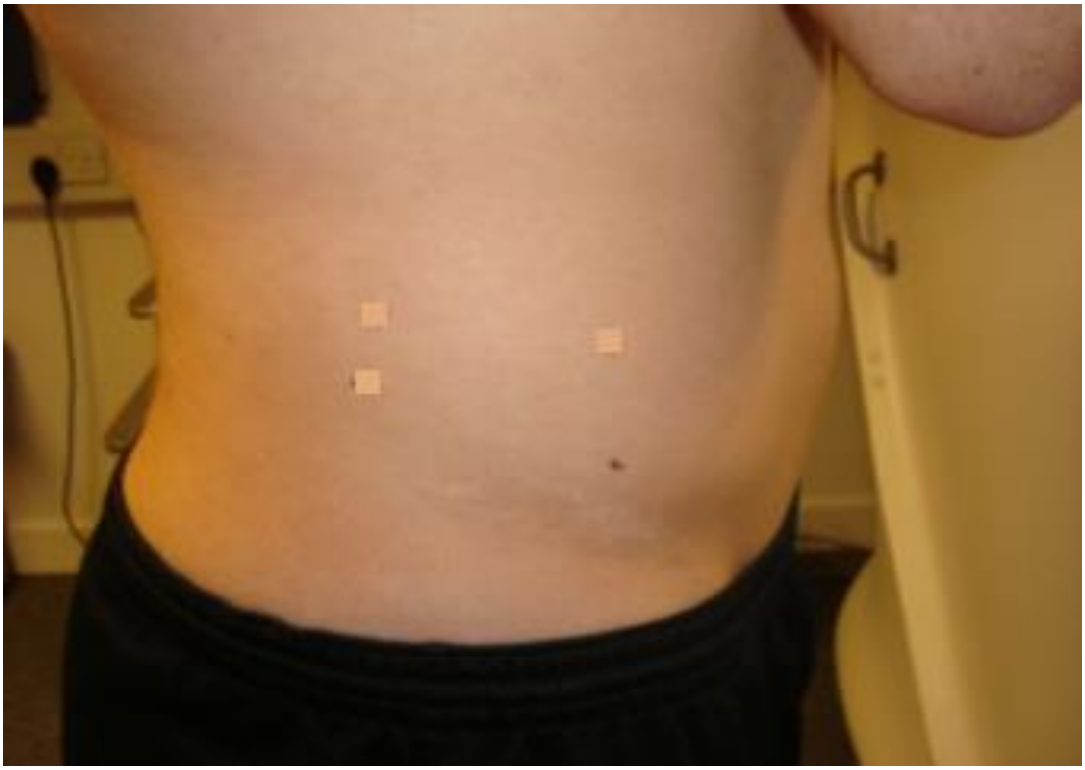


Plate 35 Anthropometric Landmark – Trochanterion

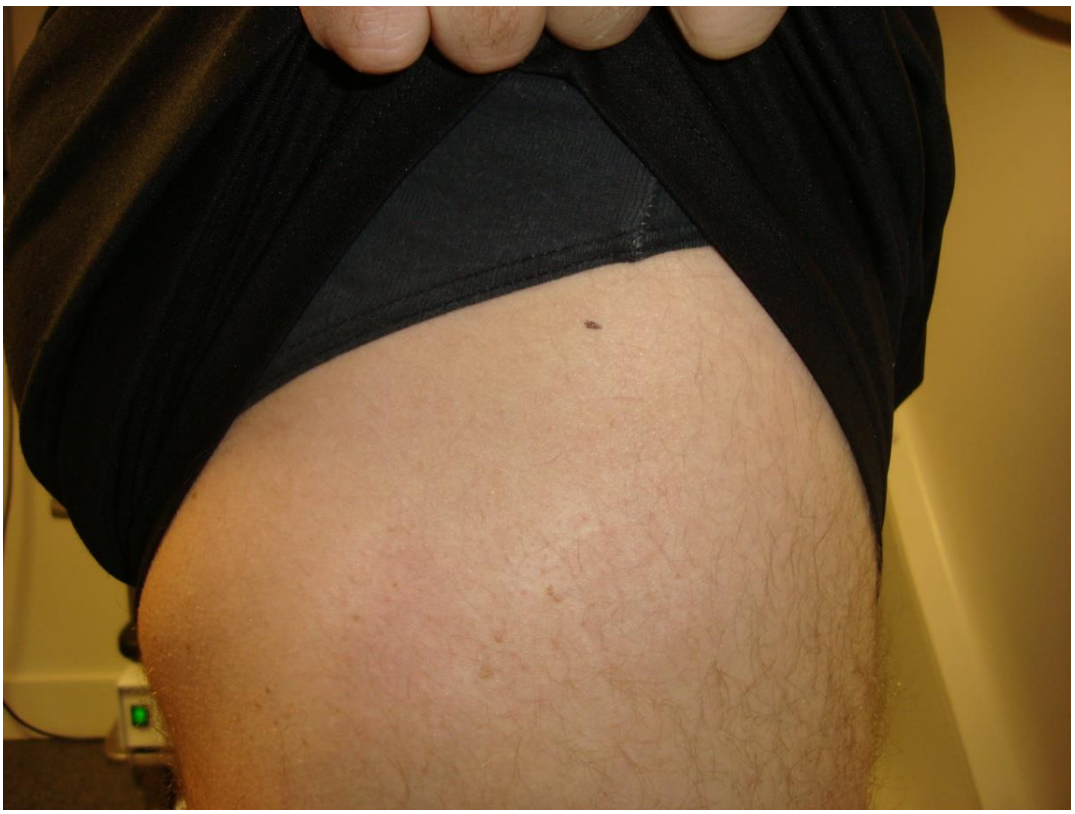


Plate 36 Anthropometric Landmark – Tibiale Laterale

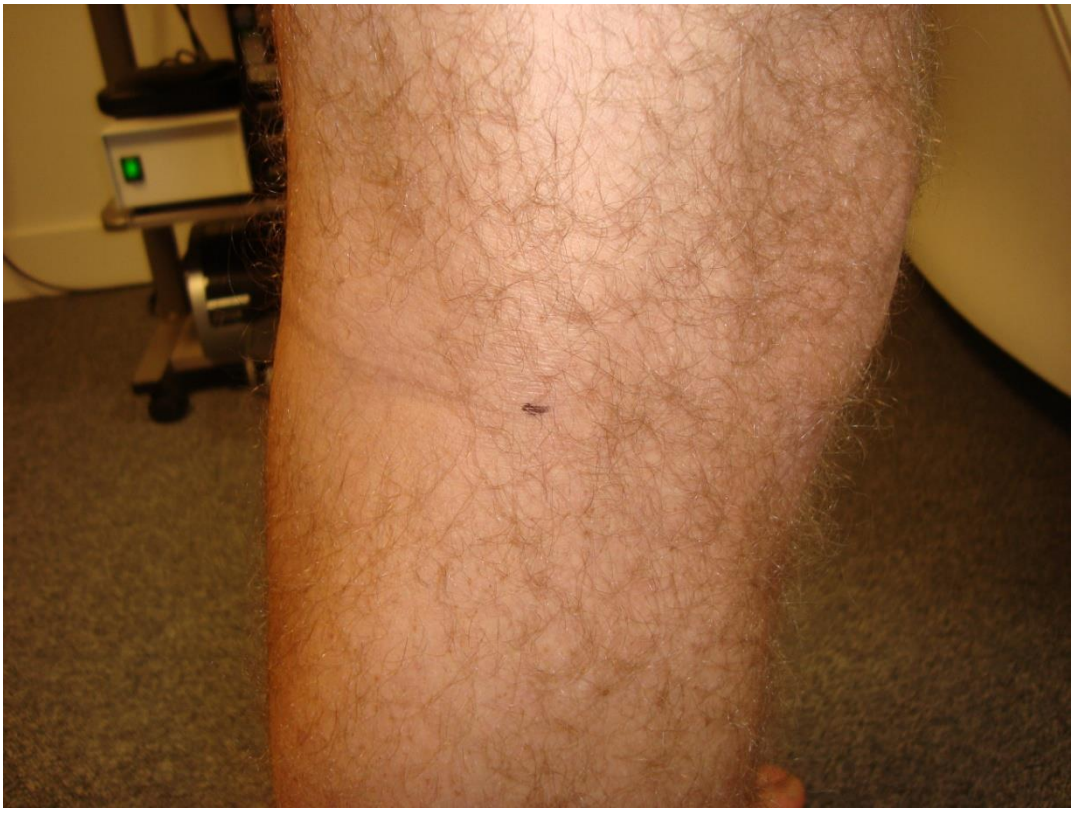


Plate 37 Anthropometric Skinfold Site – Tricep

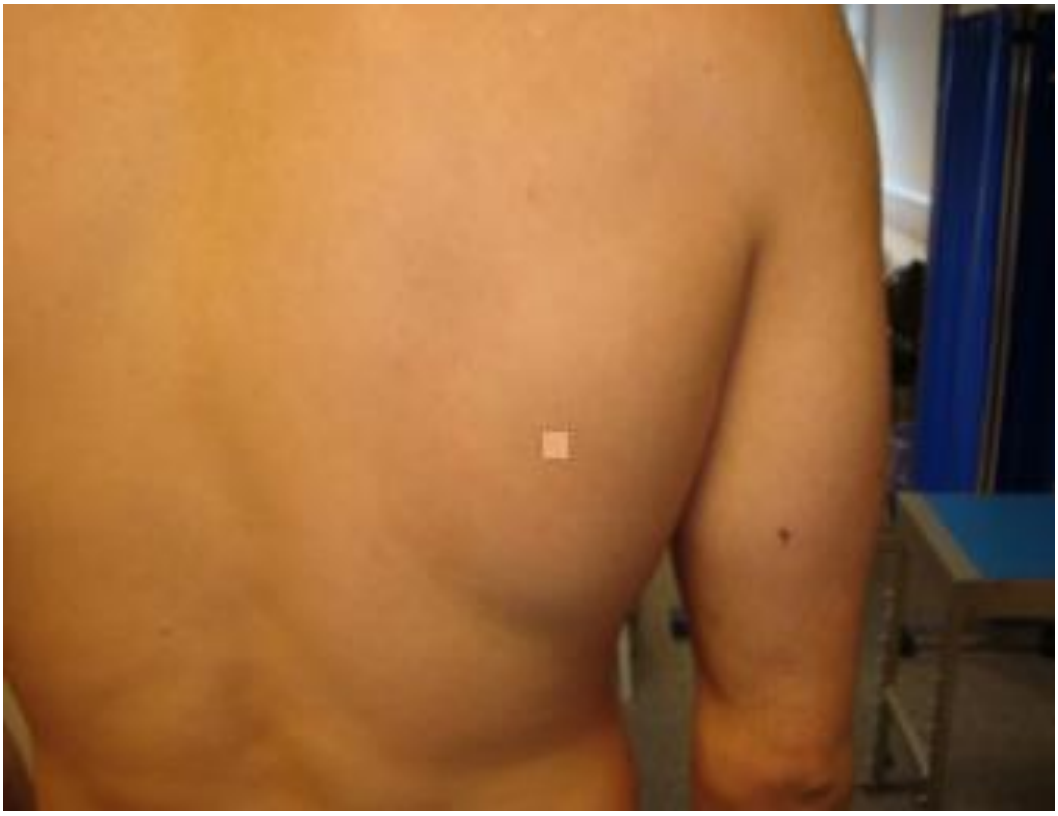


Plate 38 Anthropometric Skinfold Measurement – Tricep (mm)

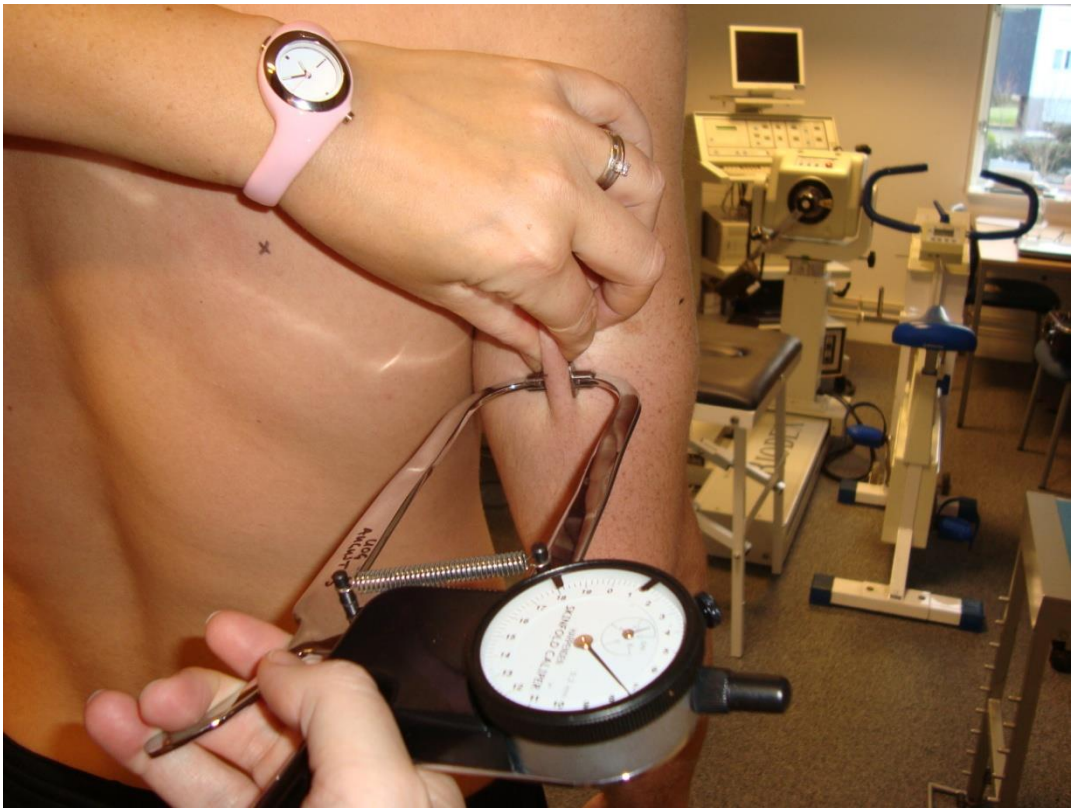


Plate 39 Anthropometric Skinfold Site – Bicep

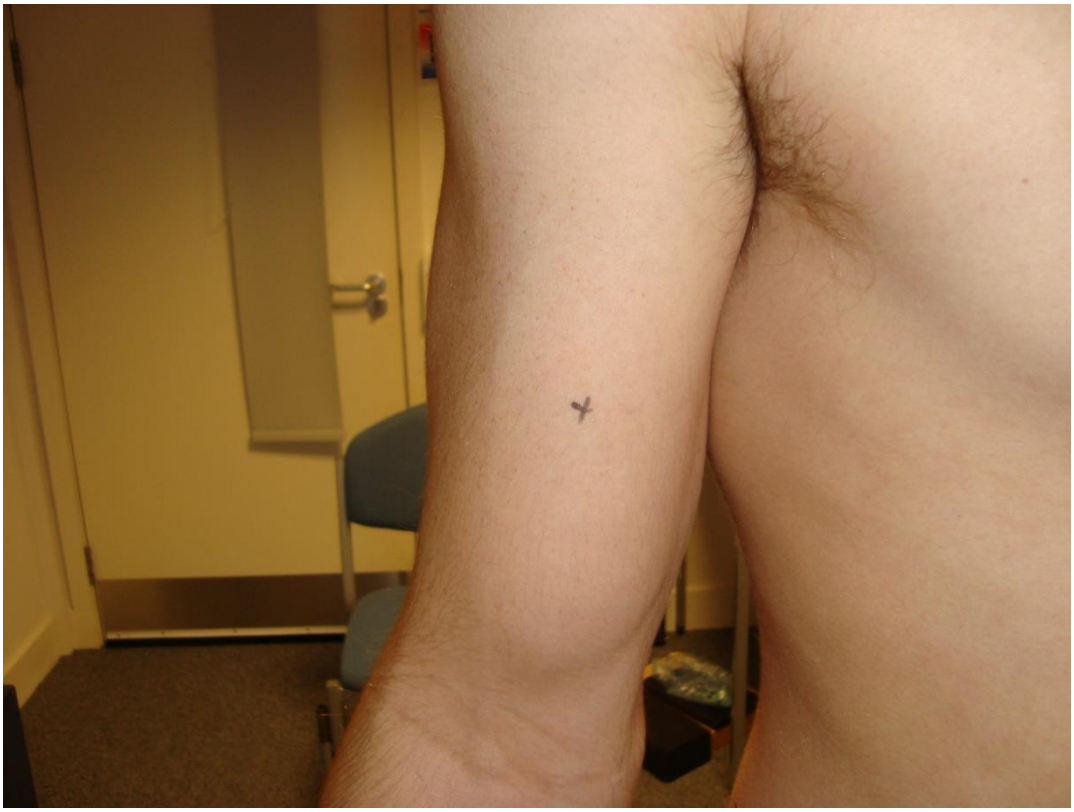


Plate 40 Anthropometric Skinfold Measurement – Bicep (mm)

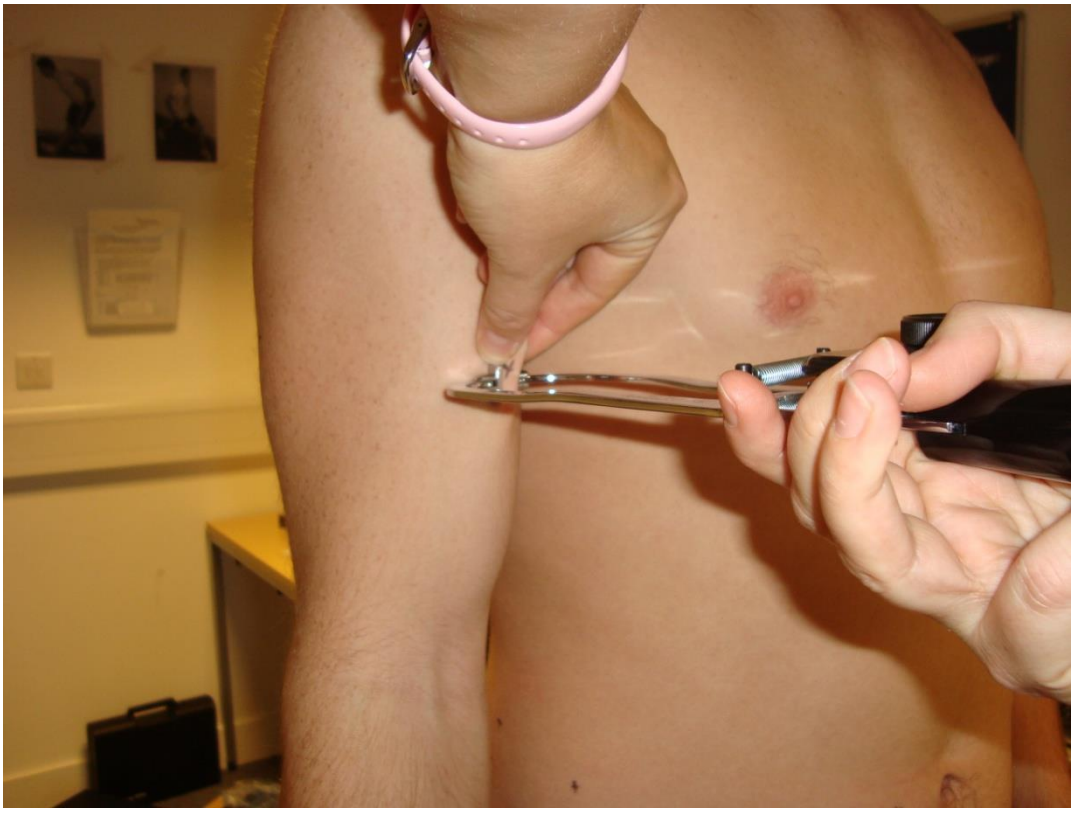


Plate 41 Anthropometric Skinfold Site – Subscapular

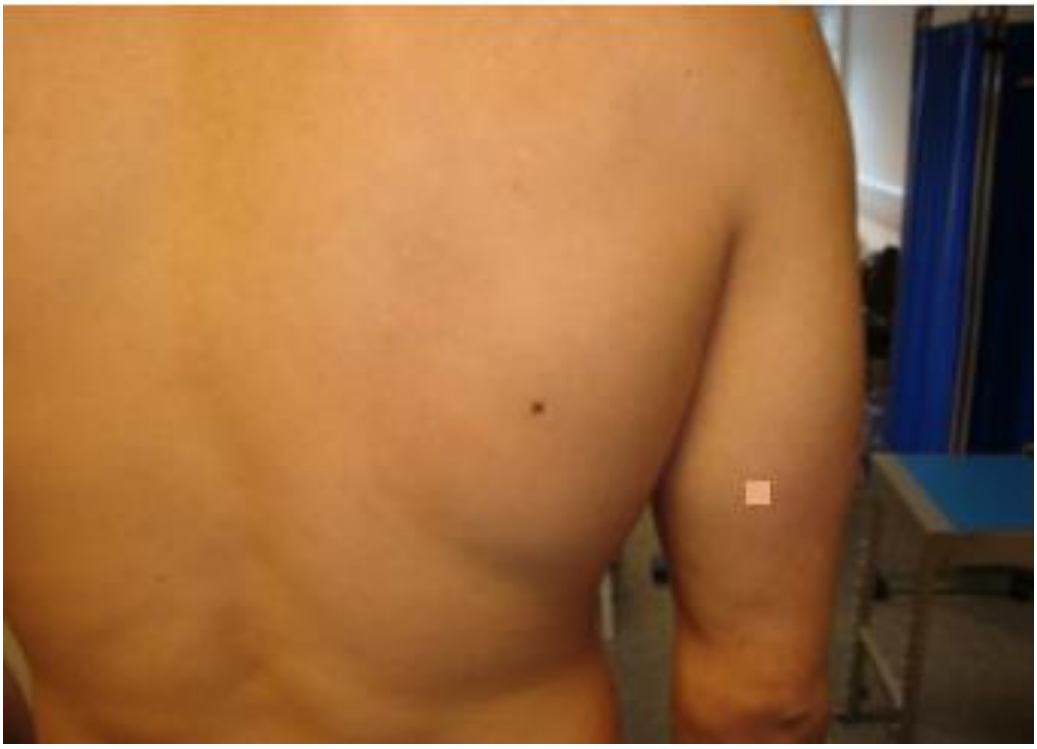


Plate 42 Anthropometric Skinfold Measurement – Subscapular (mm)

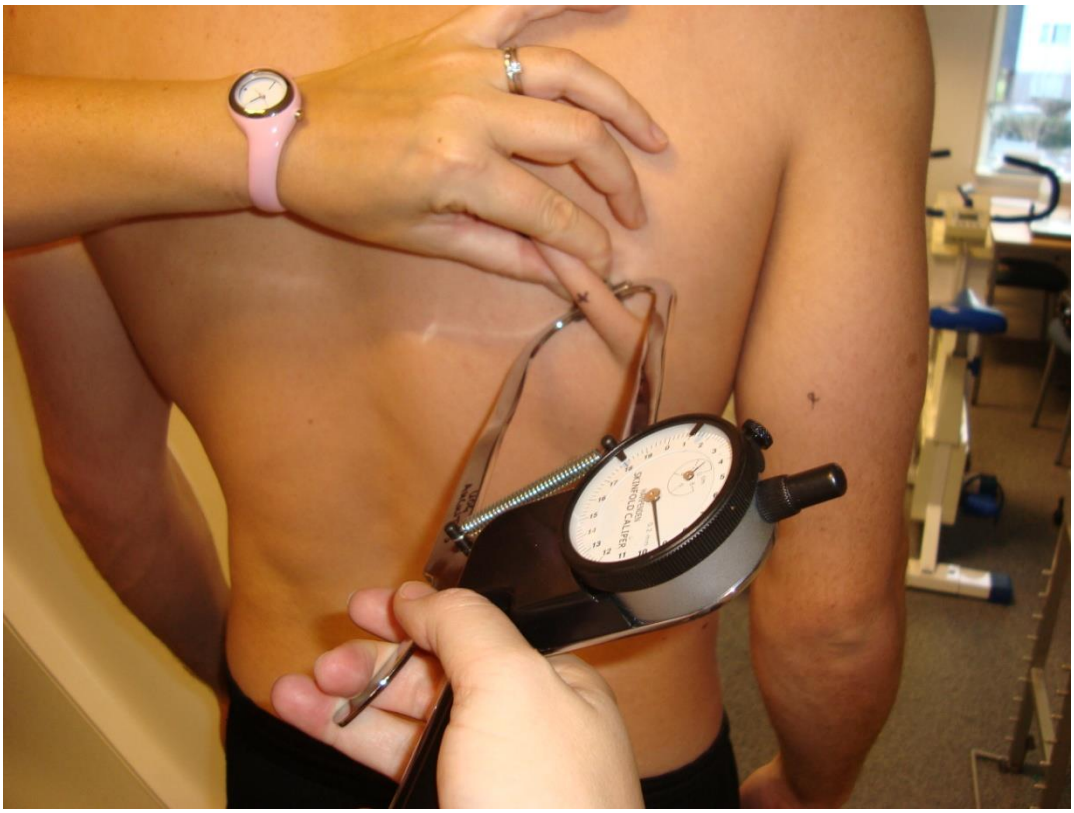


Plate 43 Anthropometric Skinfold Site – Suprailiac

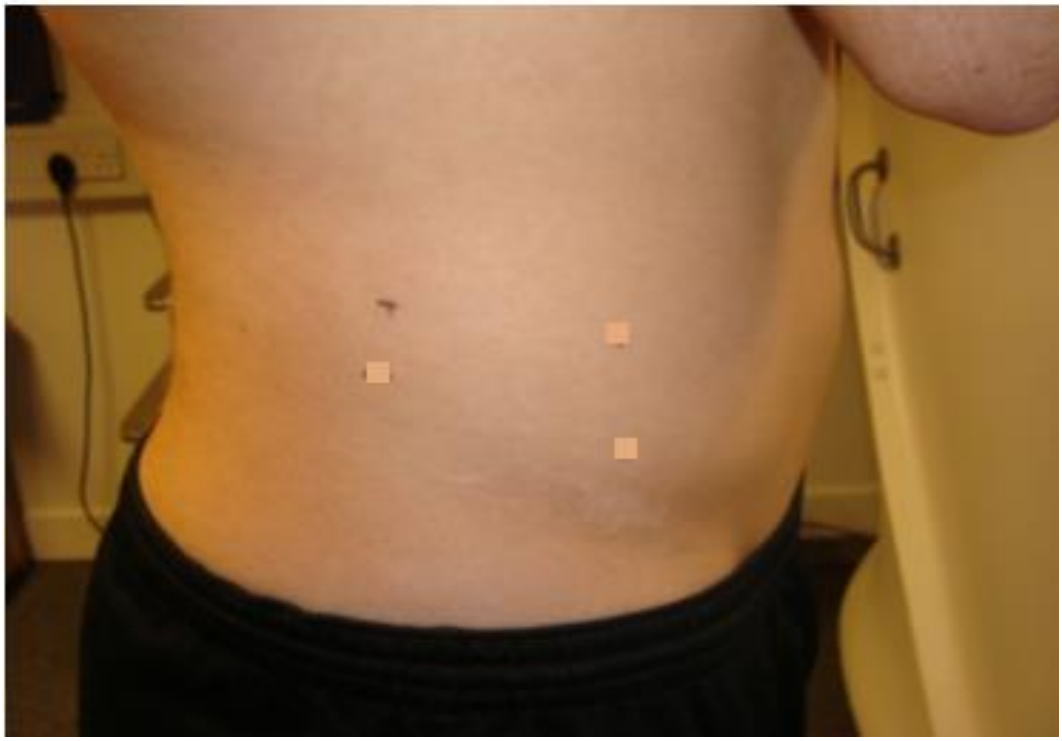


Plate 44 Anthropometric Skinfold Measurement – Suprailiac (mm)

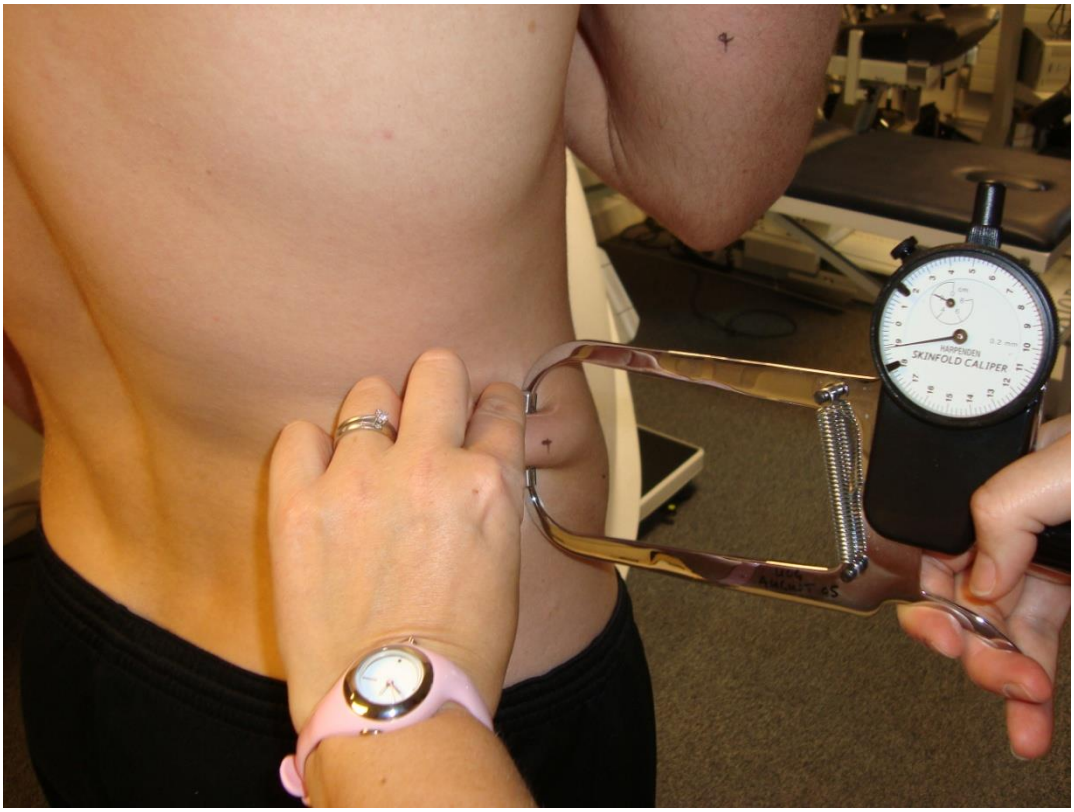


Plate 45 Anthropometric Skinfold Site – Supraspinale

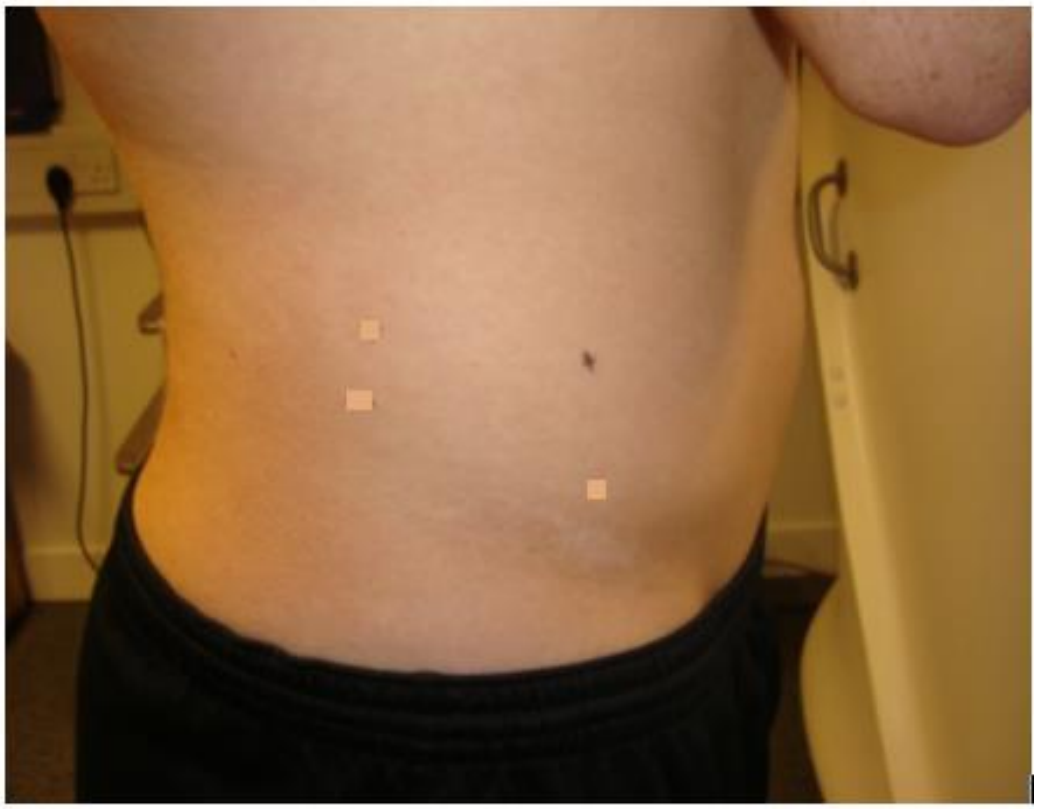


Plate 46 Anthropometric Skinfold Measurement – Supraspinale (mm)

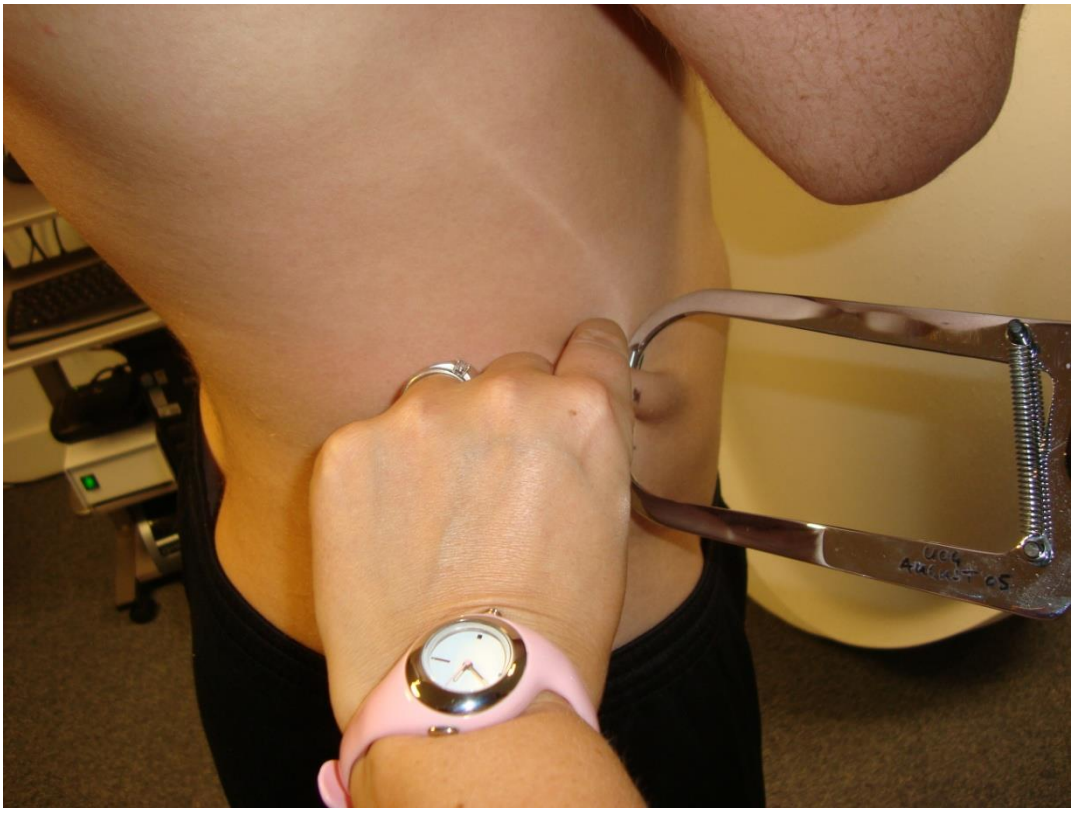


Plate 47 Anthropometric Skinfold Site – Abdominal

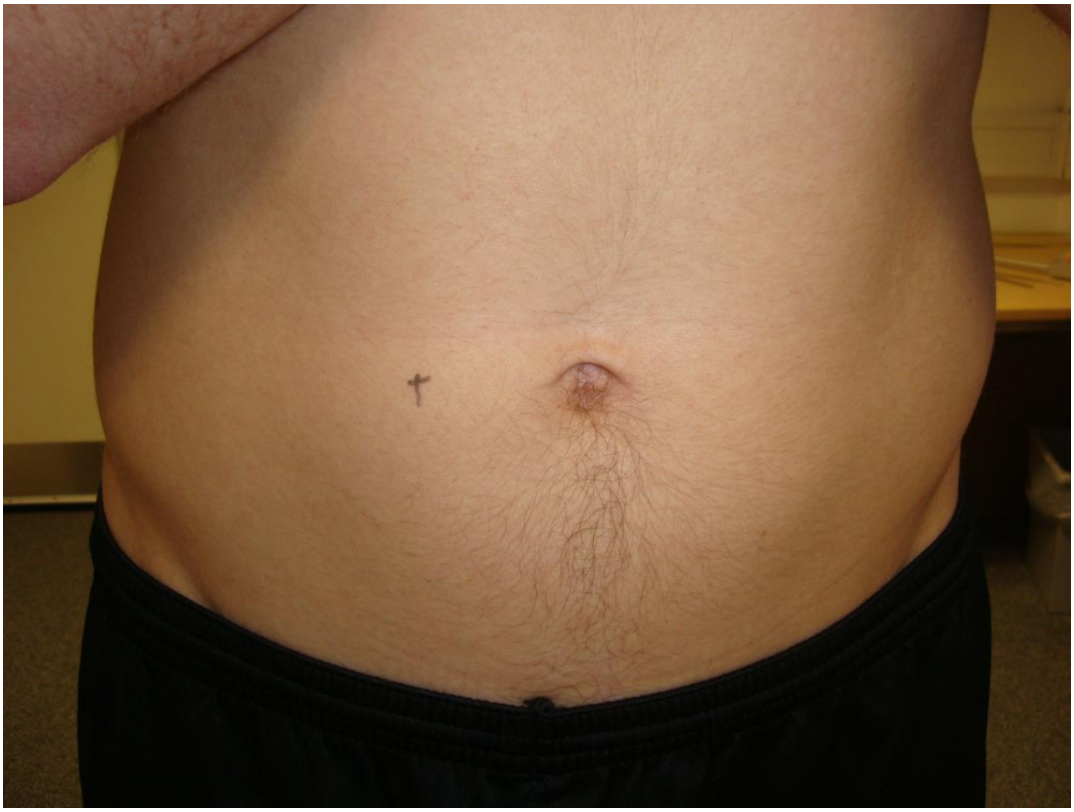


Plate 48 Anthropometric Skinfold Measurement – Abdominal (mm)

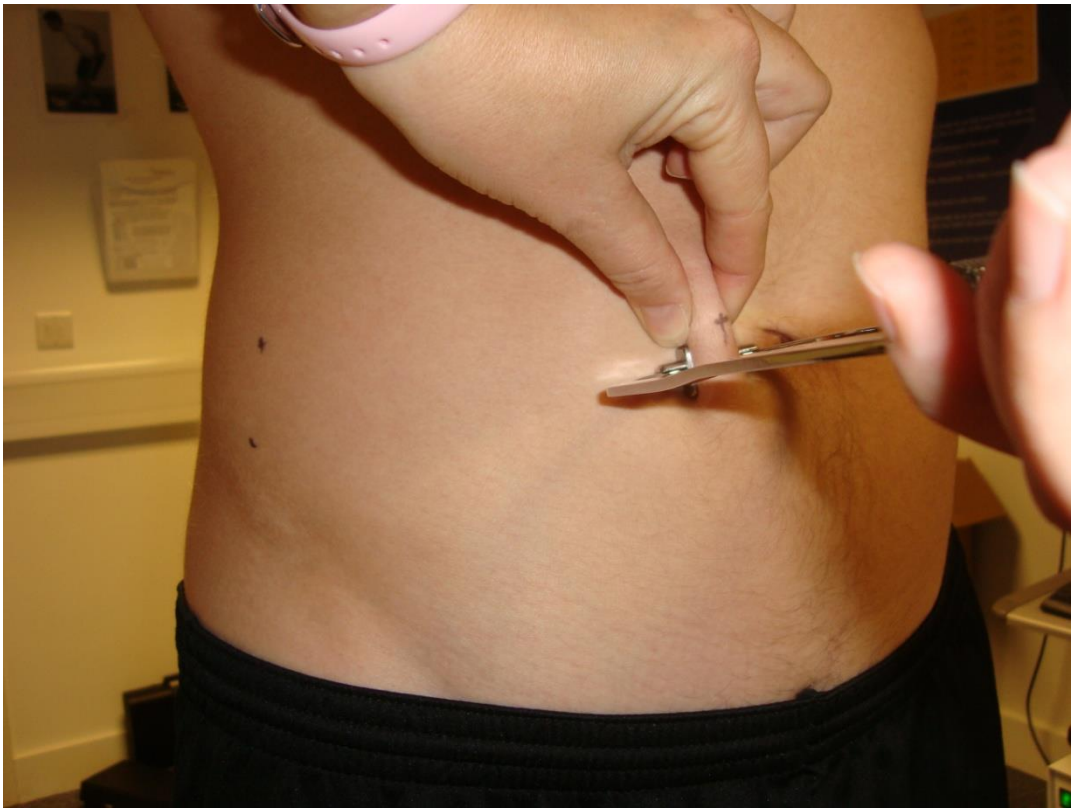


Plate 49 Anthropometric Skinfold Site – Anterior Thigh

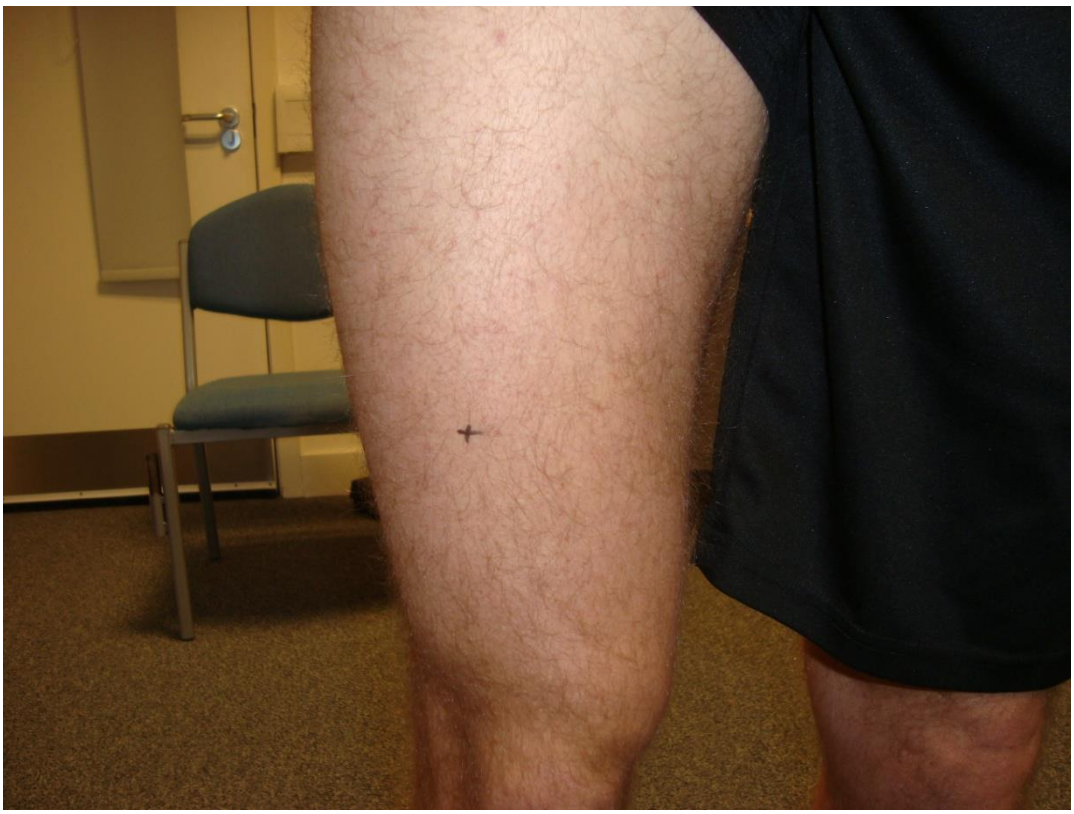


Plate 50 Anthropometric Skinfold Measurement – Anterior Thigh (mm)

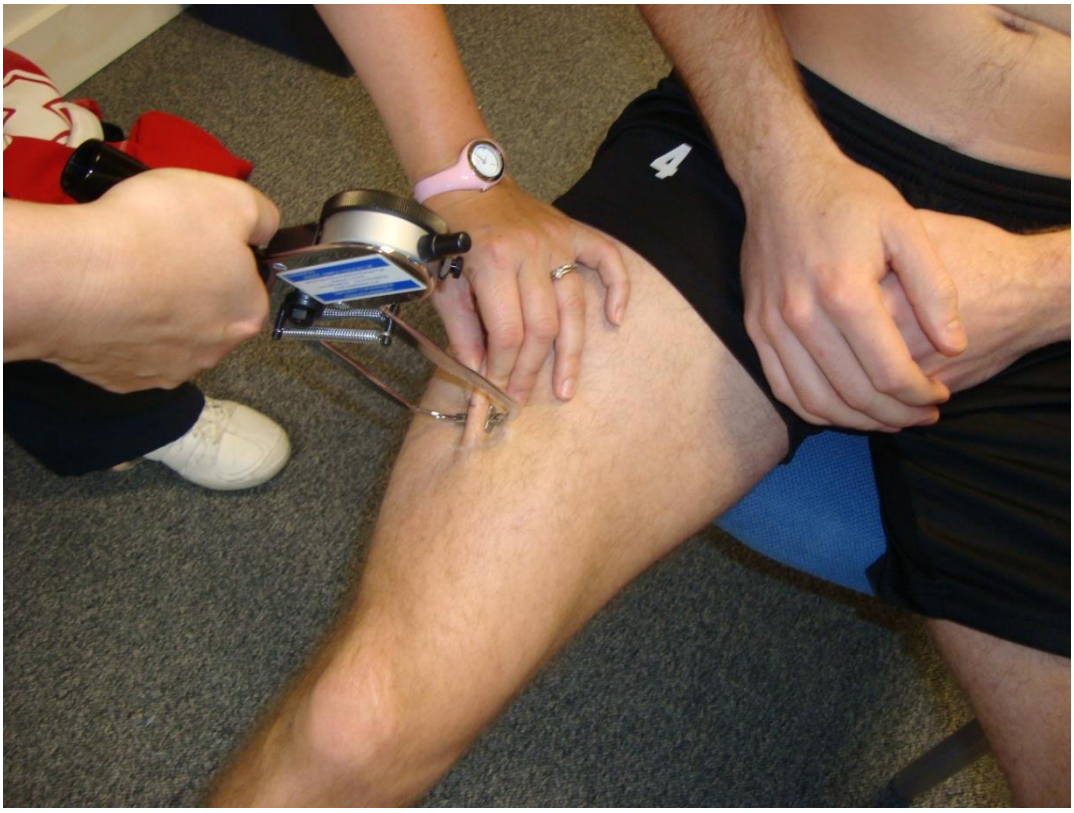


Plate 51 Anthropometric Skinfold Measurement – Anterior Thigh (mm) (participant assistance)

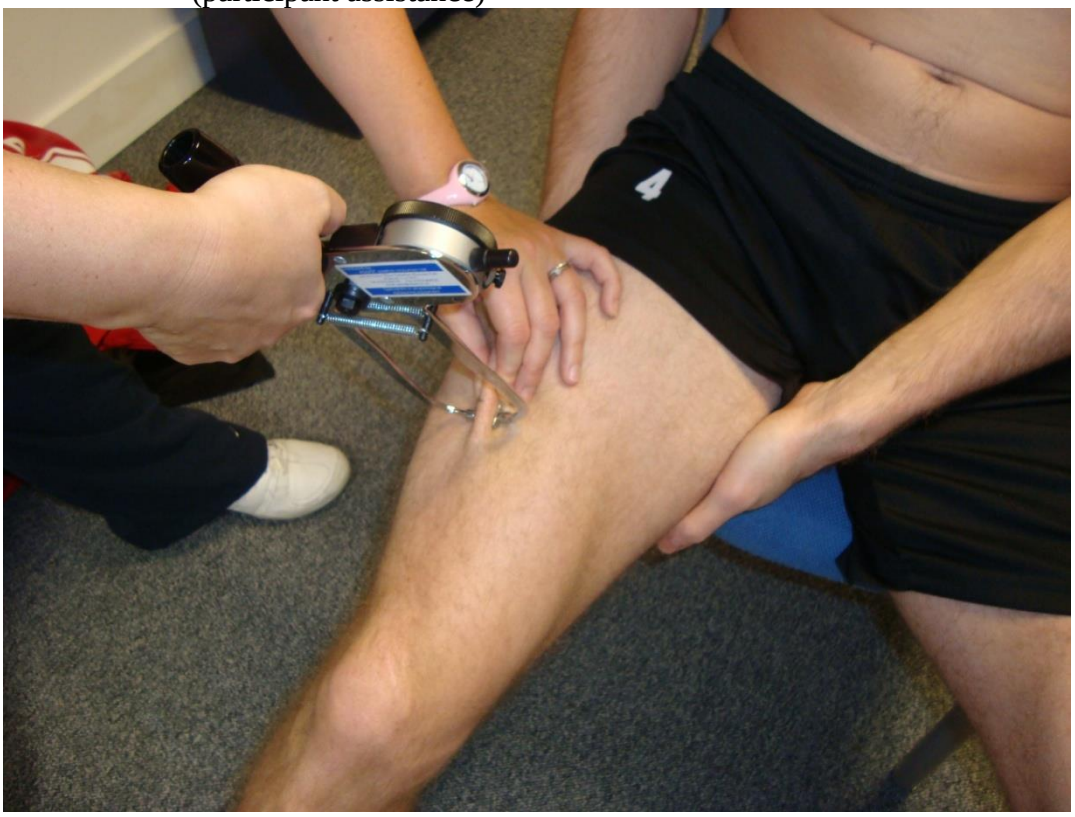


Plate 52 Anthropometric Skinfold Measurement – Anterior Thigh (mm) (recorder assistance)

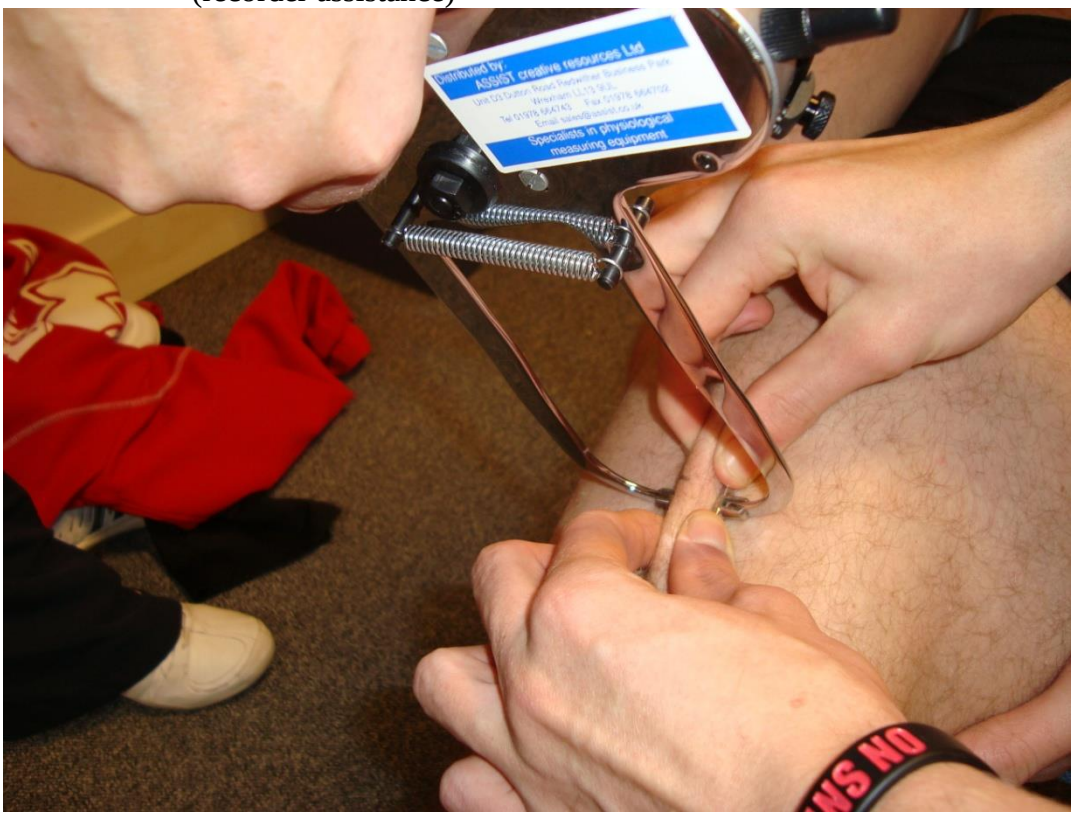


Plate 53 Anthropometric Skinfold Site – Medial Calf

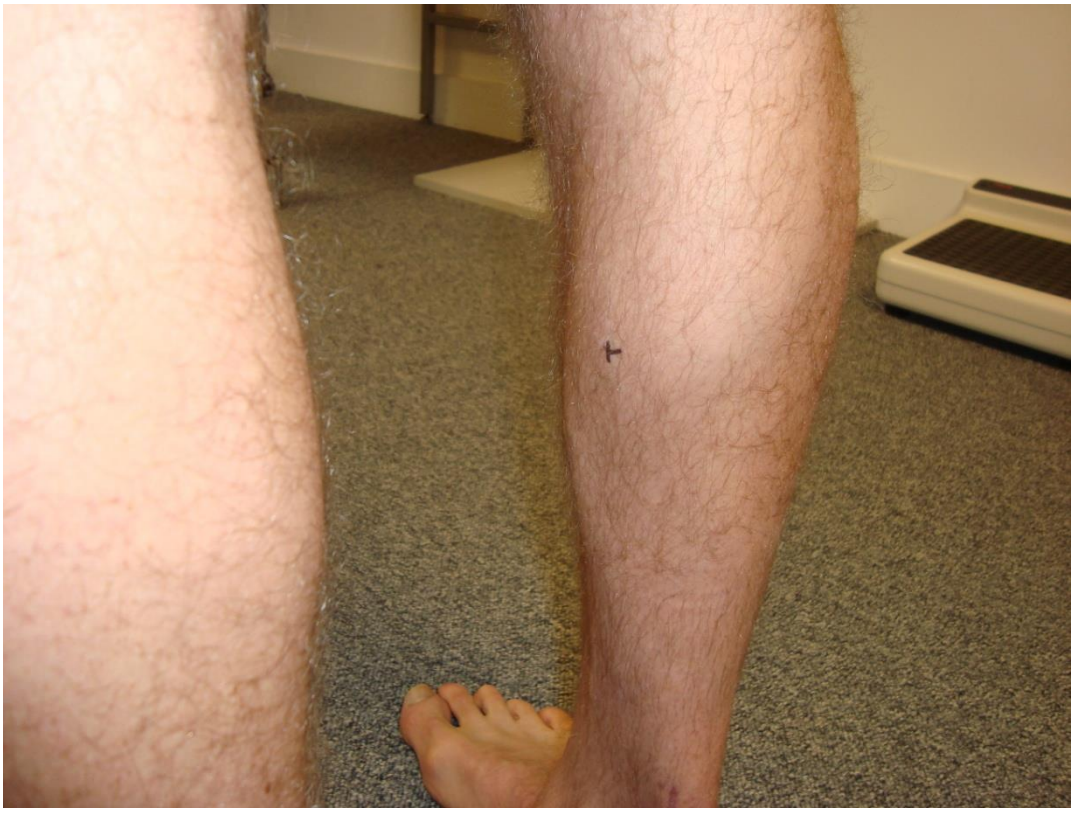


Plate 54 Anthropometric Skinfold Measurement – Medial Calf (mm)

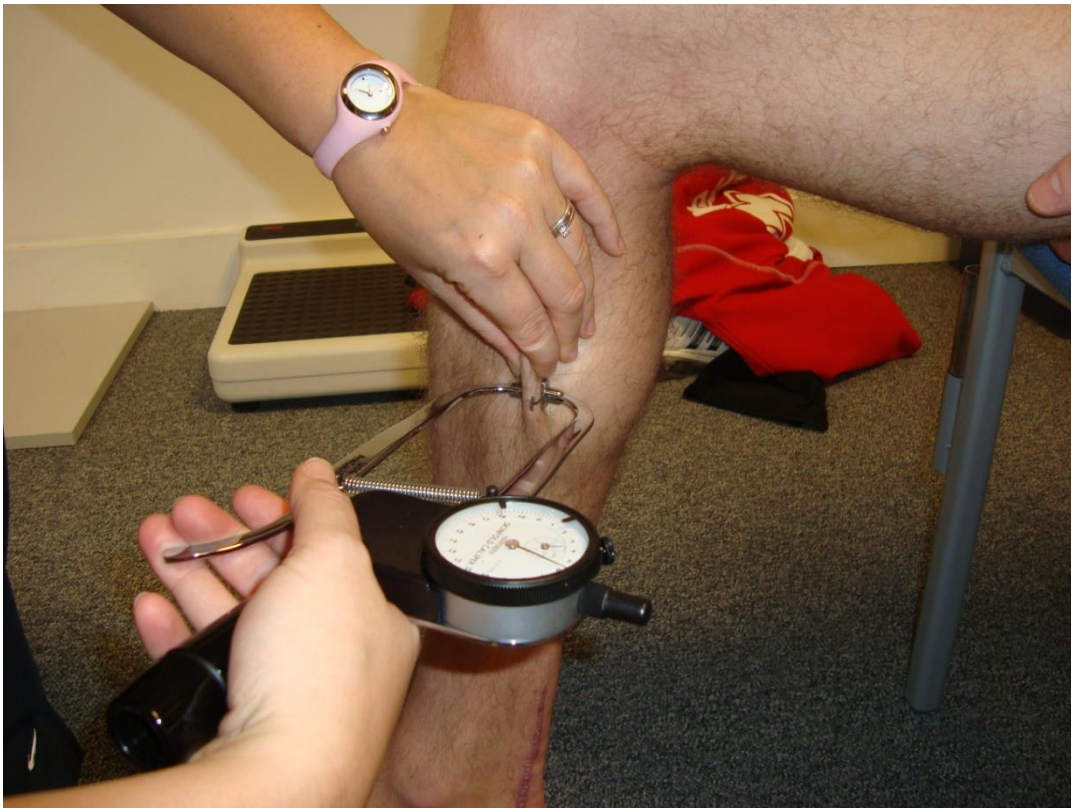


Plate 55 Harpenden Anthropometric Skinfold Caliper Application Depth

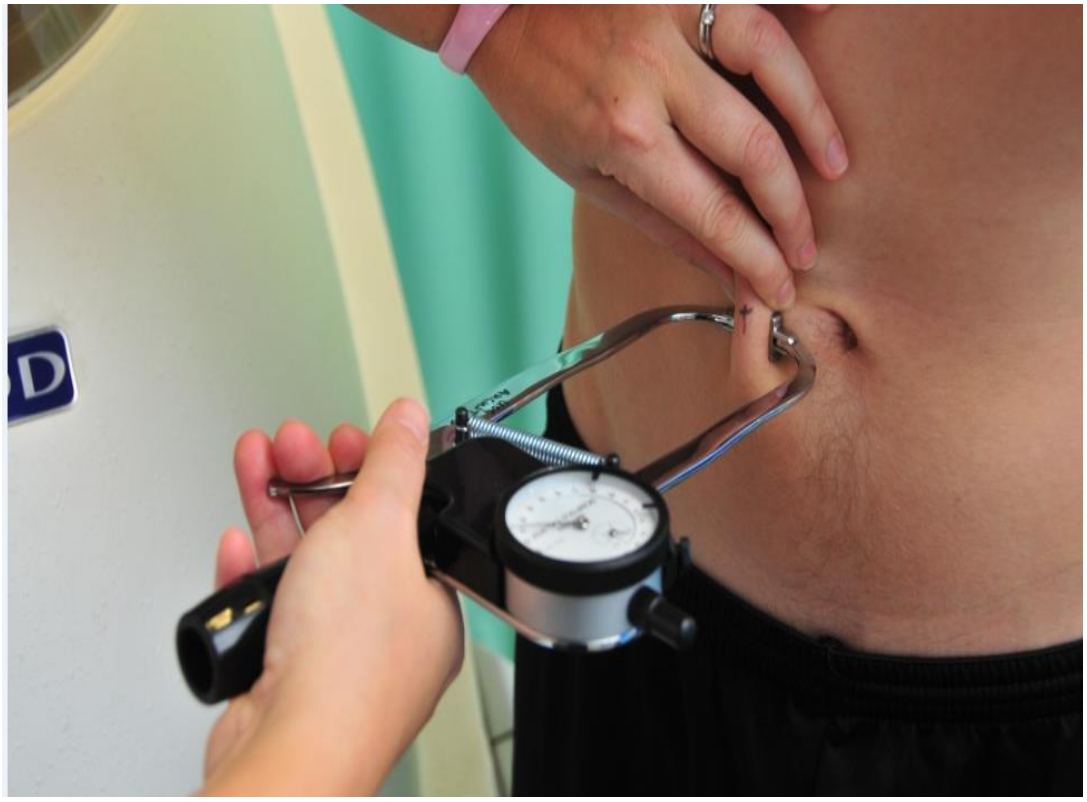


Plate 56 Harpenden Anthropometric Skinfold Caliper Measurement Reading (mm)

Plate 57 Anthropometric Girth Measurement – Neck (cm)

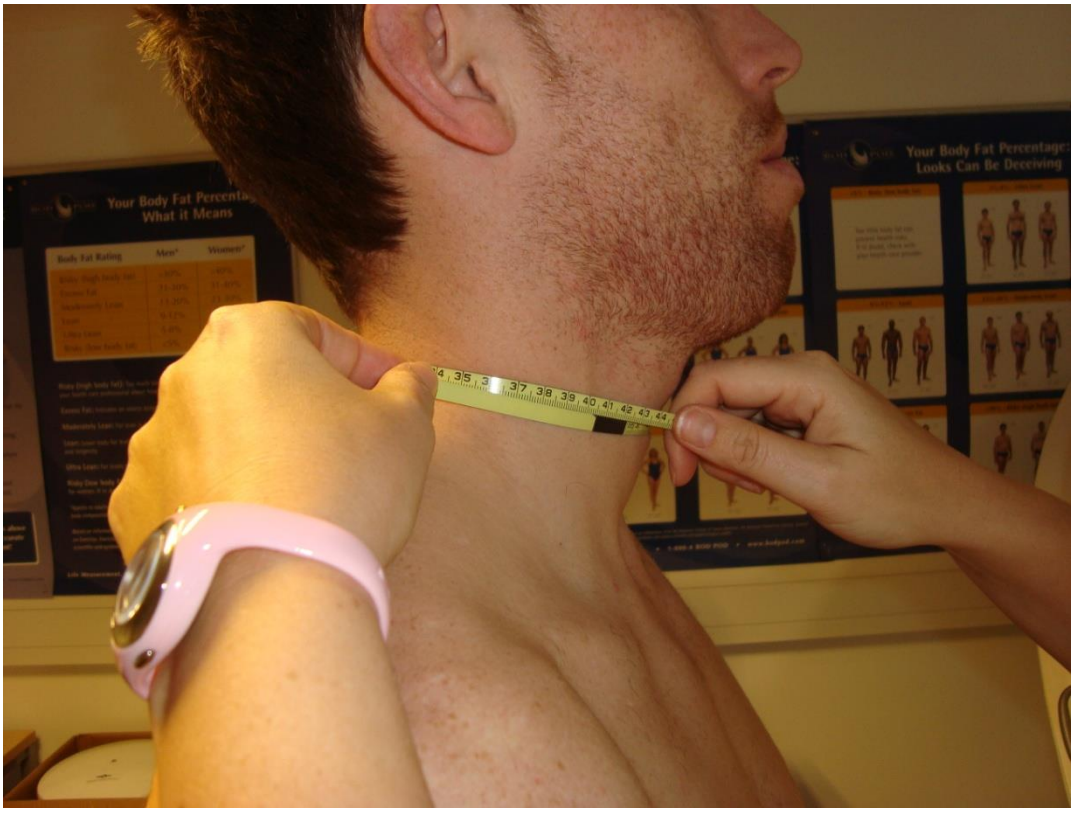


Plate 58 Anthropometric Girth Measurement – Arm (relaxed) (cm)

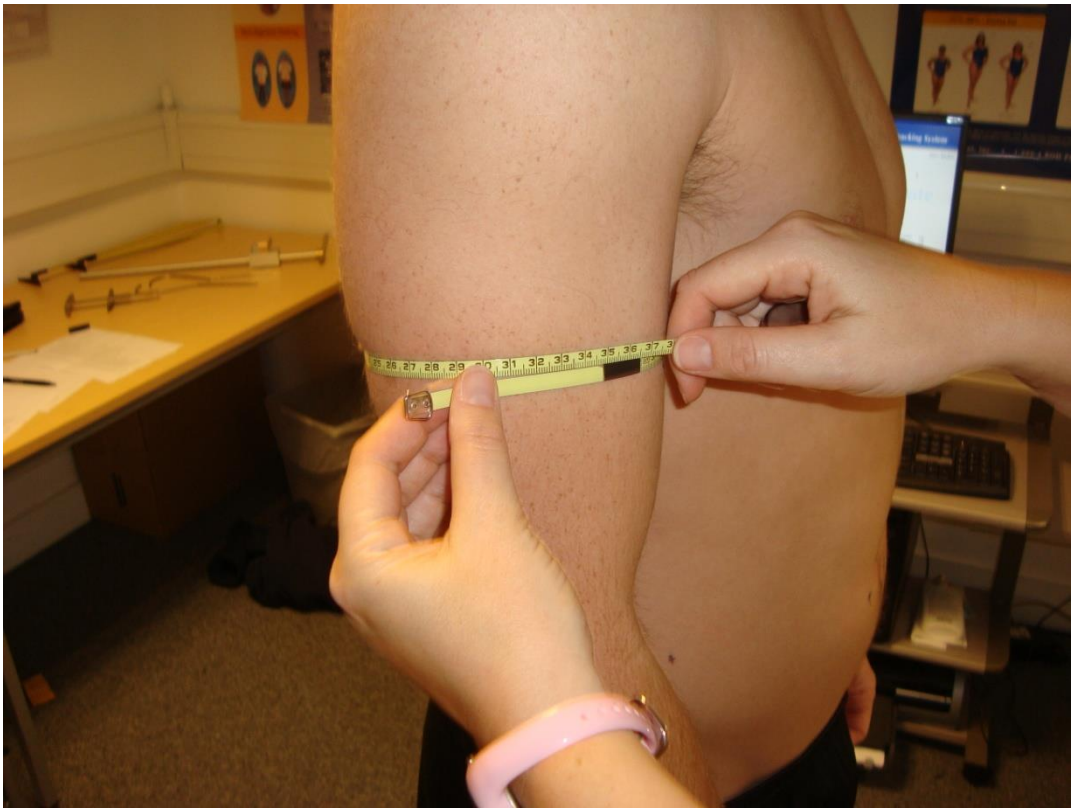


Plate 59 Anthropometric Girth Measurement – Arm (flexed) (cm)

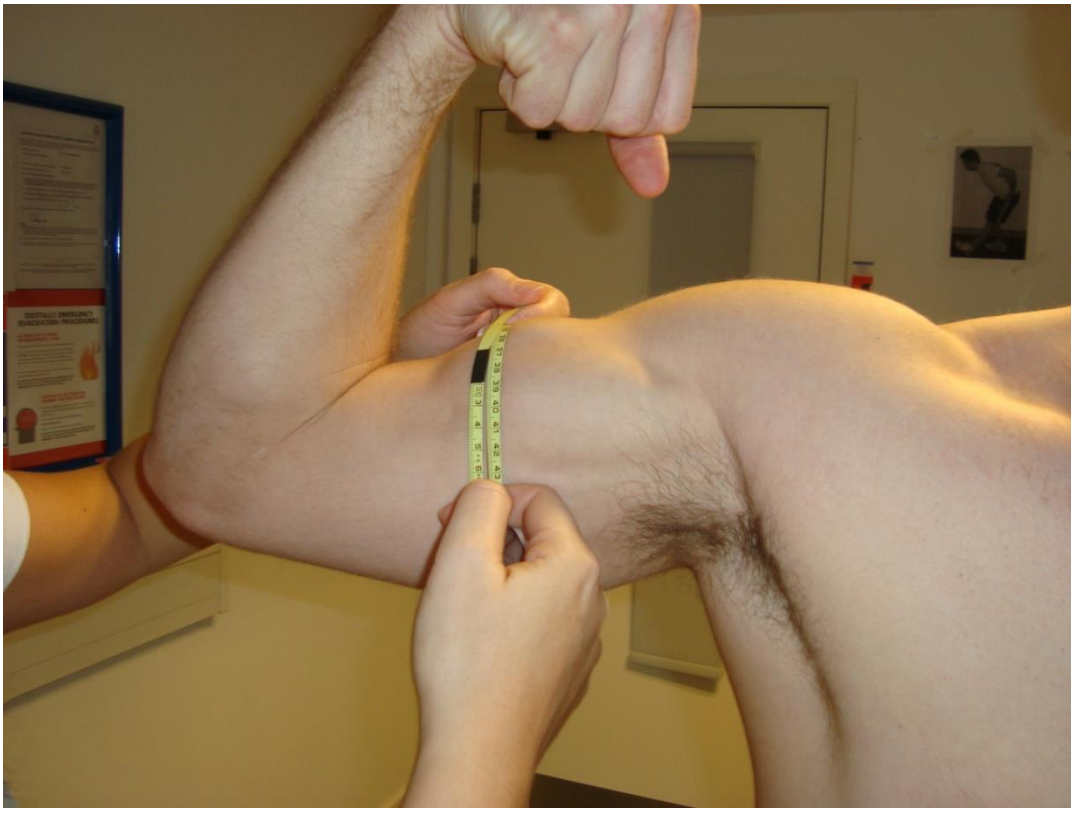


Plate 60 Anthropometric Girth Measurement – Forearm (cm)

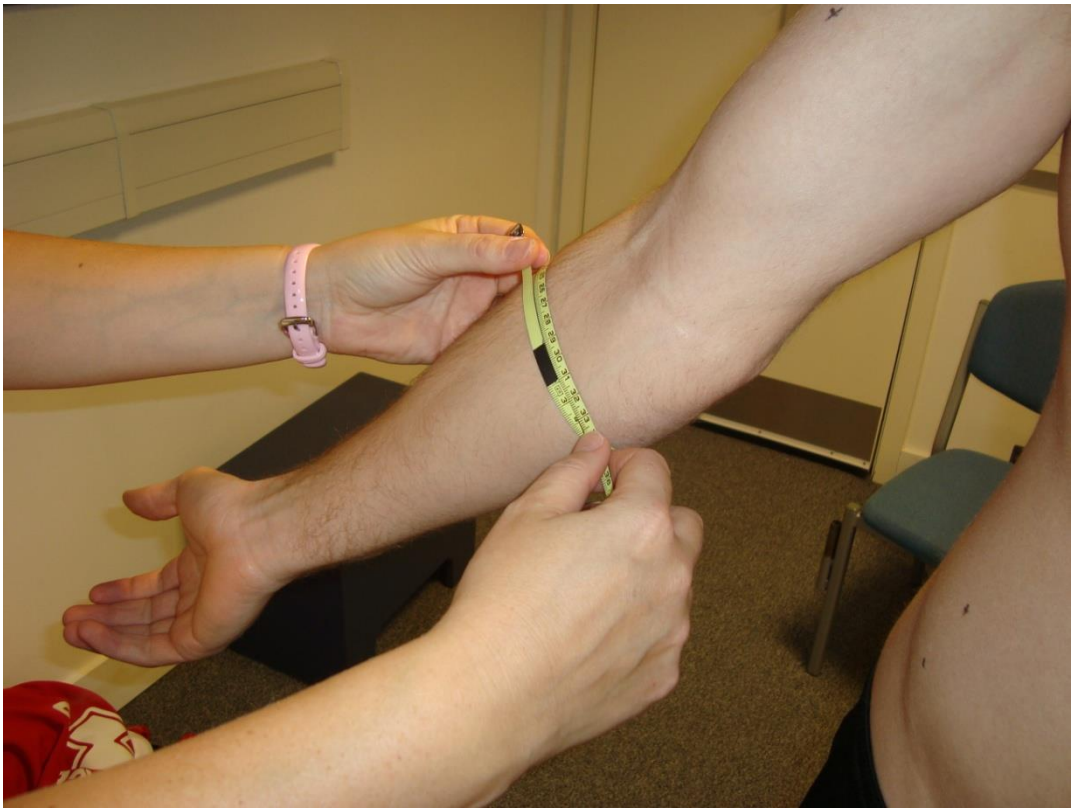


Plate 61 Anthropometric Girth Measurement – Wrist (cm)

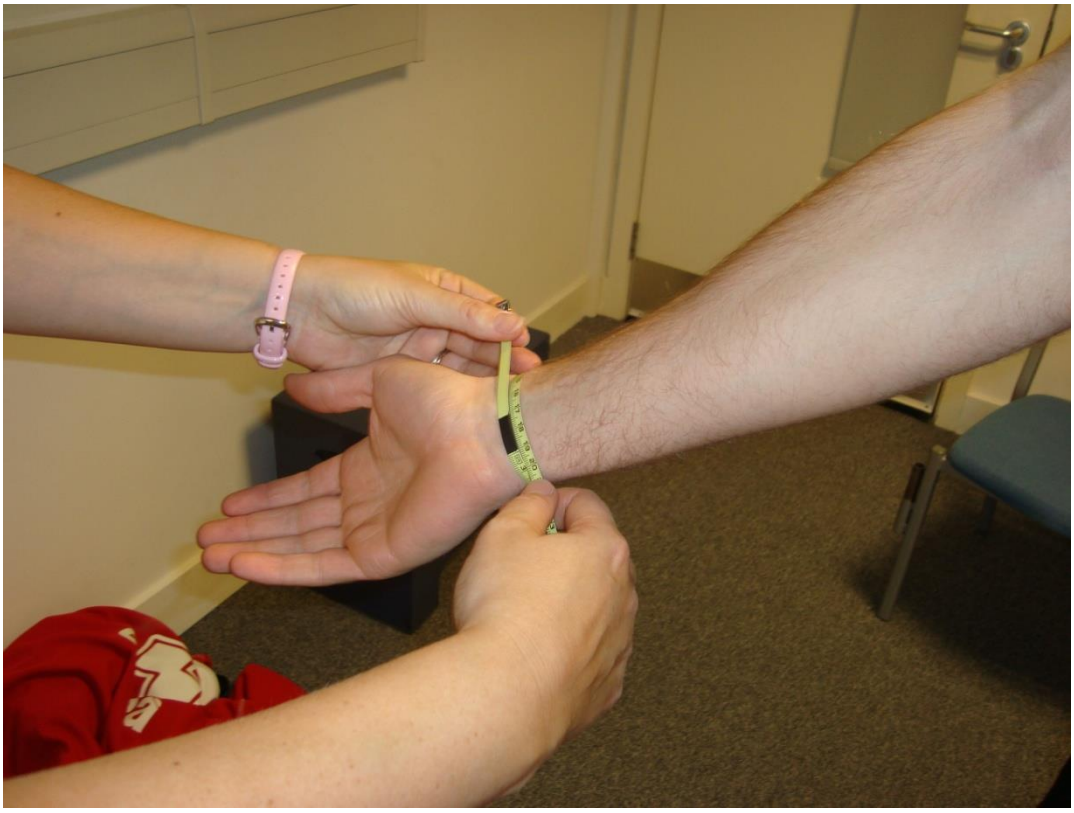


Plate 62 Anthropometric Girth Measurement – Chest (cm)

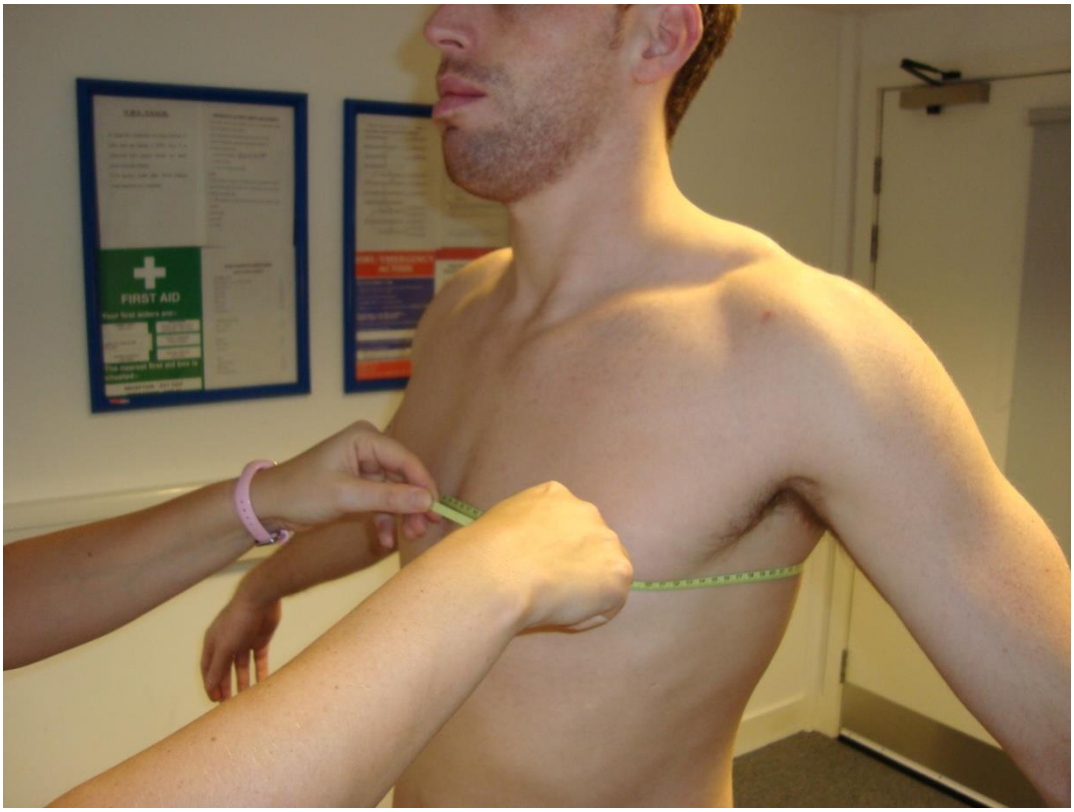


Plate 63 Anthropometric Girth Measurement – Waist (cm)

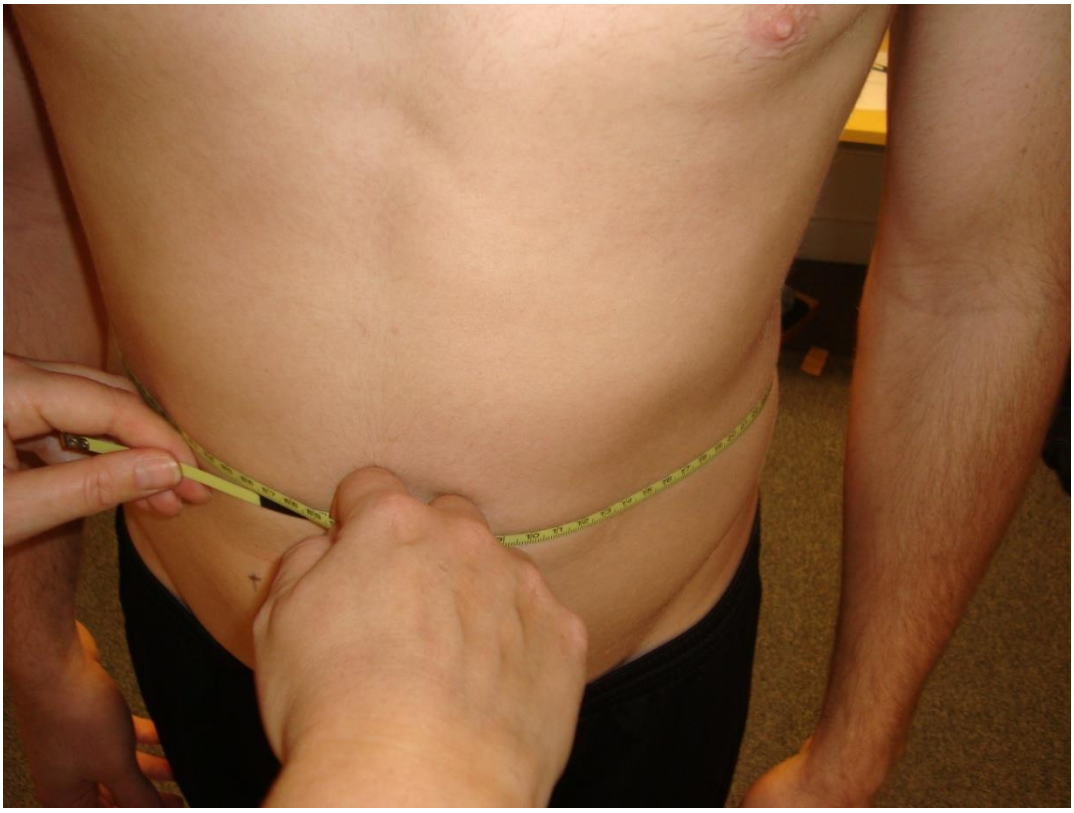


Plate 64 Anthropometric Girth Measurement – Hip (Gluteal) (cm)

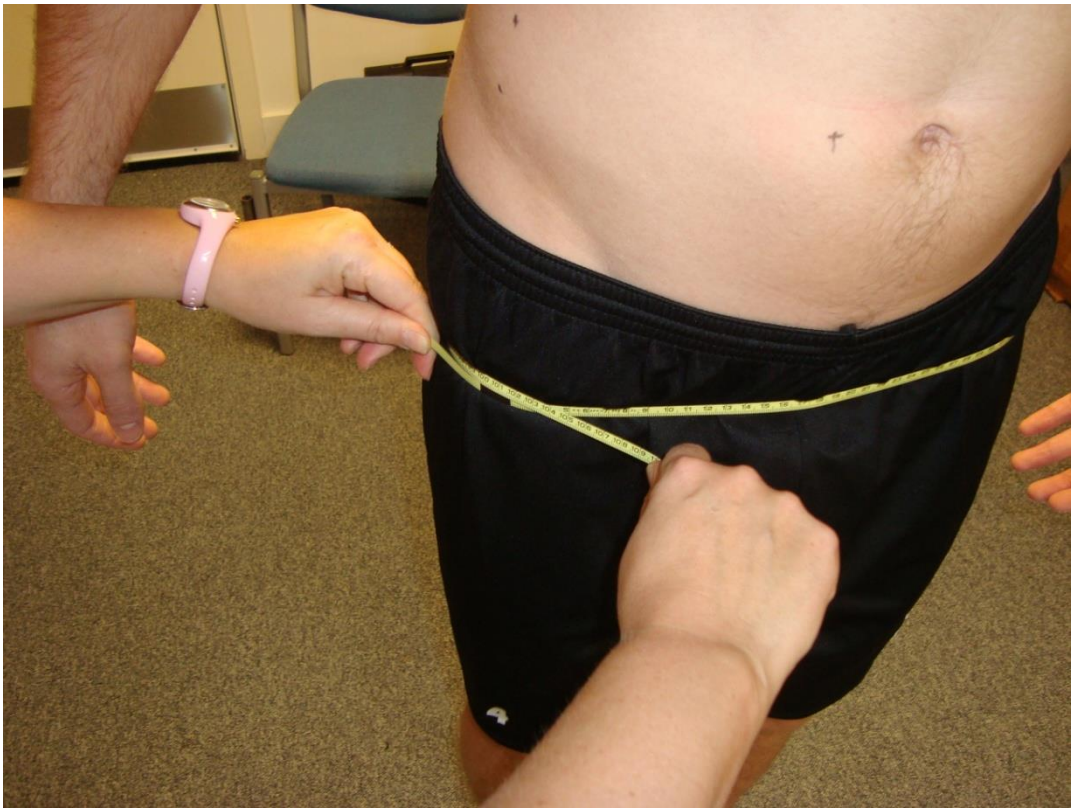


Plate 65 Anthropometric Girth Measurement – Anterior Thigh (Mid) (cm)

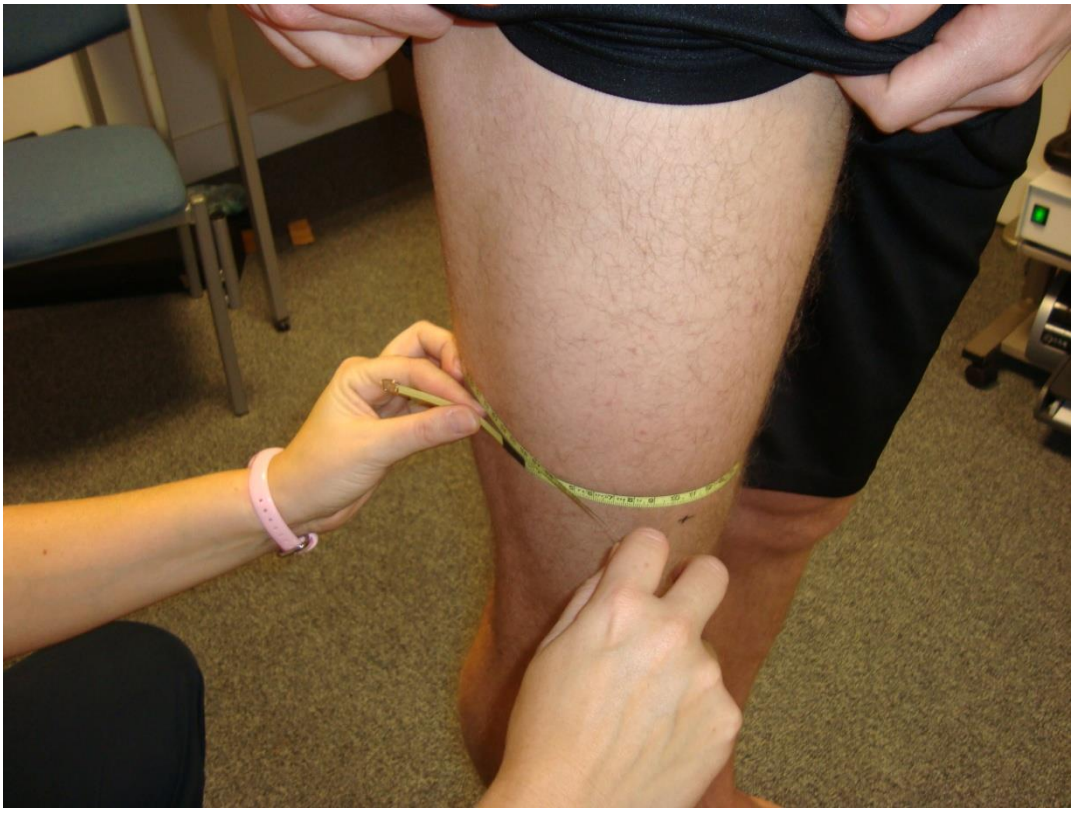


Plate 66 Anthropometric Girth Measurement – Calf (cm)

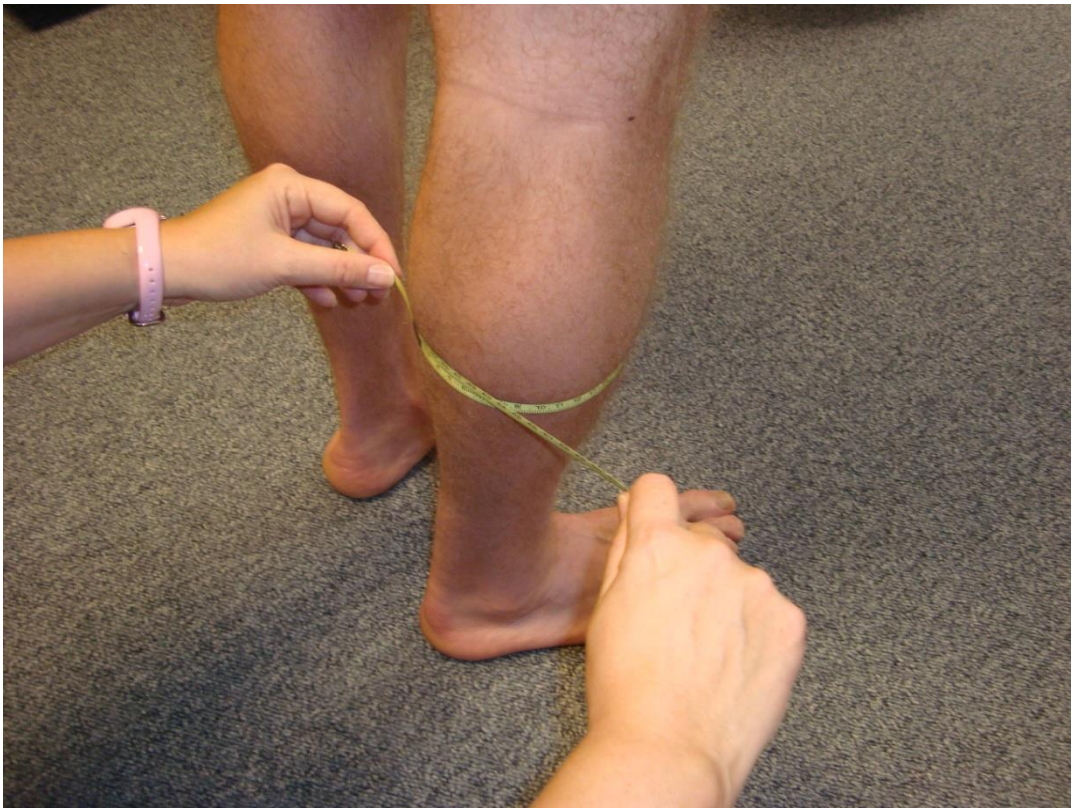


Plate 67 Anthropometric Girth Measurement – Ankle (cm)

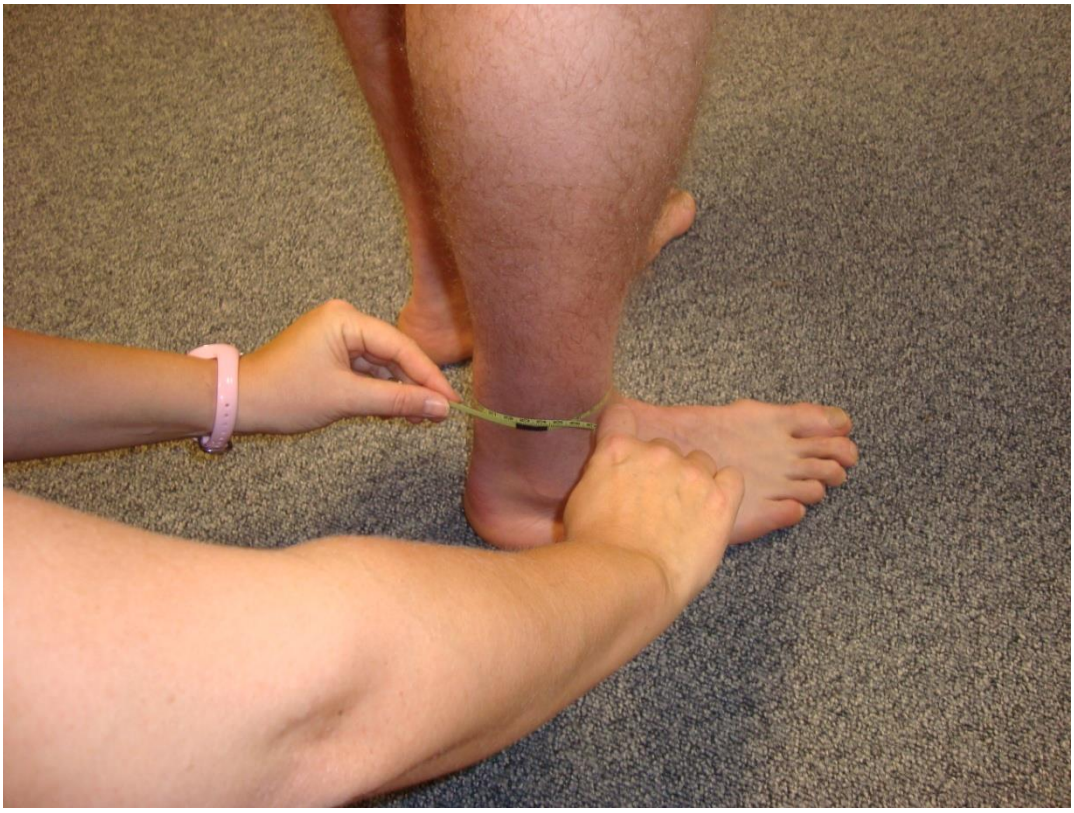


Plate 68 Harpenden Anthropometric Measuring Tape Measurement Reading (cm)

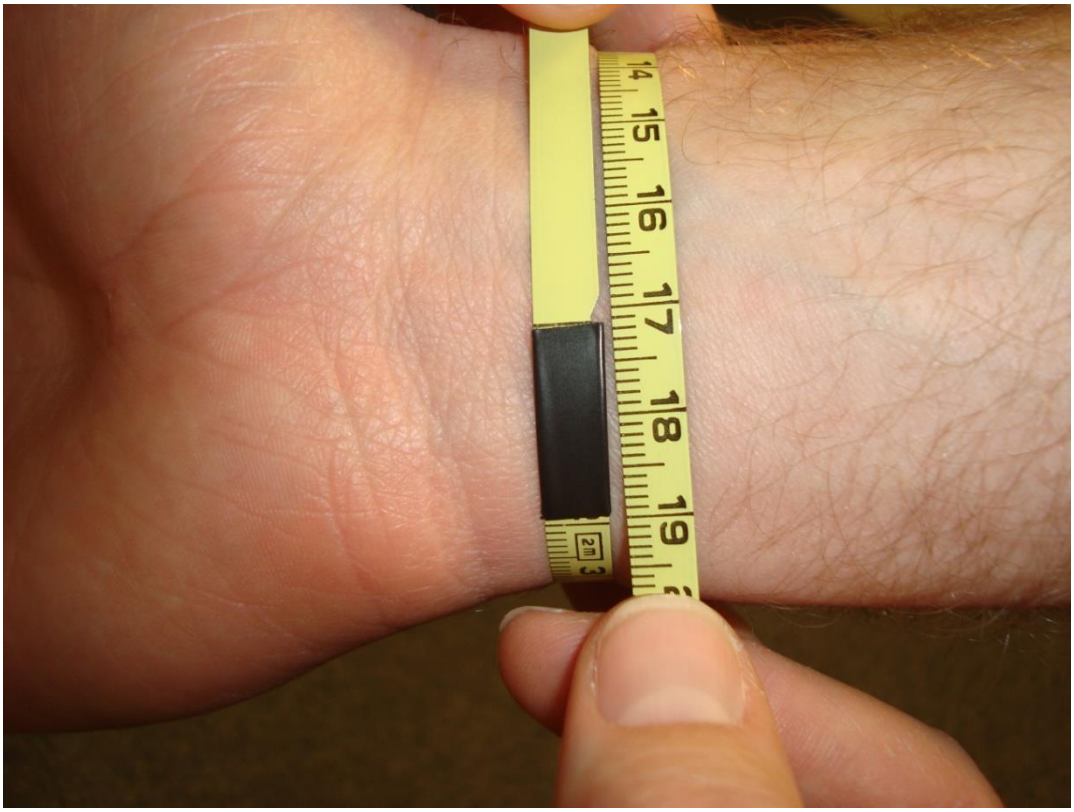


Plate 69 Anthropometric Breadth Measurement – Biacromial (cm)

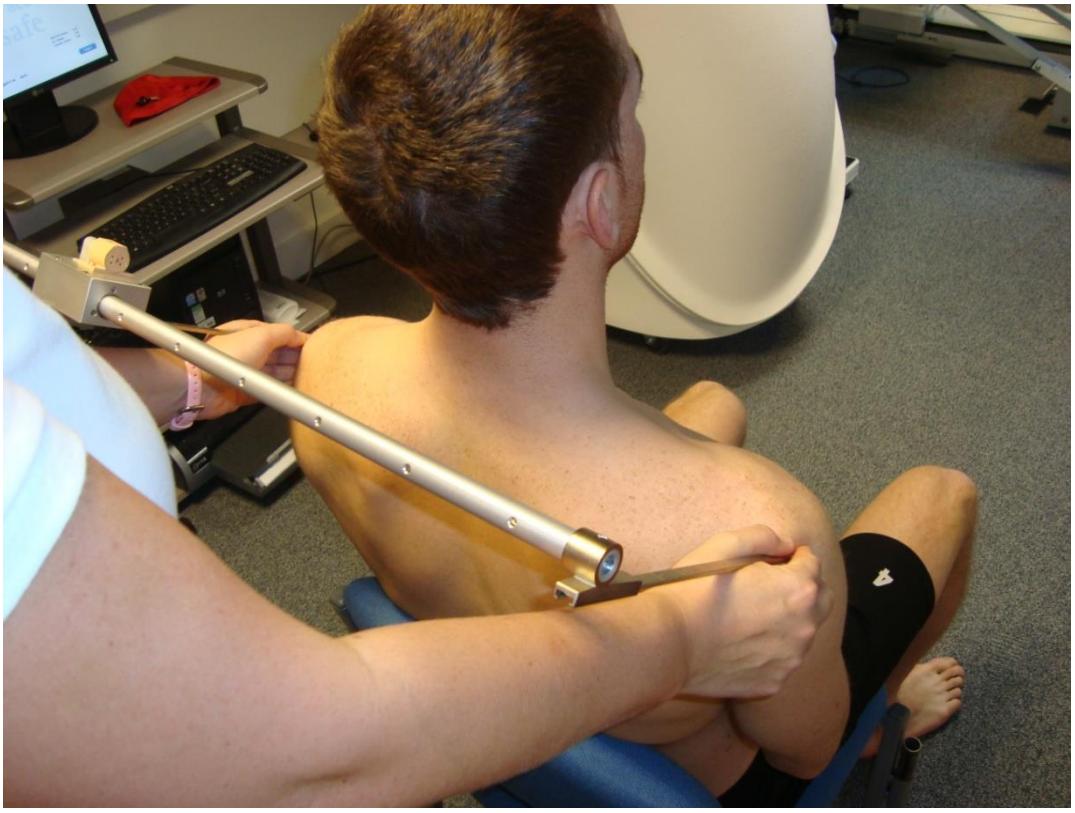


Plate 70 Anthropometric Breadth Measurement – Biliocristal (cm)

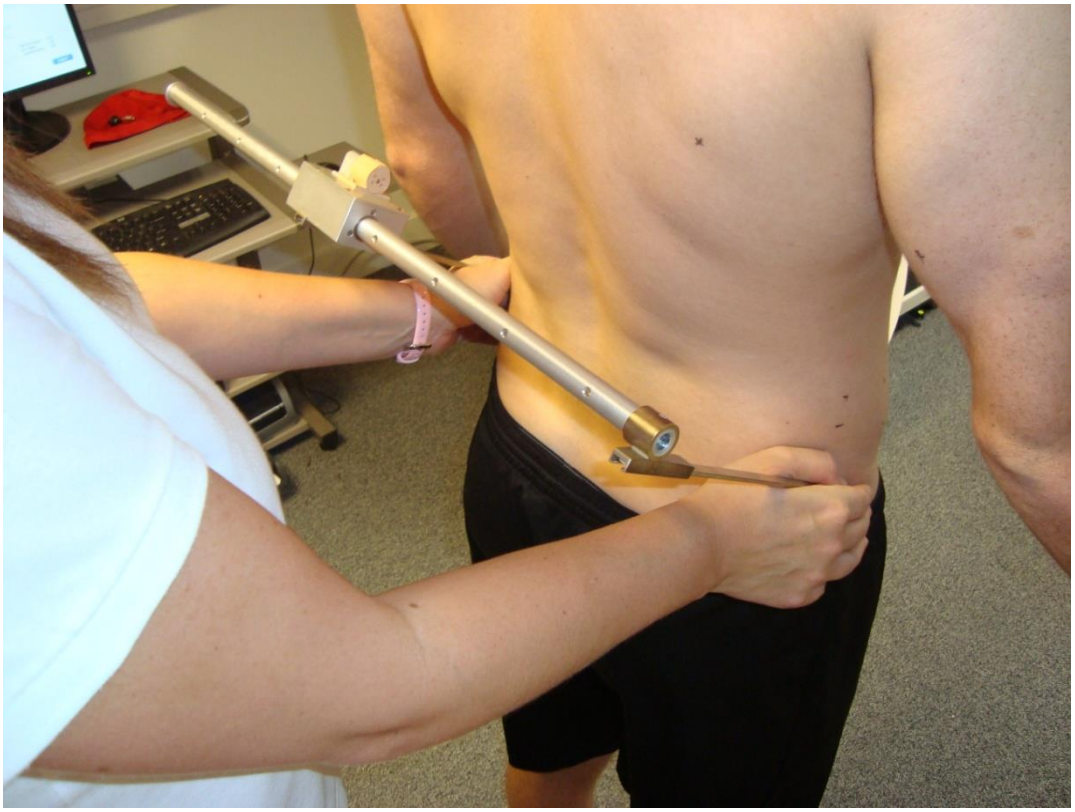


Plate 71 Anthropometric Depth Measurement – Transverse Chest (cm)

Plate 72 Anthropometric Depth Measurement – Anterior-Posterior Chest (cm)

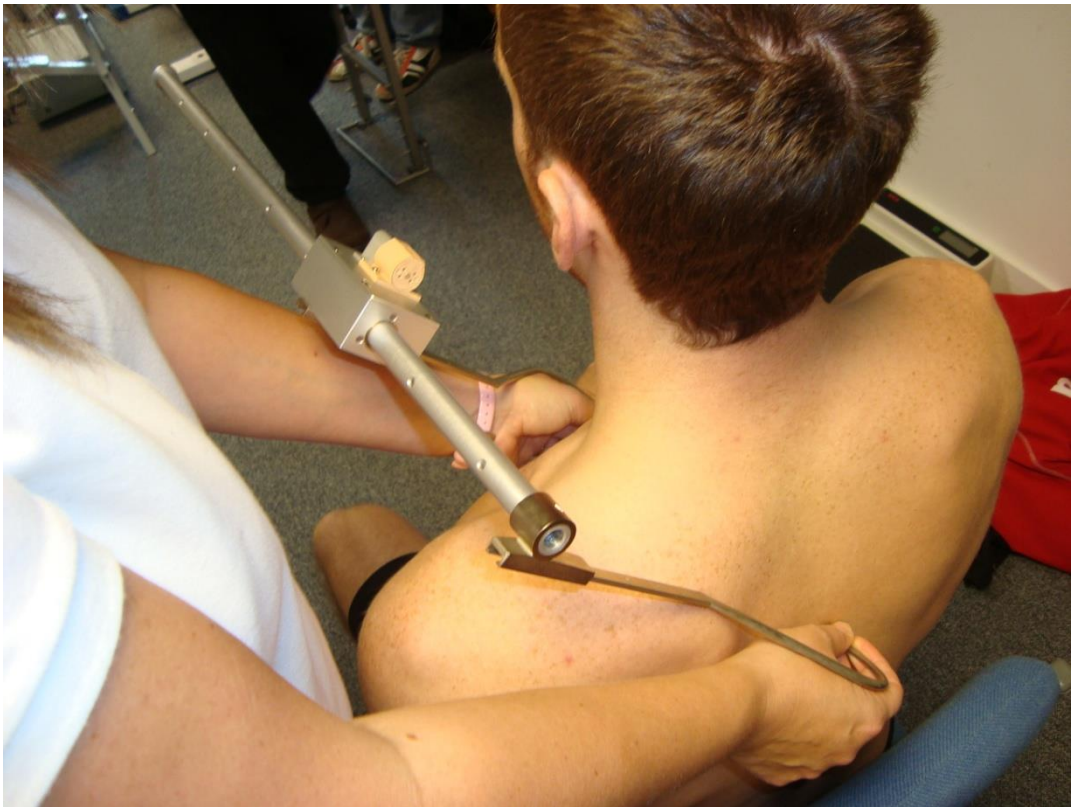


Plate 73 Harpenden Anthropometer Caliper Measurement Reading (cm)

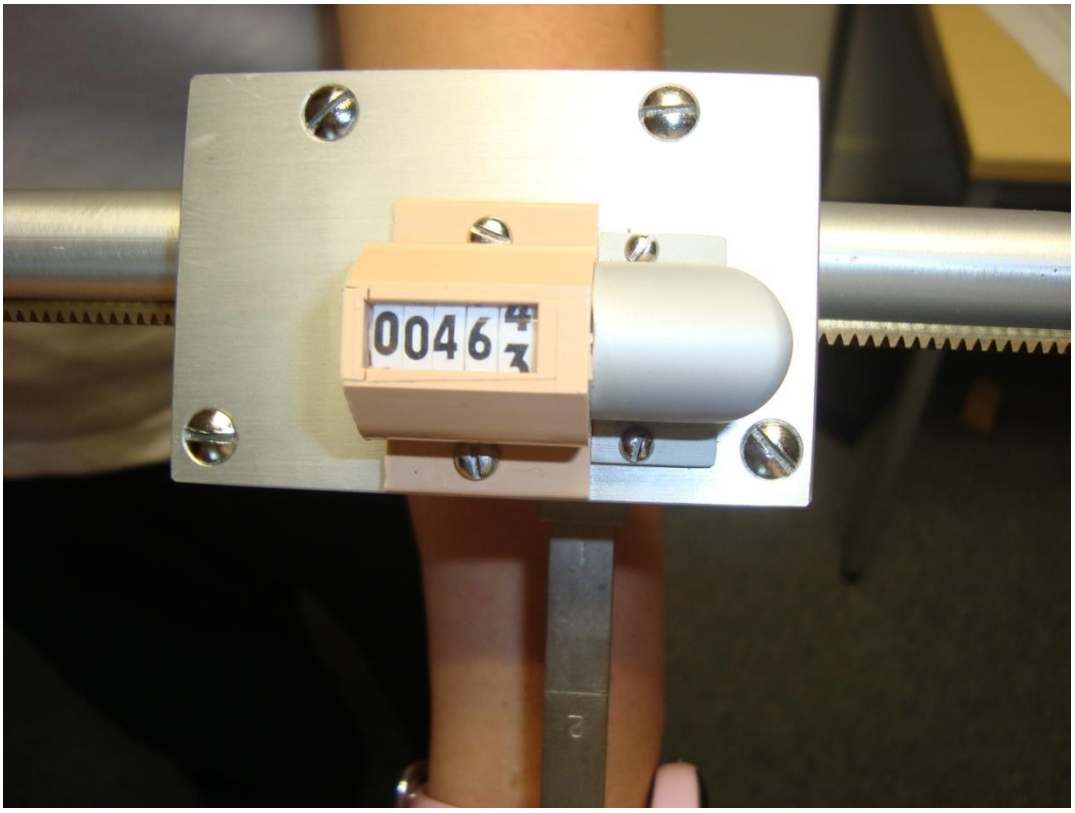


Plate 74 Anthropometric Width Measurement – Biepicondylar Humerus (cm)

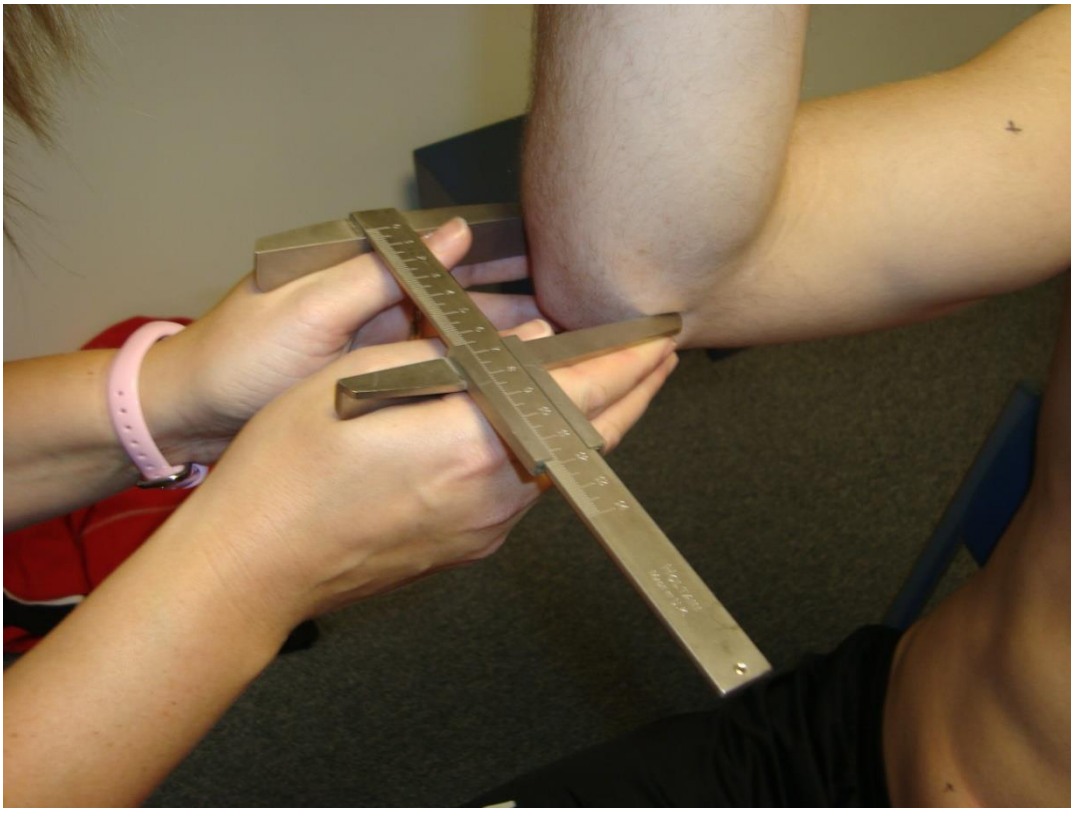


Plate 75 Anthropometric Width Measurement – Biepicondylar Femur (cm)

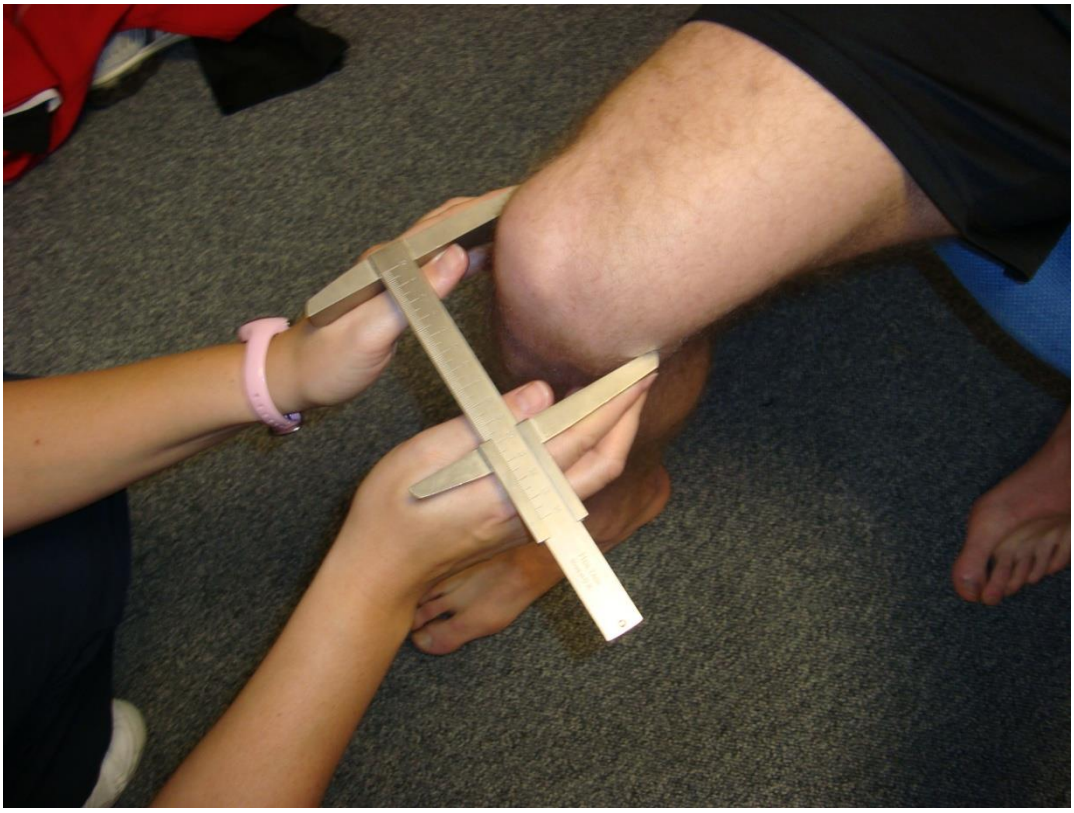
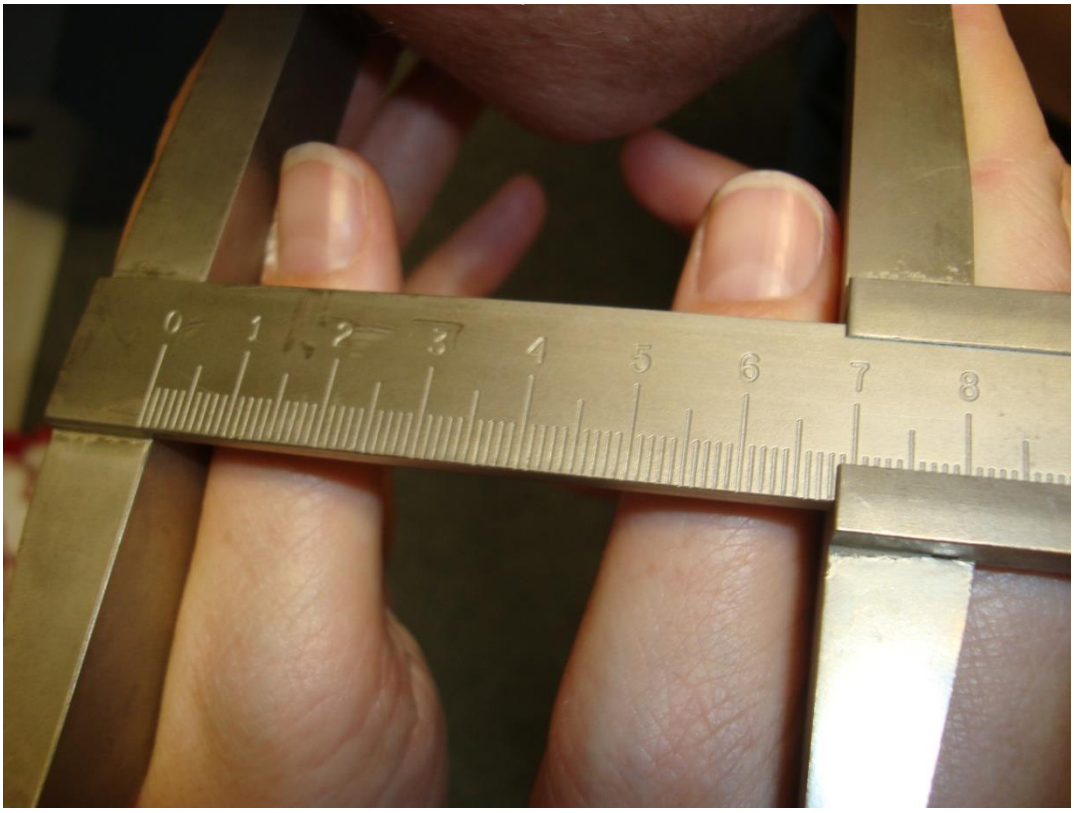


Plate 76 Harpenden Bone Caliper Measurement Reading (cm)



Appendices

Appendix A

Permission Letter to Football Manager/Coach/Physiotherapist

Claire Mills
Senior Lecturer of Sports Education and Coaching
University of Gloucestershire
Oxstalls Campus
Gloucester
GL2

01242 715156

[Their address]

January 2006

Dear [Manager's Name],

The purpose of this letter is to seek permission to carry out kinanthropometric assessments on your football players for my doctoral research at the University of Gloucestershire. The assessments will involve anthropometric variables to assess body composition, in order to estimate body density. These variables include skinfolds, girths, breadths, widths, air displacement plethysmography and underwater weighing, with the purpose of developing my own sport specific calibration model. Currently I have obtained permission from over 200 professional footballers. Therefore, your players, in the long term will have a substantial affect for the future research regarding the specificity of body composition in professional football players.

The assessments per player will take approximately half an hour. Every player will receive a letter from me informing them of my research and a health questionnaire form. All information gathered will be anonymous and treated as confidential. I very much look forward to hearing from you in the near future.

Kindest regards

Claire Mills
PhD Student

Dr Mark De Ste Croix
PhD Supervisor

Claire Mills

Appendix B

Permission Letter to Football Player

Claire Mills
Senior Lecturer of Sports Education and Coaching
University of Gloucestershire
Oxstalls Campus
Gloucester
GL2

01242 715156

[Their address]

January 2006

Dear [Player's Name],

As part of my doctoral research at the University of Gloucestershire I will be testing professional football players' body composition that requires three types of assessment. The first assessment would be anthropometry (including skinfolds, girths, breadths, depths and widths), secondly underwater weighing and finally air displacement plethysmography to enable me to estimate body density. Currently I have obtained permission from over 200 professional footballers. Therefore, the purpose of this letter is to seek permission to carry out these assessments on you for my doctoral research.

You will be assessed via anthropometric, underwater weighing and Air Displacement Plethysmography methods and will take approximately half an hour. All information gathered will be anonymous and treated as confidential.

Your cooperation is very much appreciated.

Kindest regards

Claire Mills	Dr Mark De Ste Croix	[Manager's Name]
PhD Student	PhD Supervisor	Manager

Claire Mills

University of Gloucestershire Sport and Exercise Laboratories Health Questionnaire

UNIVERSITY OF GLOUCESTERSHIRE

SPORT & EXERCISE LABORATORIES

Health Questionnaire

About this questionnaire:
The purpose of this questionnaire is to gather information about your health and lifestyle. We will use this information to decide whether you are eligible to take part in the testing for which you have volunteered. It is important that you answer the questions truthfully. The information you give will be treated in confidence. Your completed form will be stored securely for 5 years and then destroyed.

Section 1, which has been completed by the tester, provides basic information about the testing for which you have volunteered. Sections 2 to 7 are for you to complete: please circle the appropriate response or write your answer in the space provided. Please also complete section 8. Sections 9 and 10 will be completed by the tester, after you have completed sections 2 to 8.

Section 1: The testing (completed by tester)

To complete the testing for which you have volunteered you will be required to undertake:

Moderate exercise (i.e., exercise that makes you breathe more heavily than you do at rest but not so heavily that you are unable to maintain a conversation) ☐

Vigorous exercise (i.e., exercise that makes you breath so heavily that you are unable to maintain a conversation) ☐

The testing involves:

Walking	☐	Generating or absorbing high forces through your arms	☐
Running	☐	Generating or absorbing high forces through your shoulders	☐
Cycling	☐	Generating or absorbing high forces through your trunk	☐
Rowing	☐	Generating or absorbing high forces through your hips	☐
Swimming	☐	Generating or absorbing high forces through your legs	☐
Jumping	☐		

Section 2: General information

Name: ..... Sex: M F Age:

Height (approx.): ..... Weight (approx.):

Section 3: Initial considerations

		No	Yes
1.	Do any of the following apply to you?		
a)	I have HIV, Hepatitis A, Hepatitis B or Hepatitis C		
b)	I am pregnant		
c)	I have a muscle or joint problem that could be aggravated by the testing described in section 1		
d)	I am feeling unwell today		
e)	I have had a fever in the last 7 days		

(If you have answered "Yes" to question 1, go straight to section 8)

1

Section 4: Habitual physical activity

2a. Do you typically perform moderate exercise (as defined in section 1) for 20 minutes or longer at least twice a week?	No	Yes
2b. Have you performed this type of exercise within the last 10 days?	No	Yes
3a. Do you typically perform vigorous exercise (as defined in section 1) at least once a week?	No	Yes
3b. Have you performed this type of exercise within the last 10 days?	No	Yes

Section 5: Known medical conditions

4. Do **any** of the following apply to you? a) I have had insulin-dependent diabetes for more than 15 years b) I have insulin-dependent diabetes and am over 30 years old c) I have non-insulin-dependent diabetes and am over 35 years old	No	Yes
5. Have you ever had a stroke?	No	Yes
6. Has your doctor ever said you have heart trouble?	No	Yes
7. Do **both** of the following apply to you? a) I take asthma medication b) I have experienced shortness of breath or difficulty with breathing in the last 4 weeks?	No	Yes
8. Do you have any of the following: cancer, COPD, cystic fibrosis, other lung disease, liver disease, kidney disease, mental illness, osteoporosis, severe arthritis, a thyroid problem?	No	Yes

(If you have answered "Yes" to any questions in section 5, go straight to section 8.)

Section 6: Signs and symptoms

9. Do you often have pains in your heart, chest, or the surrounding areas?	No	Yes
10. Do you experience shortness of breath, either at rest or with mild exertion?	No	Yes
11. Do you often feel faint or have spells of severe dizziness?	No	Yes
12. Have you, in the last 12 months, experienced difficulty with breathing when lying down or been awakened at night by shortness of breath?	No	Yes
13. Do you experience swelling or a build up of fluid in or around your ankles?	No	Yes
14. Do you often get the feeling that your heart is racing or skipping beats, either at rest or during exercise?	No	Yes
15. Do you regularly get pains in your calves and lower legs during exercise that are not due to soreness or stiffness?	No	Yes
16. Has your doctor ever told you that you have a heart murmur?	No	Yes
17. Do you experience unusual fatigue or shortness of breath during everyday activities?	No	Yes

(If you have answered "Yes" to any questions in section 6, go straight to section 8.)

2

Section 7: Risk factors

18. Does **either** of the following apply to you? a) I smoke cigarettes on a daily basis b) I stopped smoking cigarettes on a daily basis less than 6 months ago	No	Yes
19. Has your doctor ever told you that you have high blood pressure?	No	Yes
20. Has your doctor ever told you that you have high cholesterol?	No	Yes
21. Has your father or any of your brothers had a heart attack, heart surgery, or a stroke before the age of 55?	No	Yes
22. Has your mother or any of your sisters had a heart attack, heart surgery, or a stroke before the age of 65?	No	Yes
23. Do **any** of the following apply to you? a) I have had insulin-dependent diabetes for less than 15 years b) I have insulin-dependent diabetes and am 30 or younger c) I have non-insulin-dependent diabetes and am 35 or younger	No	Yes

Section 8: Signatures

Participant: ..... Date: .....

Guardian*: ..... Date: .....
(*Required only if the participant is under 18 years of age.)

Section 9: Additional risk factors (to be completed by the tester if relevant)

24. Is the participant's body mass index >30 kg/m^2?	No	Yes
25. Has the participant answered no to questions 2a **and** 3a?	No	Yes

Section 10: Eligibility (to be completed by the tester)

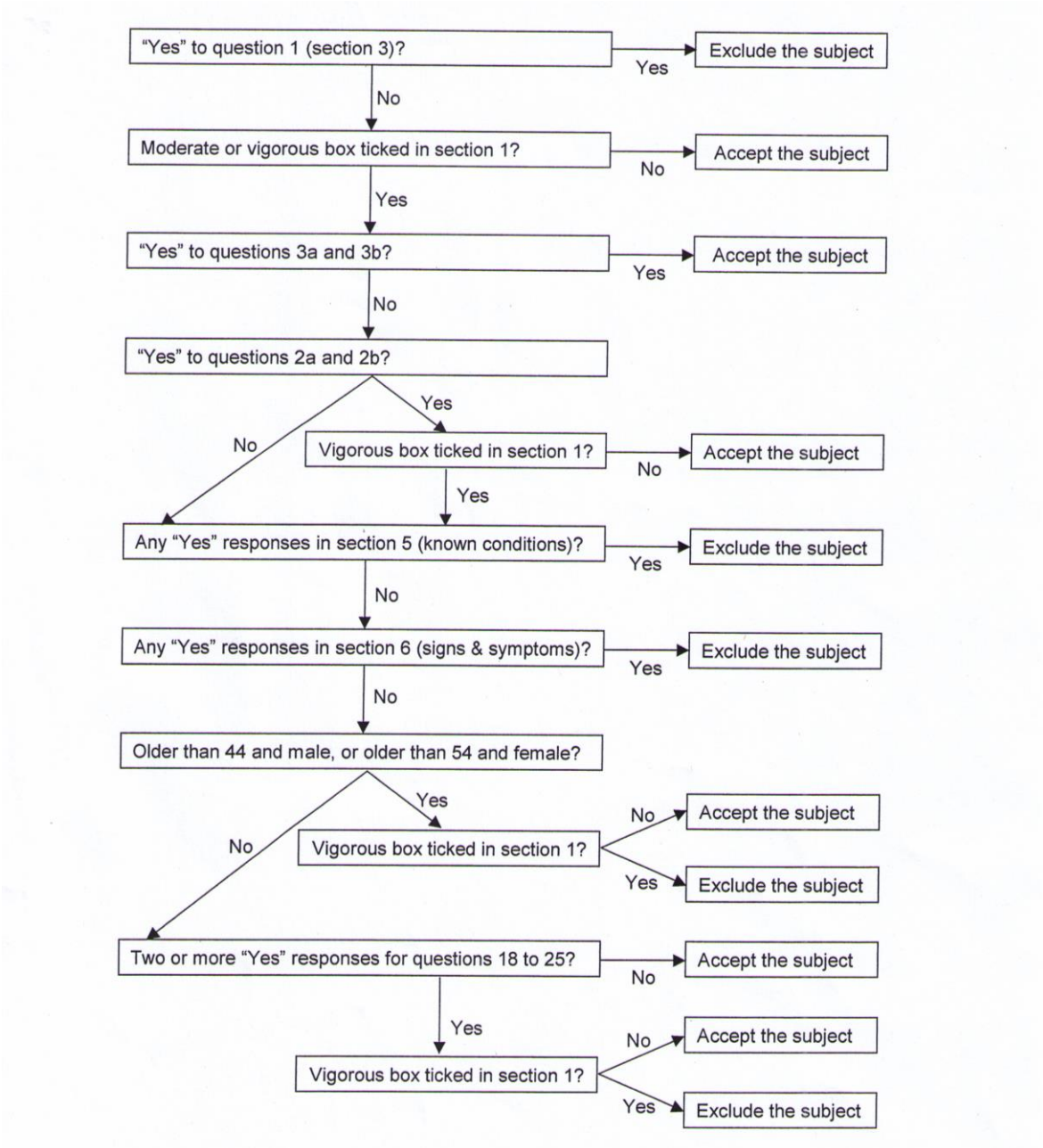
26. Is the participant eligible for the testing?	No	Yes

Name (of tester): .....

Signature: ..... Date: .....

Flow Diagram to determine the selection of participants for assessment after completing the University of Gloucestershire Health Questionnaire

UNIVERSITY OF GLOUCESTERSHIRE



Informed Consent Form

UNIVERSITY OF GLOUCESTERSHIRE

SPORT & EXERCISE LABORATORIES

Informed Consent Form

Description of study:

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw from the tests at any point. I confirm that I have completed a health questionnaire, and I am in a fit condition to undertake the required exercise.

Name: .....

Signed: ..... Date: .....

Name of Guardian*: .....

Signed*: ..... Date* .....

Tester: .....

Signed: ..... Date: .....

*to be completed only if the participant is under 18 years of age

5

Kinanthropometric Data Proforma

University of Gloucestershire
Kinanthropometric Data Proforma

Personal

001	Subjects Name	_____
002	Identification Nº	_____
003	Date of Measurement	_____
004	Date of Birth	_____
005	Subjects Age	_____
006	Football Position	_____
007	Football Zone	_____

Basic

		Trial 1	Trial 2	Mean
008	Body Mass (kg)	___.__	___.__	___.__
009	Stretched Stature (cm)	___.__	___.__	___.__
010	Sitting Height (cm)	___.__	___.__	___.__

Skinfold Assessments (mm)

011	Triceps	___.__	___.__	___.__
012	Subscapular	___.__	___.__	___.__
013	Biceps	___.__	___.__	___.__
014	Iliac Crest	___.__	___.__	___.__
015	Supraspinale	___.__	___.__	___.__
016	Abdominal	___.__	___.__	___.__
017	Anterior Thigh	___.__	___.__	___.__
018	Medial Calf	___.__	___.__	___.__

Girths (cm)

019	Neck	__.__	__.__	__.__
020	Arm (relaxed)	__.__	__.__	__.__
021	Arm (flexed)	__.__	__.__	__.__
022	Forearm (Maximum)	__.__	__.__	__.__
023	Chest	___.__	___.__	___.__
024	Waist	__.__	__.__	__.__
025	Hips (Gluteal)	__.__	__.__	__.__
026	Thigh (Mid-Troch-Tib)	__.__	__.__	__.__
027	Calf (Maximum)	__.__	__.__	__.__
028	Ankle (Maximum)	__.__	__.__	__.__

Breadths (cm), Depths (cm) and Widths (cm)

029	Biacromial Breadth	__.__	__.__	__.__
030	Biliocristal Breadth	__.__	__.__	__.__
031	Transverse Chest Depth	__.__	__.__	__.__
032	A-P Chest Depth	__.__	__.__	__.__
033	Humerus Width	__.__	__.__	__.__
034	Femur Width	__.__	__.__	__.__

Claire Mills BA (Hons.), P.G.C.E, MSc, FHEA
ISAK Kinanthropometrist

Hydrostatic Weighing Data Proforma

University of Gloucestershire
Hydrostatic Weighing Data Proforma

Personal

001	Subjects Name	_____
002	Identification Nº	_____
003	Date of Measurement	_____
004	Date of Birth	_____
005	Subjects Age	_____
006	Football Position	_____
007	Football Zone	_____

Vital Capacity Assessments

		Trial 1	Trial 2	Trial 3	Mean
008	Vital Capacity	_ _. _ _	_ _. _ _	_ _. _ _	_ _. _ _

Assessments

009	Body Mass (kg)	_ _ _. _ _	_ _ _. _ _	_ _ _. _ _	_ _ _. _ _
010	Total Mass in Water (kg)	_ _ _. _ _	_ _ _. _ _	_ _ _. _ _	_ _ _. _ _
011	Tare Weight (kg)	_ _. _ _			
012	Water Temperature (^{O}C)	_ _. _ _			

Trials

Trial 1	_. _ _ _
Trial 2	_. _ _ _
Trial 3	_. _ _ _
Trial 4	_. _ _ _
Trial 5	_. _ _ _
Trial 6	_. _ _ _
Trial 7	_. _ _ _
Trial 8	_. _ _ _
Trial 9	_. _ _ _
Trial 10	_. _ _ _

Claire Mills B.A. (Hons.), P.G.C.E, MSc., FHEA
ISAK Kinanthropometrist

Air Displacement Plethysmography Data Proforma

University of Gloucestershire
Air Displacement Plethysmography Data Proforma

Personal

001	Subjects Name	_____
002	Identification Nº	_____
003	Date of Measurement	_____
004	Date of Birth	_____
005	Subjects Age	_____
006	Football Position	_____
007	Football Zone	_____

Assessments

		Trial 1
008	Body Mass (kg)	_ _ _ . _
009	Body Volume (L)	_ _ . _ _
010	Body Density (kg/L)	_ _ . _ _

Claire Mills BA (Hons), PGCE, MSc
ISAK Kinanthropometrist

Specifications for assessing participants for Body Mass

Body Mass

All participants wore lightweight shorts and stood in the relaxed position with hands by their side. Body mass was recorded at a time standardised in relation to ingestion and defecation of the participant (Gordon *et al.*, 1991). The participant was asked to stand on the centre of the electronic scale without support, the weight distributed evenly on both feet (ISAK, 2011). They remained motionless until part of the standardised procedure for the air displacement model was finalised. Measurement value was given was given to the nearest 0.1 kg (Plate 21).

Table J Density of water at different temperatures

Temperature (^{o}C)	D_w* (grams/ml.)
21	0.9980
22	0.9978
23	0.9975
24	0.9973
25	0.9971
26	0.9968
27	0.9965
28	0.9963
29	0.9960
30	0.9957
31	0.9954
32	0.9951
33	0.9947
34	0.9944
35	0.9941
36	0.9937
37	0.9934
38	0.9930
39	0.9926
40	0.9922

Extracted from Sinning, W.E., (1975). *Experiments and Demonstrations in Exercise Physiology*. Philadelphia: W.B. Saunders Company. p. 109

* Rounded to 0.0001

Specifications for assessing participants for Hydrostatic Weighing

Hydrostatic Weighing exhalation technique

All participants were informed to initiate their own breathing rate and when ready, take a small inhalation, lean forwards and submerge themselves fully. Once underwater and keeping as still as possible the participant exhaled maximally. The rater watched for the ending of exhalation bubbles and took the measurement of body mass in water (kg) from the wall mounted digital weighing scale adjacent to the hydrostatic weighing tank. Following the measurement, the rater rapped loudly on the side of the tank instructing the participants to return to the surface and the measurement was taken to the nearest 0.1 kg (ISAK, 2011) (Plate 15 – 16).

Table L Body Temperature and Pressure Saturated (BTPS) Conversion Factors

Temperature (^{o}C)	BTPS* Factor
20	1.102
21	1.096
22	1.091
23	1.085
24	1.080
25	1.075
26	1.068
27	1.063
28	1.057
29	1.045
30	1.039

Extracted from Sinning, W.E., (1975). *Experiments and Demonstrations in Exercise Physiology*. Philadelphia: W.B. Saunders Company. p. 102

* Body temperature, ambient pressure, saturated with water vapour

Specifications for assessing participants for Air Displacement Plethysmograph

All participants followed a measurement protocol, with step by step instructions given on the BodPod system computer (Plate 6). After the participant stood on the electronic scale to determine body mass (See Appendix M) the participants were asked to apply the nose clip and hat (See Plate 7) and enter the BodPod and sit quietly on the moulded front seat with an erect posture with their hands folded on their laps and feet placed on the floor of the chamber (Plate 22) (Biaggi *et al*., 1999; McArdle *et al*., 2006). The aluminous panic release button was shown to participants should they at any time feel at all claustrophobic (Plate 23). The chamber door was then closed and sealed (Plate 28). During the test, participants were instructed to continue breathing normally whilst a minimum of two 50s tests were conducted (Biaggi *et al*., 1999, Hoffman *et al*., 2001). Once the measurements were completed (after ≈ 3-5 minutes) derivation of body volume together with measurement of body mass permitted calculations for body density (g ml^{-1}) (Dempster & Aitkens 1995).

Specifications for assessing participants for Forced Vital Capacity

All participants sat in an upright position and applied a nose clip, whilst holding the Spirometer (Micro Medical MicroLoop Spirometer model 3535) breathing tube in their dominant hand (Plate 25). The rater called the rate of breathing for the participant that comprised of three cycles of inhalation and exhalation. On the third cycle call, the rater asked the participant to take a large inhalation and then a maximal exhalation that was blown out through the tube (Plate 26). The participant was given three attempts to obtain their best value. The greatest value was then corrected for Body Temperature and Pressure Saturated (BTPS) that was determined by using a correction table (Appendix L) (Sinning, 1975).

Specifications for assessing participants for Stretched Stature

All participants stood barefoot, in the relaxed position with hands by their side, with the back of their heels held together on the bracket fixed to the floor. Their buttocks and shoulders were against the vertical wall, and their weight evenly distributed on both feet with their arms hanging freely by the sides. The orbital was located on the inferior portion of the eye socket and positioned such that it was exactly in line with the Frankfort plane with the superior part of the zygomatic bone. When aligned, the vertex was the highest point on the skull (ISAK, 2011). The participant was instructed to look anteriorly as the Brocca plate was lowered firmly onto the vertex, crushing the hair as much as possible. The rater stood anteriorly and cupped the mastoid processes, whilst the participant was asked to inhale. At this point, the mastoid processes were raised and the measurement was then taken to the nearest 0.1 cm (ISAK, 2011) (Plate 27).

Specifications for assessing participants for Sitting Height

All participants sat on the table platform with their back against the anthropometer, their legs hanging freely and hands resting on their thighs. The participant was instructed to position the back of their knees at the edge of the table and sit as erect as possible with their head in the Frankfort plane. If necessary, the rater applied gentle pressure simultaneously with the right hand over the lumbar area with the left hand on the superior part of the sternum to reinforce the erect seated position (Lohman *et al*., 1988; ISAK, 2011). In addition the upward traction of the mastoid processes ensured the fully erect seated position (Lohman *et al*., 1988).

The orbital was located on the inferior portion of the eye socket and positioned such that it was exactly in line with the Frankfort plane with the superior part of the zygomatic bone. When aligned, the vertex was the highest point on the skull (ISAK, 2011). The participant was instructed to look anteriorly as the Brocca plate was lowered firmly onto the vertex, crushing the hair as much as possible. The rater stood anteriorly and cupped the mastoid processes, whilst the participant was asked to inhale. The mastoid processes were raised and the measurement was then taken to the nearest 0.1 cm (ISAK, 2011) (Plate 28).

Specifications for marking Anthropometric Landmarks

Acromiale

The participant stood in the relaxed position with hands by their side whilst the rater stood behind and on the right hand side of the subject and palpated along the spine of the scapula to the corner of the acromiale (ISAK, 2011). A horizontal line was marked, along the lateral and inferior border (Plate 31).

Radiale

The participant stood in the relaxed position with hands by their side whilst the rater palpated downward into the lateral dimple of the right elbow and felt the space between the capitulum of the humerus and the head of the radius. The rater moved their thumb distally onto the most lateral part of the proximal radial head and a horizontal line was marked (ISAK, 2011) (Plate 32).

Mid-Acromiale-Radiale

The participant stood in the relaxed position with hands by their side whilst the rater measured the distance between the acromiale and the radiale landmarks with a segmometer (ISAK, 2011). The distance was read and the centre was found between the two marks, and a horizontal line drawn.

Subscapular

The participant stood in the anatomical position whilst the rater stood behind and palpated for the inferior border angle of the scapular (ISAK, 2011). A horizontal line was made (Plate 41).

Iliocristale

The participant stood in the relaxed position with their right arm crossed over their chest, whilst the rater stood behind and palpated for the most lateral edge of the iliac crest on the ilium (ISAK, 2011). A horizontal mark was made at the most lateral point of the ilium (Plate 33).

Iliospinale

The participant stood in the relaxed position with their right arm abducted to the horizontal and the rater palpated for the superior aspect of the ilium and followed anteriorly and inferiorly along the crest to the anterior superior iliac spine. A horizontal mark was made at the posterior side of Iliospinale (ISAK, 2011) (Plate 34).

Abdominal

The participant stood in the relaxed position with their arms folded across the thorax and breathing normally (ISAK, 2011) whilst the rater stood anteriorly and found the umbilicus. The rater used an anthropometric measuring tape and measured 5cm to the participants' right from the midpoint of the umbilicus and a horizontal mark made (Lohman *et al*., 1988; MacDougall *et al*., 1991; ISAK, 2011). A second mark was made at the vertical fold to show a cross (Plate 47).

Trochanterion

The participant stood in the relaxed position with their right arm abducted to the horizontal. The rater stood behind the participant and palpated for the lateral aspect of the gluteal muscle with the heel of the hand. Once the greater trochanter was identified the rater palpated upwards to locate the highest point and a horizontal mark made (ISAK, 2011) (Plate 35).

Tibiale Laterale

The participant stood in the relaxed position with hands by their side with their feet separated and weight evenly distributed. The raters' thumbnail was used to palpate for the lateral condyle of the femur and the anterior-lateral portion of the lateral tibial condyle (ISAK, 2011). A horizontal mark was made approximately one third of the distance along the border moving in an anterior-posterior direction (ISAK, 2011) (Plate 36).

Mid-Trochanterion-Tibiale Laterale

The participant stood in the relaxed position with hands by their side with their right forearm across the torso. The rater measured the distance between the mid-trochanterion and tibiale laterale landmarks with a segmometer (ISAK, 2011). The distance was read and the centre was located between the two marks and a horizontal line drawn.

Medial Calf

The participant stood barefoot in the relaxed position with hands by their side on the anthropometric box with their feet separated and weight evenly distributed. The rater stood on the anterior side of the participant and held the anthropometric measuring tape at a diagonal angle to the leg. The cross-hand technique was used to obtain a maximum girth of the calf by positioning the tape with the right hand in a series of up and down movements. The tape was pulled together by both hands, but not compressing any soft tissues which might alter the contour of the limb (ISAK, 2011). A horizontal mark was made on the medial aspect of the calf (Plate 53).

Specifications for assessing participants for Anthropometric Skinfold Sites

Triceps

The rater found the mid-acromiale-radiale landmark and using a steel anthropometric measuring tape the horizontal line was projected around to the posterior surface of the arm as a horizontal line (ISAK, 2011). The rater then found the mid-line of the triceps and drew a vertical line to show a cross (Plate 37). The Harpenden skinfold caliper was applied 1.0 cm distally from the left thumb and index finger, raising a vertical fold on the posterior surface (MacDougall *et al*., 1991) (Plate 38).

Biceps

The rater found the mid-acromiale-radiale landmark and using a steel anthropometric measuring tape the horizontal line was projected around to the anterior surface of the arm as a horizontal line (ISAK, 2011). The rater then found the most anterior part of the biceps and drew a vertical line to show a cross (Plate 39). The Harpenden skinfold caliper was applied 1.0 cm distally from the left thumb and index finger, raising a vertical fold on the anterior surface (MacDougall *et al*., 1991) (Plate 40).

Subscapular

The rater used a steel anthropometric measuring tape to locate 2.0 cm from the subscapular landmark at an angle of 45^{o} adjacent to the inferior angle of the scapular and drew a line in a direction lateral and downwards to show a cross (ISAK, 2011) (Plate 41).

The Harpenden skinfold caliper was applied 1.0 cm distally from the left thumb and index finger, raising a fold that was oblique to the inferior angle of the scapular from the horizontal on the posterior surface (MacDougall *et al*., 1991) (Plate 42).

Suprailiac

The rater raised a skinfold superior to the iliocristale and exerted pressure inwards so that the fingers rolled over the iliac crest. A horizontal mark was made at the centre of the raised skinfold, and downwards anteriorly as determined by the natural fold of the skin to show a cross (ISAK, 2011) (Plate 43). The Harpenden skinfold caliper was applied 1.0 cm anteriorly from the left thumb and index finger, raising a fold immediately superior to the iliac crest at the mid-axillary line on the anterior surface (MacDougall *et al*., 1991) (Plate 44).

Supraspinale

The rater held an anthropometric measuring tape from the anterior axillary border to the iliospinale landmark and a vertical mark made (ISAK, 2011). This line was also at the same level of the iliocristale landmark and a horizontal mark made to show a cross (Plate 45). The Harpenden skinfold caliper was applied 1.0 cm anteriorly from the left thumb and index finger, raising a fold at the inter-section of the border of the ilium on a line from the spinale to the anterior axillary border on the anterior surface (MacDougall *et al*., 1991) (Plate 46).

Abdominal

The rater located the abdominal landmark and applied the Harpenden skinfold caliper 1.0 cm inferiorly from the left thumb and index finger, raising a vertical fold 5.0 cm lateral to and at the level of the mid point of the umbilicus on the anterior surface (MacDougall *et al*., 1991) (Plate 47). Care was taken to ensure a firm grasp was taken as some underlying muscle may be poorly developed (Lohman *et al*., 1988) (Plate 48).

Anterior Thigh

The rater faced the right side of the thigh and located the mid-trochanterion-tibiale laterale landmark. A horizontal mark is made on the long axis of the thigh at the mid-point of the distance between the inguinal fold and the superior margin of the anterior surface of the patella (ISAK, 2011). A second line was drawn perpendicular to intersect with the horizontal line to show a cross (Plate 49). The Harpenden skinfold caliper was applied 1.0 cm distally to the left thumb and index finger, raising a fold on the anterior of the right thigh along the long axis of the femur on the anterior surface (MacDougall *et al*., 1991) (Plate 50).

If a participant's fold is difficult to raise in the seated position, the calipers can be pushed to the muscle level and slightly retracted as the participant assists by relieving the tension of the muscle by shaking and supporting the underside of the thigh with both their hands (MacDougall *et al*., 1991) (Plate 51). If this procedure still proves difficult an alternative tactic can be executed with the recorder raising the fold with two hands (Plate 52). Recording of this procedure is noted (MacDougall *et al*., 1991).

Medial Calf

The subject placed their right foot onto an anthropometric box at an angle of 90^{o}. The rater found the medial calf landmark and then applied a second mark on a vertical line to show a cross (ISAK, 2011) (Plate 53). The Harpenden skinfold caliper was applied 1.0 cm anteriorly from the left thumb and index finger, raising a vertical fold on the relaxed calf at the estimated greatest circumference on the medial surface (MacDougall *et al*., 1991) (Plate 54).

Specifications for marking and assessing participants for Anthropometric Girths

Neck

The participant stood in the relaxed position with hands by their side with their head positioned in the Frankfort plane (Lohman *et al*., 1988). The rater stood laterally on the left hand side and placed the anthropometric measuring tape perpendicular to the long axis of the neck, superior to the laryngeal prominence thyroid cartilage and the measurement taken in less than 5 seconds to avoid discomfort (Lohman *et al*., 1988; ISAK, 2011) (Plate 57).

Arm (relaxed)

The participant stood in the relaxed position with hands by their side whilst the rater laterally located the landmark of both the bicep and tricep (the distance between the acromiale and radiale) (MacDougall *et al*., 1991). These two landmarks were used to determine a midpoint level via an anthropometric measuring tape and a line was marked accordingly. The anthropometric measuring tape was placed on this perpendicular long axis line and passed around the arm from left to right, whilst ensuring that the tape was not pulled too tightly as to compress the soft tissues and alter the contour of the arm (ISAK, 2011) (Plate 58).

Arm (flexed)

The participant stood in the relaxed position with their right arm raised anteriorly at a 45^{o} horizontal angle. The rater stood laterally with the anthropometric measuring tape loosely positioned at the site of maximal tension, where the participant was asked to

make a fist and tense their bicep muscle. A preliminary flexing permitted the rater to identify the probable peak of the muscle (MacDougall *et al*., 1991). The rater then requested the participant to fully contract the bicep muscle as strongly as possible and hold it while the anthropometric measuring tape was adjusted. Finally the tape was pulled tighter so that a reading could be made (Plate 59).

Forearm

The participant stood in the relaxed position with hands by their side with their forearm supinated whilst the rater stood anteriorly. The anthropometric measuring tape was placed loosely around the proximal part of the forearm by the humerus epicondyles (ISAK, 2011). The cross-hand technique was used to move the tape up and down the forearm until the maximum girth was located (Lohman *et al*., 1988; ISAK, 2011) (Plate 60).

Wrist

The participant stood in the relaxed position with hands by their side with one arm flexed at the elbow and the forearm supinated in which the rater could palpate for the styloid processes of the ulna. The anthropometric measuring tape was then positioned perpendicular to the long axis of the forearm and in the same plane as the anterior and posterior positions of the wrist. The cross-hand technique was used to obtain a minimum girth whilst care taken not to compress the soft tissues (Lohman *et al*., 1988; ISAK, 2011) (Plate 61).

Chest

The participant stood in the relaxed position with hands by their side with their arms abducted to the horizontal position. This allowed for the anthropometric measuring tape to be passed around the chest from the lateral position and adjusted to the level of the Mesosternale. The participant was instructed to lower their arms to the relaxed position and breath normally. Measurements were taken at the end of the expiratory excursion (Lohman *et al*., 1988; ISAK, 2011) (Plate 62).

Waist

The participant stood in the relaxed position with hands by their side with their arms folded across the thorax and breathing normally (ISAK, 2011). The rater passed the anthropometric measuring tape around the waist from the anterior position. The cross-hand technique was used to obtain a minimum girth of the waist at approximately the lower costal (10^{th} rib) border and the iliac crest (MacDougall *et al*., 1991; ISAK, 2011). Measurements were taken at the end of the expiratory excursion (Lohman *et al*., 1988; ISAK, 2011) (Plate 63).

Hip (Gluteal)

The participant stood in the relaxed position with hands by their side with their arms folded across the thorax and gluteal muscles relaxed (ISAK, 2011). The rater passed the anthropometric measuring tape around the hips from the lateral position. The cross-hand technique was used to obtain a maximum girth of the hips at the greatest posterior protuberance, approximately at the anterior level of the pubis symphysis (MacDougall *et al*., 1991; ISAK, 2011) (Plate 64).

Anterior Thigh (Mid)

The participant stood in the relaxed position with hands by their side with their arms folded across the thorax on the anthropometric box with their feet separated and weight evenly distributed. The rater stood on the lateral side of the participant and held the anthropometric measuring tape in a plane perpendicular to the axis of the leg. The cross-hand technique was used to obtain a maximum girth of the thigh at the marked mid trochanterion-tibiale-laterale anthropometric skinfold site (ISAK, 2011) (Plate 65).

Calf

The participant stood barefoot in the relaxed position with hands by their side on the anthropometric box with their feet separated and weight evenly distributed. The rater stood on the lateral side of the participant and held the anthropometric measuring tape in a plane perpendicular to the axis of the leg. The cross-hand technique was used to obtain a maximum girth of the calf at the marked medial calf anthropometric skinfold site (ISAK, 2011) (Plate 66).

Ankle

The participant stood barefoot in the relaxed position with hands by their side on the anthropometric box with their feet separated and weight evenly distributed. The rater stood behind the participant and the cross-hand technique was used to find the narrowest point of the ankle along the long axis of the tibia, which was superior to the sphyrion tibiale, with care taken not to compress the soft tissues (MacDougall *et al*., 1991; ISAK, 2011) (Plate 67).

Specifications for assessing participants for Anthropometric Breadths

Biacromial

The participant stood in the relaxed position with hands by their side with their shoulders slightly hunched forwards as the rater stood behind with the Harpenden anthropometer. The anthropometer was brought downwards at an angle of 45^{o} to the most lateral points of the acromion processes that were located by the index fingers (ISAK, 2011). The large sliding calipers branches of the Harpenden anthropometer were firmly applied to the acromion processes landmarks in order to compress the subcutaneous tissues, but not enough to move the shoulders (ISAK, 2011) (Plate 69).

Biilocristal

The participant stood in the relaxed position with hands by their side with their arms abducted horizontally. The rater stood behind the participant and palpated for the most lateral borders of the iliac crest (iliocristale). The Harpenden anthropometer was angled at approximately 45^{o} from a horizontal position and the large sliding calipers branches of the anthropometer were firmly applied to the lateral borders of the crests in order to compress the subcutaneous tissues, but not enough to move the hips (ISAK, 2011) (Plate 70).

Specifications for assessing participants for Anthropometric Depths

Transverse Chest

The participant stood in the relaxed position with hands by their side with their arms abducted sufficiently to allow the Harpenden caliper branches to be positioned. The rater stood anterior to the participant and palpated for the most lateral aspect of the fourth ribs and angled the anthropometer caliper blades at the level of the Mesosternale at approximately 30^{o} downwards from the horizontal plane (ISAK, 2011). Care was taken to avoid the Pectoralis Major and Latissimus Dorsi muscles. The participant was asked to inhale and exhale and the measurement was taken at the end of the expiratory excursion (ISAK, 2011) (Plate 71).

Anterior-Posterior Chest

The participant sat upright on a chair whilst the rater palpated for the Mesosternale and made a mark both horizontally and vertically. The rater then stood laterally to the participant whilst the L-shaped branches of the Harpenden anthropometer were brought downwards over the shoulders of the subject and placed on the Mesosternale and the spinous process of the vertebra at a horizontal level. The rounded tips of the calipers were applied to the body with very light pressure whilst instructing the participant to breathe normally. Measurements were taken at the end of the expiratory excursion (ISAK, 2011) (Plate 72).

Specifications for assessing participants for Anthropometric Widths

Biepicondylar Humerus

The participant sat upright on a chair with their right arm and elbow raised anteriorly at a right angle of 90^{o} with the palm of their hand facing them. The rater palpated for the medial and lateral epicondyles of the humerus. On location of the site, the rater applied the caliper faces to the epicondyles, and kept them at a horizontal position. The caliper faces were applied to the body segment firmly in order to compress the subcutaneous tissues and maintain caliper position (ISAK, 2011) (Plate 73).

Biepicondylar Femur

The participant sat upright on a chair with their right leg flexed at the knee to form a right angle with the thigh (ISAK, 2011). The rater palpated for the medial and lateral epicondyles of the femur. On location of the site, the rater applied the caliper faces to the epicondyles, and kept them at a horizontal position. The caliper faces were applied to the body segment firmly in order to compress the subcutaneous tissues and maintain caliper position (ISAK, 2011) (Plate 74).

Written communication with Life Measurement, Inc.

From: Technical Support [mailto:techsupport@bodpod.com]
Sent: 14 February 2008 22:18
To: MILLS, Claire
Cc: Manoj Raghuraman
Subject: RE: Bod Pod Calibration

Hi Claire,

Sorry for the delay. Here is the feedback from our Research Manager, Manoj Raghuraman:

"The BOD POD as part of its QA process has multiple volume tests where known volumes of 30L and 90L are measured along with the calibration cylinder in question. Similarly the accuracy and linearity of the scale is measured at various weights starting from 20Kg to 80Kg as part of the QA process. The acceptance criteria include a mean value as well as SD values. Since the QA data for each of the units tested is stored separately, we do not have a single database that we can export data from.

We can assure you that the BOD POD is rigorously tested to establish accuracy and linearity of both volume and mass measurements."

Let me know if that answers your questions.

Sincerely,

Francisco Taylor

Written communication with Professor Marfell-Jones

From: Prof Marfell-Jones [profmike@clear.net.nz]
Sent: 21 June 2013 22:21
To: MILLS, Claire
Subject: RE: ISAK clarification to assist with PhD query

Dear Claire

Whereas I'm not sure of the significance of the use of the word "attempts"
(see below), I shall assume that all the Study 1 measures below were deemed acceptable and that you have therefore benchmarked the anthropometric variables for each subject against your measurement of their density. You are then using these densities in Study 2 as the criterion values against which you will compare density predictions from a number of selected equations in order to see how good, or acceptable, those predictions are.
[If I'm astray on this, let me know.]

Your original question (far below) asked what ISAK considered to be acceptable a priori limits of agreement for your sample once body density has been predicted, as you could not find reference to such. The reason for that is that ISAK as an entity does not publish limits of agreement for the prediction of body density, primarily because its position is that calculating body density (and the subsequent conversion of those densities to percentage fat) adds nothing to our understanding of the adiposity of an individual over and above the understanding provided by the individual and summed skinfold measurements (other than potential error). Nevertheless, Study 2 is a perfectly valid exercise and, as such, needs a priori limits.

In that case, and purely as advice from me as an individual, I would endorse your choice of $p < 0.05$ as perfectly acceptable from both a statistical and a biological viewpoint.

Kind regards

Professor M.J. Marfell-Jones
Chair, ISAK Accreditation Working Group

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Correlation Matrix (Study 3)

	HWDb	BMX	SSX	SHX	SFTX	SFSSX	SFBX	SFICX	SFsupX
BMX	-0.439								
	0.000								
SSX	-0.271	0.668							
	0.000	0.000							
SHX	-0.188	0.547	0.769						
	0.007	0.000	0.000						
SFTX	-0.249	0.106	-0.014	-0.129					
	0.000	0.130	0.840	0.065					
SFSSX	-0.302	0.287	0.026	-0.073	0.610				
	0.000	0.000	0.708	0.298	0.000				
SFBX	-0.129	0.009	-0.121	-0.255	0.614	0.598			
	0.066	0.901	0.084	0.000	0.000	0.000			
SFICX	-0.378	0.257	0.066	-0.016	0.536	0.672	0.455		
	0.000	0.000	0.345	0.820	0.000	0.000	0.000		
SFsupX	-0.337	0.238	0.047	-0.060	0.525	0.716	0.499	0.758	
	0.000	0.001	0.502	0.395	0.000	0.000	0.000	0.000	
SFabX	-0.354	0.292	0.049	0.015	0.421	0.673	0.386	0.794	0.737
	0.000	0.000	0.485	0.829	0.000	0.000	0.000	0.000	0.000
SFATX	-0.271	0.151	0.060	-0.043	0.646	0.431	0.430	0.530	0.456
	0.000	0.030	0.395	0.540	0.000	0.000	0.000	0.000	0.000
SFMCX	-0.203	0.118	0.030	-0.088	0.688	0.572	0.647	0.432	0.426
	0.003	0.090	0.671	0.209	0.000	0.000	0.000	0.000	0.000
GNX	-0.269	0.562	0.367	0.258	0.046	0.231	0.032	0.057	0.128
	0.000	0.000	0.000	0.000	0.511	0.001	0.649	0.412	0.066
GArX	-0.233	0.529	0.288	0.212	0.097	0.118	-0.001	0.125	0.118
	0.001	0.000	0.000	0.002	0.165	0.091	0.994	0.074	0.091
GAfX	-0.191	0.446	0.258	0.214	0.002	0.051	-0.057	0.046	0.054
	0.006	0.000	0.000	0.002	0.973	0.470	0.412	0.510	0.442
GFaX	-0.079	0.418	0.272	0.259	-0.059	0.008	-0.042	-0.077	-0.023
	0.260	0.000	0.000	0.000	0.402	0.909	0.552	0.272	0.746
GWX	-0.022	0.441	0.369	0.340	0.019	-0.017	-0.119	-0.048	-0.055
	0.756	0.000	0.000	0.000	0.784	0.808	0.089	0.492	0.431
GchX	-0.163	0.571	0.381	0.369	0.087	0.158	-0.039	0.130	0.087
	0.019	0.000	0.000	0.000	0.215	0.023	0.576	0.062	0.216
GwaX	-0.235	0.478	0.310	0.308	0.080	0.212	0.001	0.253	0.259
	0.001	0.000	0.000	0.000	0.255	0.002	0.989	0.000	0.000
GHX	-0.283	0.607	0.435	0.327	0.144	0.269	0.098	0.216	0.244
	0.000	0.000	0.000	0.000	0.039	0.000	0.159	0.002	0.000

	HWDb	BMX	SSX	SHX	SFTX	SFSSX	SFBX	SFICX	SFsupX
GthX	-0.138	0.564	0.308	0.281	0.127	0.139	-0.087	0.129	0.122
	0.048	0.000	0.000	0.000	0.069	0.047	0.215	0.064	0.080
GCX	-0.173	0.486	0.281	0.199	0.018	0.058	-0.079	0.025	0.074
	0.013	0.000	0.000	0.004	0.800	0.409	0.262	0.720	0.293
GAX	-0.117	0.345	0.223	0.199	0.039	0.002	-0.016	-0.047	-0.021
	0.094	0.000	0.001	0.004	0.582	0.975	0.818	0.506	0.767
BBiaX	-0.135	0.412	0.352	0.271	-0.138	-0.052	-0.063	-0.114	-0.096
	0.054	0.000	0.000	0.000	0.049	0.458	0.367	0.102	0.168
BBilX	-0.240	0.543	0.356	0.272	0.146	0.201	0.040	0.230	0.211
	0.001	0.000	0.000	0.000	0.036	0.004	0.566	0.001	0.002
DTCX	-0.201	0.438	0.338	0.251	0.092	0.173	0.078	0.166	0.130
	0.004	0.000	0.000	0.000	0.188	0.013	0.267	0.017	0.062
DAPX	-0.177	0.377	0.198	0.280	-0.016	0.150	-0.087	0.023	0.091
	0.011	0.000	0.004	0.000	0.821	0.032	0.213	0.740	0.195
WHX	-0.100	0.247	0.199	0.167	0.107	0.093	-0.054	-0.050	0.021
	0.155	0.000	0.004	0.016	0.126	0.181	0.441	0.471	0.763
WFX	0.004	0.192	0.064	0.058	0.108	0.110	0.090	0.041	0.103
	0.956	0.006	0.359	0.410	0.123	0.115	0.198	0.558	0.140

	SFabX	SFATX	SFMCX	GNX	GArX	GAfX	GFaX	GWX	GchX
SFATX	0.464								
	0.000								
SFMCX	0.371	0.634							
	0.000	0.000							
GNX	0.132	-0.057	0.046						
	0.059	0.418	0.515						
GArX	0.116	0.090	0.061	0.551					
	0.096	0.199	0.385	0.000					
GAfX	0.032	0.021	-0.009	0.511	0.854				
	0.649	0.769	0.895	0.000	0.000				
GFaX	-0.043	-0.109	-0.102	0.449	0.483	0.488			
	0.538	0.120	0.145	0.000	0.000	0.000			
GWX	-0.026	-0.013	0.032	0.404	0.507	0.510	0.496		
	0.707	0.848	0.652	0.000	0.000	0.000	0.000		
GchX	0.156	0.064	0.054	0.428	0.488	0.465	0.385	0.436	
	0.025	0.360	0.440	0.000	0.000	0.000	0.000	0.000	
GwaX	0.246	0.061	0.083	0.398	0.401	0.399	0.177	0.203	0.534
	0.000	0.383	0.234	0.000	0.000	0.000	0.011	0.003	0.000
GHX	0.208	0.089	0.156	0.454	0.420	0.379	0.291	0.305	0.443
	0.003	0.203	0.025	0.000	0.000	0.000	0.000	0.000	0.000

	SFabX	SFATX	SFMCX	GNX	GArX	GAfX	GFaX	GWX	GchX
GthX	0.125	0.092	0.014	0.428	0.584	0.537	0.324	0.470	0.562
	0.074	0.190	0.837	0.000	0.000	0.000	0.000	0.000	0.000
GCX	0.070	0.015	-0.037	0.399	0.487	0.405	0.311	0.433	0.426
	0.317	0.832	0.594	0.000	0.000	0.000	0.000	0.000	0.000
GAX	-0.017	0.033	0.078	0.360	0.380	0.353	0.270	0.460	0.255
	0.804	0.633	0.266	0.000	0.000	0.000	0.000	0.000	0.000
BBiaX	-0.089	-0.149	-0.056	0.431	0.403	0.349	0.293	0.289	0.457
	0.201	0.032	0.427	0.000	0.000	0.000	0.000	0.000	0.000
BBilX	0.256	0.054	0.112	0.409	0.419	0.371	0.191	0.390	0.492
	0.000	0.440	0.109	0.000	0.000	0.000	0.006	0.000	0.000
DTCX	0.108	-0.013	0.015	0.419	0.348	0.294	0.260	0.238	0.580
	0.124	0.856	0.834	0.000	0.000	0.000	0.000	0.001	0.000
DAPX	0.211	-0.041	-0.038	0.324	0.255	0.257	0.206	0.279	0.422
	0.002	0.563	0.585	0.000	0.000	0.000	0.003	0.000	0.000
WHX	0.043	0.053	0.048	0.149	0.135	0.168	0.137	0.185	0.276
	0.542	0.451	0.494	0.032	0.053	0.016	0.049	0.008	0.000
WFX	0.047	0.052	0.070	0.127	0.124	-0.004	0.147	0.202	0.080
	0.505	0.461	0.317	0.068	0.076	0.957	0.035	0.004	0.254

	GwaX	GHX	GthX	GCX	GAX	BBiaX	BBilX	DTCX	DAPX
GHX	0.566								
	0.000								
GthX	0.388	0.413							
	0.000	0.000							
GCX	0.304	0.358	0.546						
	0.000	0.000	0.000						
GAX	0.163	0.295	0.348	0.509					
	0.019	0.000	0.000	0.000					
BBiaX	0.217	0.273	0.363	0.286	0.206				
	0.002	0.000	0.000	0.000	0.003				
BBilX	0.457	0.463	0.377	0.293	0.332	0.374			
	0.000	0.000	0.000	0.000	0.000	0.000			
DTCX	0.436	0.422	0.376	0.271	0.198	0.470	0.485		
	0.000	0.000	0.000	0.000	0.004	0.000	0.000		
DAPX	0.378	0.349	0.304	0.335	0.124	0.157	0.251	0.195	
	0.000	0.000	0.000	0.000	0.076	0.024	0.000	0.005	
WHX	0.154	0.179	0.164	0.199	0.086	0.035	0.141	0.037	0.257
	0.027	0.010	0.018	0.004	0.220	0.620	0.044	0.595	0.000
WFX	0.024	0.188	0.176	0.170	0.216	0.185	0.244	0.154	0.043
	0.733	0.007	0.011	0.014	0.002	0.008	0.000	0.027	0.536

	WHX
WFX	-0.190
	0.006

Regression Analysis: HWDb versus BMX

```
The regression equation is
HWDb = 1.13 - 0.000753 BMX

Predictor         Coef    SE Coef       T      P
Constant       1.13466    0.00857  132.41  0.000
BMX         -0.0007534  0.0001081   -6.97  0.000

S = 0.0129039   R-Sq = 19.2%   R-Sq(adj) = 18.8%

Analysis of Variance

Source           DF         SS         MS      F      P
Regression        1  0.0080909  0.0080909  48.59  0.000
Residual Error  204  0.0339680  0.0001665
Total           205  0.0420589
```

Regression Analysis: HWDb versus SSX

```
The regression equation is
HWDb = 1.18 - 0.000555 SSX

Predictor         Coef    SE Coef      T      P
Constant       1.17517    0.02489  47.22  0.000
SSX         -0.0005546  0.0001381  -4.02  0.000

S = 0.0138223   R-Sq = 7.3%   R-Sq(adj) = 6.9%

Analysis of Variance

Source           DF         SS         MS      F      P
Regression        1  0.0030837  0.0030837  16.14  0.000
Residual Error  204  0.0389752  0.0001911
Total           205  0.0420589
```

Regression Analysis: HWDb versus SHX

```
The regression equation is
HWDb = 1.13 - 0.000558 SHX

Predictor         Coef    SE Coef      T      P
Constant       1.12741    0.01911  59.00  0.000
SHX         -0.0005576  0.0002040  -2.73  0.007

S = 0.0141028   R-Sq = 3.5%   R-Sq(adj) = 3.1%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0014853  0.0014853  7.47  0.007
Residual Error  204  0.0405736  0.0001989
Total           205  0.0420589
```

Regression Analysis: HWDb versus SFTX

The regression equation is
HWDb = 1.08 - 0.00115 SFTX

Predictor	Coef	SE Coef	T	P
Constant	1.08489	0.00279	388.48	0.000
SFTX	-0.0011532	0.0003135	-3.68	0.000

S = 0.0139050 R-Sq = 6.2% R-Sq(adj) = 5.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0026159	0.0026159	13.53	0.000
Residual Error	204	0.0394430	0.0001933		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFSSX

The regression equation is
HWDb = 1.09 - 0.00173 SFSSX

Predictor	Coef	SE Coef	T	P
Constant	1.09306	0.00404	270.38	0.000
SFSSX	-0.0017311	0.0003819	-4.53	0.000

S = 0.0136861 R-Sq = 9.1% R-Sq(adj) = 8.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0038480	0.0038480	20.54	0.000
Residual Error	204	0.0382109	0.0001873		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFBX

The regression equation is
HWDb = 1.08 - 0.000906 SFBX

Predictor	Coef	SE Coef	T	P
Constant	1.07938	0.00244	442.15	0.000
SFBX	-0.0009058	0.0004893	-1.85	0.066

S = 0.0142396 R-Sq = 1.7% R-Sq(adj) = 1.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0006948	0.0006948	3.43	0.066
Residual Error	204	0.0413641	0.0002028		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFICX

The regression equation is
HWDb = 1.09 - 0.000875 SFICX

Predictor	Coef	SE Coef	T	P
Constant	1.08889	0.00252	432.84	0.000
SFICX	-0.0008746	0.0001500	-5.83	0.000

S = 0.0132932 R-Sq = 14.3% R-Sq(adj) = 13.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0060101	0.0060101	34.01	0.000
Residual Error	204	0.0360487	0.0001767		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFsupX

The regression equation is
HWDb = 1.09 - 0.00123 SFsupX

Predictor	Coef	SE Coef	T	P
Constant	1.08731	0.00254	427.89	0.000
SFsupX	-0.0012341	0.0002416	-5.11	0.000

S = 0.0135202 R-Sq = 11.3% R-Sq(adj) = 10.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0047686	0.0047686	26.09	0.000
Residual Error	204	0.0372903	0.0001828		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFabX

The regression equation is
HWDb = 1.09 - 0.000855 SFabX

Predictor	Coef	SE Coef	T	P
Constant	1.08776	0.00249	436.03	0.000
SFabX	-0.0008553	0.0001581	-5.41	0.000

S = 0.0134279 R-Sq = 12.5% R-Sq(adj) = 12.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0052759	0.0052759	29.26	0.000
Residual Error	204	0.0367829	0.0001803		
Total	205	0.0420589			

Regression Analysis: HWDb versus SFATX

```
The regression equation is
HWDb = 1.09 - 0.000877 SFATX

Predictor         Coef    SE Coef        T      P
Constant       1.08593    0.00283   384.10  0.000
SFATX      -0.0008771  0.0002184    -4.02  0.000

S = 0.0138227   R-Sq = 7.3%   R-Sq(adj) = 6.9%

Analysis of Variance

Source            DF         SS         MS      F      P
Regression         1  0.0030811  0.0030811  16.13  0.000
Residual Error   204  0.0389778  0.0001911
Total            205  0.0420589
```

Regression Analysis: HWDb versus SFMCX

```
The regression equation is
HWDb = 1.08 - 0.00116 SFMCX

Predictor         Coef    SE Coef        T      P
Constant       1.08344    0.00293   369.77  0.000
SFMCX      -0.0011601  0.0003912    -2.97  0.003

S = 0.0140589   R-Sq = 4.1%   R-Sq(adj) = 3.7%

Analysis of Variance

Source            DF         SS         MS     F      P
Regression         1  0.0017379  0.0017379  8.79  0.003
Residual Error   204  0.0403210  0.0001977
Total            205  0.0420589
```

Regression Analysis: HWDb versus GNX

```
The regression equation is
HWDb = 1.16 - 0.00230 GNX

Predictor         Coef    SE Coef       T      P
Constant       1.16363    0.02220   52.42  0.000
GNX        -0.0023017  0.0005776   -3.98  0.000

S = 0.0138304   R-Sq = 7.2%   R-Sq(adj) = 6.8%

Analysis of Variance

Source            DF         SS         MS      F      P
Regression         1  0.0030375  0.0030375  15.88  0.000
Residual Error   204  0.0390213  0.0001913
Total            205  0.0420589
```

Regression Analysis: HWDb versus GArX

```
The regression equation is
HWDb = 1.13 - 0.00160 GArX

Predictor        Coef    SE Coef      T      P
Constant      1.12635    0.01495  75.36  0.000
GArX       -0.0015950  0.0004655  -3.43  0.001

S = 0.0139625   R-Sq = 5.4%   R-Sq(adj) = 5.0%

Analysis of Variance

Source           DF         SS         MS      F      P
Regression        1  0.0022889  0.0022889  11.74  0.001
Residual Error  204  0.0397700  0.0001950
Total           205  0.0420589
```

Regression Analysis: HWDb versus GAfX

```
The regression equation is
HWDb = 1.12 - 0.00118 GAfX

Predictor        Coef    SE Coef      T      P
Constant      1.11584    0.01461  76.37  0.000
GAfX       -0.0011820  0.0004246  -2.78  0.006

S = 0.0140934   R-Sq = 3.7%   R-Sq(adj) = 3.2%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0015394  0.0015394  7.75  0.006
Residual Error  204  0.0405194  0.0001986
Total           205  0.0420589
```

Regression Analysis: HWDb versus GFaX

```
The regression equation is
HWDb = 1.09 - 0.000643 GFaX

Predictor        Coef    SE Coef      T      P
Constant      1.09348    0.01617  67.64  0.000
GFaX       -0.0006432  0.0005694  -1.13  0.260

S = 0.0143140   R-Sq = 0.6%   R-Sq(adj) = 0.1%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0002614  0.0002614  1.28  0.260
Residual Error  204  0.0417975  0.0002049
Total           205  0.0420589
```

Regression Analysis: HWDb versus GWX

```
The regression equation is
HWDb = 1.08 - 0.00036 GWX

Predictor       Coef   SE Coef      T      P
Constant     1.08161   0.02043  52.93  0.000
GWX        -0.000363  0.001166  -0.31  0.756

S = 0.0143552   R-Sq = 0.0%   R-Sq(adj) = 0.0%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0000200  0.0000200  0.10  0.756
Residual Error  204  0.0420389  0.0002061
Total           205  0.0420589
```

Regression Analysis: HWDb versus GchX

```
The regression equation is
HWDb = 1.12 - 0.000485 GchX

Predictor        Coef    SE Coef      T      P
Constant      1.12332    0.02034  55.23  0.000
GchX       -0.0004852  0.0002051  -2.37  0.019

S = 0.0141656   R-Sq = 2.7%   R-Sq(adj) = 2.2%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0011232  0.0011232  5.60  0.019
Residual Error  204  0.0409356  0.0002007
Total           205  0.0420589
```

Regression Analysis: HWDb versus GwaX

```
The regression equation is
HWDb = 1.13 - 0.000689 GwaX

Predictor        Coef    SE Coef      T      P
Constant      1.13190    0.01644  68.85  0.000
GwaX       -0.0006889  0.0001996  -3.45  0.001

S = 0.0139569   R-Sq = 5.5%   R-Sq(adj) = 5.1%

Analysis of Variance

Source           DF         SS         MS      F      P
Regression        1  0.0023206  0.0023206  11.91  0.001
Residual Error  204  0.0397383  0.0001948
Total           205  0.0420589
```

Regression Analysis: HWDb versus GHX

```
The regression equation is
HWDb = 1.16 - 0.000899 GHX

Predictor         Coef    SE Coef      T      P
Constant       1.15979    0.02011  57.67  0.000
GHX         -0.0008991  0.0002137  -4.21  0.000

S = 0.0137733   R-Sq = 8.0%   R-Sq(adj) = 7.5%

Analysis of Variance

Source            DF         SS         MS      F      P
Regression         1  0.0033595  0.0033595  17.71  0.000
Residual Error   204  0.0386994  0.0001897
Total            205  0.0420589
```

Regression Analysis: HWDb versus GthX

```
The regression equation is
HWDb = 1.11 - 0.000679 GthX

Predictor         Coef    SE Coef      T      P
Constant       1.11324    0.01916  58.12  0.000
GthX        -0.0006788  0.0003419  -1.99  0.048

S = 0.0142219   R-Sq = 1.9%   R-Sq(adj) = 1.4%

Analysis of Variance

Source            DF         SS         MS     F      P
Regression         1  0.0007974  0.0007974  3.94  0.048
Residual Error   204  0.0412615  0.0002023
Total            205  0.0420589
```

Regression Analysis: HWDb versus GCX

```
The regression equation is
HWDb = 1.12 - 0.00120 GCX

Predictor         Coef    SE Coef      T      P
Constant       1.12100    0.01824  61.47  0.000
GCX         -0.0011993  0.0004774  -2.51  0.013

S = 0.0141415   R-Sq = 3.0%   R-Sq(adj) = 2.5%

Analysis of Variance

Source            DF         SS         MS     F      P
Regression         1  0.0012624  0.0012624  6.31  0.013
Residual Error   204  0.0407965  0.0002000
Total            205  0.0420589
```

Regression Analysis: HWDb versus GAX

```
The regression equation is
HWDb = 1.10 - 0.00120 GAX

Predictor        Coef    SE Coef      T      P
Constant      1.10300    0.01651  66.82  0.000
GAX        -0.0011982  0.0007115  -1.68  0.094

S = 0.0142599   R-Sq = 1.4%   R-Sq(adj) = 0.9%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0005767  0.0005767  2.84  0.094
Residual Error  204  0.0414821  0.0002033
Total           205  0.0420589
```

Regression Analysis: HWDb versus BBiaX

```
The regression equation is
HWDb = 1.12 - 0.000997 BBiaX

Predictor        Coef    SE Coef      T      P
Constant      1.11856    0.02234  50.06  0.000
BBiaX      -0.0009967  0.0005137  -1.94  0.054

S = 0.0142280   R-Sq = 1.8%   R-Sq(adj) = 1.3%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0007619  0.0007619  3.76  0.054
Residual Error  204  0.0412969  0.0002024
Total           205  0.0420589
```

Regression Analysis: HWDb versus BBilX

```
The regression equation is
HWDb = 1.13 - 0.00196 BBilX

Predictor        Coef    SE Coef      T      P
Constant      1.13340    0.01647  68.83  0.000
BBilX      -0.0019571  0.0005533  -3.54  0.001

S = 0.0139376   R-Sq = 5.8%   R-Sq(adj) = 5.3%

Analysis of Variance

Source           DF         SS         MS      F      P
Regression        1  0.0024305  0.0024305  12.51  0.001
Residual Error  204  0.0396284  0.0001943
Total           205  0.0420589
```

Regression Analysis: HWDb versus DTCX

```
The regression equation is
HWDb = 1.12 - 0.00158 DTCX

Predictor        Coef    SE Coef       T      P
Constant      1.12423    0.01678   67.01  0.000
DTCX       -0.0015830  0.0005413   -2.92  0.004

S = 0.0140668   R-Sq = 4.0%   R-Sq(adj) = 3.6%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0016921  0.0016921  8.55  0.004
Residual Error  204  0.0403667  0.0001979
Total           205  0.0420589
```

Regression Analysis: HWDb versus DAPX

```
The regression equation is
HWDb = 1.10 - 0.00143 DAPX

Predictor        Coef    SE Coef       T      P
Constant      1.10483    0.01156   95.58  0.000
DAPX       -0.0014253  0.0005550   -2.57  0.011

S = 0.0141320   R-Sq = 3.1%   R-Sq(adj) = 2.7%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0013172  0.0013172  6.60  0.011
Residual Error  204  0.0407417  0.0001997
Total           205  0.0420589
```

Regression Analysis: HWDb versus WHX

```
The regression equation is
HWDb = 1.09 - 0.00189 WHX

Predictor       Coef   SE Coef       T      P
Constant     1.08905   0.00971  112.13  0.000
WHX        -0.001894  0.001326   -1.43  0.155

S = 0.0142874   R-Sq = 1.0%   R-Sq(adj) = 0.5%

Analysis of Variance

Source           DF         SS         MS     F      P
Regression        1  0.0004165  0.0004165  2.04  0.155
Residual Error  204  0.0416424  0.0002041
Total           205  0.0420589
```

Regression Analysis: HWDb versus WFX

The regression equation is
HWDb = 1.07 + 0.00008 WFX

Predictor	Coef	SE Coef	T	P
Constant	1.07446	0.01436	74.84	0.000
WFX	0.000082	0.001486	0.06	0.956

S = 0.0143585 R-Sq = 0.0% R-Sq(adj) = 0.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.0000006	0.0000006	0.00	0.956
Residual Error	204	0.0420582	0.0002062		
Total	205	0.0420589			

Table Z[1] Raw Data (*n* = 206) Date of Birth, Age, Race, Playing Position and Football Club

Participant Nº	Date of Birth	Age	Race	Playing Position	Football Club
001	13/06/1981	26	C	M	1
002	01/08/1981	26	C	M	1
003	16/04/1982	25	C	M	1
004	14/05/1984	23	C	F	1
005	26/03/1985	22	C	D	1
006	26/08/1983	24	C	D	1
007	05/12/1980	27	C	F	1
008	30/07/1987	20	C	M	1
009	13/10/1982	25	C	GK	1
010	03/06/1987	20	C	D	1
011	23/04/1986	21	C	F	1
012	06/01/1976	31	C	M	1
013	04/02/1984	23	NC	F	1
014	24/03/1984	23	C	M	1
015	30/01/1987	20	C	D	1
016	07/07/1982	25	C	D	1
017	20/05/1979	28	C	M	1
018	17/10/1986	21	C	M	1
019	25/06/1986	21	C	F	1
020	08/02/1984	21	C	F	1
021	13/08/1978	27	C	D	1
022	11/11/1976	29	C	F	1
023	03/10/1968	37	C	M	1
024	06/12/1985	20	C	GK	1
025	29/09/1975	30	C	D	1
026	23/05/1979	26	C	M	1
027	26/10/1971	34	C	D	1
028	01/09/1974	32	C	F	1
029	06/09/1979	30	C	M	1
030	01/11/1980	26	NC	D	1
031	02/10/1980	26	C	D	1
032	28/09/1972	34	C	D	1
033	29/01/1980	26	C	S	1
034	31/08/1983	23	C	D	1
035	25/06/1979	27	C	S	1
036	23/11/1975	31	C	D	1
037	30/08/1986	22	C	F	1
038	14/10/1986	22	C	M	1
039	01/04/1989	19	C	D	1
040	10/06/1983	25	C	M	1
041	10/02/1981	27	C	GK	1
042	28/05/1973	32	C	F	2
043	05/05/1985	20	C	D	2
044	23/06/1983	22	C	D	2
045	18/12/1969	36	C	M	2
046	14/06/1969	36	C	M	2
047	16/03/1987	18	C	F	2
048	13/05/1977	28	C	M	2
049	03/02/1967	38	C	F	2
050	04/10/1983	22	C	D	2

051	09/06/1980	25	C	F	2
052	18/09/1983	22	C	D	3
053	14/05/1984	21	NC	F	3
054	14/01/1976	29	C	M	3
055	29/04/1974	31	C	M	3
056	20/10/1980	25	C	D	3
057	17/12/1987	18	C	M	3
058	17/12/1987	18	C	D	3
059	30/12/1977	28	C	D	3
060	16/05/1979	26	C	GK	3
061	28/05/1983	22	NC	D	3
062	28/09/1982	23	C	M	3
063	03/03/1983	22	C	M	3
064	22/03/1977	28	C	D	3
065	10/09/1978	27	C	F	3
066	14/08/1986	19	C	F	3
067	10/10/1978	28	C	M	4
068	22/10/1985	21	C	D	4
069	24/01/1970	36	C	D	4
070	15/11/1971	35	C	D	4
071	18/11/1985	21	C	D	4
072	04/09/1985	21	C	M	4
073	19/03/1985	21	C	M	4
074	13/05/1979	27	C	M	4
075	08/11/1985	21	C	M	4
076	17/07/1976	30	C	D	4
077	17/12/1985	21	C	GK	4
078	05/06/1979	27	C	F	4
079	16/09/1979	27	C	GK	4
080	30/09/1979	27	NC	D	4
081	27/07/1973	33	NC	F	4
082	08/10/1981	25	C	M	4
083	06/11/1981	25	C	F	4
084	27/01/1981	24	C	M	5
085	29/10/1985	20	C	D	5
086	26/01/1978	27	C	M	5
087	19/09/1972	33	C	M	5
088	18/09/1982	23	C	M	5
089	11/06/1980	25	C	M	5
090	21/02/1972	33	C	D	5
091	03/09/1985	20	C	M	5
092	04/06/1982	23	C	GK	5
093	02/12/1981	24	C	D	5
094	10/04/1970	35	C	D	5
095	12/04/1981	24	C	F	5
096	16/09/1977	28	C	D	5
097	03/06/1977	28	C	M	5
098	19/08/1986	19	NC	F	5
099	16/02/1982	23	C	F	5
100	20/09/1987	18	NC	F	5
101	19/11/1979	26	C	D	5
102	24/10/1974	31	C	F	5
103	03/12/1983	22	C	M	5
104	25/08/1981	24	C	F	5
105	16/08/1977	28	C	D	5

106	01/05/1987	18	C	M	5
107	20/12/1981	24	NC	M	5
108	05/12/1970	35	C	GK	5
109	25/08/1971	34	C	D	5
110	02/06/1984	21	C	CF	5
111	19/04/1983	22	C	CF	5
112	19/02/1988	18	C	D	6
113	17/02/1987	19	C	M	6
114	10/12/1988	18	C	F	6
115	03/12/1988	18	C	M	6
116	10/03/1988	18	C	M	6
117	30/12/1987	19	C	D	6
118	20/11/1987	19	C	GK	6
119	12/02/1988	18	NC	F	6
120	22/01/1987	19	C	F	6
121	17/11/1987	19	C	F	6
122	08/03/1987	19	NC	D	6
123	09/11/1988	18	C	D	6
124	21/10/1986	20	C	F	6
125	19/03/1987	18	C	D	6
126	22/07/1987	18	NC	D	6
127	27/11/1987	18	NC	M	6
128	05/01/1988	18	C	GK	7
129	24/03/1987	19	C	M	7
130	15/11/1986	20	C	D	7
131	14/10/1987	19	C	D	7
132	19/09/1987	19	C	M	7
133	10/12/1987	19	C	M	7
134	03/02/1987	19	C	F	7
135	25/07/1988	18	C	M	7
136	08/10/1986	20	C	D	7
137	07/10/1985	21	C	M	7
138	11/05/1986	20	C	GK	7
139	24/09/1986	20	C	D	7
140	27/11/1987	19	C	M	8
141	02/11/1987	19	C	M	8
142	16/10/1987	19	C	F	8
143	17/12/1987	19	C	M	8
144	27/09/1987	19	C	M	8
145	29/03/1976	31	C	M	8
146	04/06/1985	22	C	F	8
147	07/08/1987	20	NC	F	8
148	19/09/1981	26	NC	F	8
149	26/04/1985	22	C	GK	8
150	17/05/1986	21	C	D	8
151	17/10/1986	21	C	M	8
152	26/05/1985	22	NC	F	8
153	17/12/1985	22	C	F	8
154	12/01/1979	28	C	F	8
155	20/09/1983	24	NC	D	8
156	04/10/1987	20	C	D	8
157	26/12/1984	23	C	M	8
158	02/04/1982	25	C	D	8
159	13/05/1977	30	C	GK	8
160	08/09/1970	37	C	D	8

161	10/04/1986	21	C	M	8
162	10/09/1980	27	C	M	8
163	06/01/1987	20	C	D	8
164	16/03/1985	22	C	D	8
165	04/10/1987	20	C	GK	8
166	05/12/1981	26	C	D	8
167	15/11/1988	19	C	M	8
168	27/03/1987	20	C	M	8
169	08/05/1985	22	C	M	8
170	23/05/1975	30	C	M	8
171	15/11/1971	36	C	M	8
172	07/01/1987	20	C	M	8
173	21/02/1982	23	NC	F	8
174	11/02/1982	23	C	M	8
175	15/04/1980	25	C	M	8
176	24/12/1975	30	C	F	8
177	14/11/1975	30	NC	D	8
178	30/12/1982	23	C	F	8
179	09/05/1983	22	C	D	8
180	21/11/1982	23	C	D	8
181	08/01/1973	32	C	D	8
182	01/06/1980	25	C	D	8
183	08/03/1983	22	C	M	8
184	25/02/1983	22	C	M	8
185	06/04/1983	22	C	D	8
186	27/11/1983	22	C	D	8
187	13/09/1985	22	C	D	8
188	11/11/1983	22	C	S	8
189	28/09/1971	36	C	D	8
190	01/06/1984	23	NC	S	8
191	23/07/1987	18	C	D	8
192	21/06/1987	18	C	M	8
193	16/12/1986	19	C	F	8
194	12/10/1988	19	C	M	8
195	13/11/1983	24	C	F	8
196	17/10/1990	18	C	F	8
197	22/10/1985	23	C	M	8
198	06/05/1991	18	C	M	8
199	16/10/1980	28	NC	F	8
200	04/12/1989	19	C	F	8
201	10/10/1990	18	NC	D	8
202	24/07/1989	20	C	D	8
203	06/10/1980	28	NC	F	8
204	28/05/1973	37	C	F	8
205	17/05/1972	38	NC	F	8
206	04/01/1973	37	NC	M	8

Table Z^2 Raw Data (n = 206) Body Mass, Stretched Stature and Sitting Height

Participant N°	Body Mass	Stretched Stature	Sitting Height
001	74.2	177.3	90.1
002	81.0	182.7	95.4
003	83.5	189.0	97.8
004	77.5	177.3	89.1
005	76.4	179.4	91.5
006	98.9	187.0	95.5
007	80.4	180.1	90.2
008	73.2	169.2	79.5
009	85.5	187.2	94.9
010	87.2	190.8	100.5
011	81.2	177.8	94.2
012	75.2	171.1	87.9
013	64.2	162.7	86.7
014	72.1	175.6	87.5
015	72.6	182.0	94.1
016	83.2	182.1	90.5
017	85.9	188.3	98.1
018	66.4	182.2	95.2
019	75.2	172.8	96.4
020	62.4	168.2	91.1
021	74.0	172.7	96.5
022	72.8	170.5	92.5
023	83.6	183.6	96.7
024	95.0	190.0	97.1
025	77.5	183.0	96.4
026	76.8	179.3	98.2
027	75.6	175.8	90.1
028	86.1	179.1	95.1
029	82.5	186.2	97.0
030	93.7	190.1	98.0
031	77.1	177.0	90.1
032	91.4	190.8	100.4
033	72.9	172.1	89.4
034	90.0	185.9	98.9
035	84.5	180.3	94.6
036	81.0	188.5	99.1
037	69.2	176.6	94.5
038	73.3	178.6	93.4
039	82.4	186.6	98.1
040	78.9	172.8	90.3
041	89.8	186.1	98.7
042	102.3	192.5	101.2
043	78.5	178.2	96.8
044	92.5	192.4	97.5
045	82.0	176.7	93.8
046	91.1	182.7	94.5
047	71.6	180.5	94.2
048	73.6	176.3	92.7
049	82.6	179.3	94.1
050	75.9	179.9	93.2

051	69.0	168.9	86.5
052	85.4	170.3	88.4
053	72.5	172.4	89.1
054	70.3	175.2	90.3
055	78.0	174.7	89.2
056	78.2	177.4	91.0
057	69.0	171.4	82.3
058	82.0	180.3	94.1
059	80.0	179.9	92.4
060	94.6	180.6	93.5
061	85.1	175.4	82.1
062	65.9	169.5	86.3
063	82.0	187.3	96.4
064	77.0	177.7	94.3
065	72.6	174.3	90.8
066	77.0	178.0	93.5
067	83.9	185.7	94.7
068	80.4	187.4	98.9
069	90.2	180.4	94.2
070	88.4	189.1	98.2
071	83.3	182.4	95.6
072	75.0	172.5	89.5
073	73.6	184.1	95.1
074	74.2	171.8	89.1
075	78.5	180.1	92.1
076	88.0	181.1	95.6
077	82.6	191.6	100.5
078	80.9	182.8	98.4
079	104.2	201.2	109.4
080	79.3	178.6	90.2
081	80.0	172.2	89.5
082	96.7	188.8	94.9
083	91.4	193.5	100.7
084	80.5	187.0	97.5
085	64.6	186.9	86.8
086	85.5	183.4	99.2
087	73.2	176.4	95.2
088	81.2	188.3	99.9
089	78.9	175.1	93.5
090	80.5	181.5	97.3
091	76.1	183.5	95.5
092	90.0	187.1	97.9
093	72.8	172.4	92.6
094	89.3	195.0	102.1
095	90.0	184.0	97.2
096	82.0	179.9	93.2
097	80.2	179.8	96.4
098	71.6	172.9	88.7
099	92.4	188.6	100.2
100	72.9	178.5	91.9
101	76.1	172.3	93.5
102	77.1	188.7	96.1
103	88.0	179.3	94.9
104	79.8	180.9	96.7
105	78.7	179.3	91.2

106	80.0	184.6	95.6
107	79.9	177.1	87.9
108	83.3	174.2	85.4
109	78.1	178.2	88.4
110	74.1	170.9	79.5
111	70.6	169.6	79.8
112	64.0	170.9	90.7
113	70.9	174.6	94.7
114	67.7	180.2	92.7
115	79.9	178.0	92.7
116	74.5	181.2	95.0
117	85.1	193.9	100.8
118	78.2	188.8	99.6
119	68.5	175.1	90.2
120	77.9	179.2	94.6
121	77.2	187.8	98.8
122	86.4	183.7	94.2
123	73.9	186.0	98.6
124	76.0	188.5	97.9
125	68.6	170.2	90.2
126	81.8	184.2	91.8
127	60.0	180.6	88.4
128	76.1	192.2	101.0
129	74.0	178.3	88.3
130	79.8	180.5	97.5
131	76.0	180.3	92.1
132	64.6	176.8	91.0
133	59.4	170.9	89.7
134	72.4	179.1	94.9
135	68.7	174.5	92.9
136	74.2	175.4	86.4
137	77.0	176.2	87.1
138	76.8	175.7	86.4
139	74.5	172.7	83.6
140	67.0	171.6	90.6
141	74.0	176.5	94.3
142	61.5	170.9	92.3
143	63.8	180.2	96.0
144	77.3	181.6	96.0
145	73.3	173.7	93.5
146	71.7	181.2	95.1
147	69.2	172.4	88.7
148	96.9	188.3	96.3
149	93.4	187.3	97.1
150	93.7	187.7	99.7
151	77.1	185.9	98.7
152	78.1	185.2	96.4
153	76.7	177.2	89.7
154	77.5	188.1	95.1
155	94.3	186.6	97.4
156	78.4	184.6	98.4
157	82.3	179.3	92.9
158	85.4	188.2	97.1
159	94.7	190.9	98.9
160	78.3	179.1	93.8

161	75.1	176.8	91.9
162	69.4	170.5	85.4
163	79.7	187.9	99.0
164	78.9	178.0	93.9
165	81.3	181.5	89.9
166	83.6	177.4	84.6
167	80.6	181.1	94.6
168	73.5	179.3	95.6
169	77.5	171.9	90.4
170	84.0	181.6	94.3
171	63.0	176.8	89.7
172	77.5	185.7	97.9
173	83.2	187.8	95.9
174	76.7	173.4	90.6
175	83.5	181.1	95.8
176	82.8	182.4	98.7
177	81.8	180.1	92.8
178	72.0	169.3	94.0
179	75.1	179.9	92.5
180	89.0	187.2	104.0
181	88.2	188.2	100.0
182	79.2	188.3	96.8
183	60.0	167.4	85.4
184	71.0	173.3	90.1
185	84.3	187.4	97.9
186	82.1	183.4	98.4
187	86.8	187.5	96.7
188	81.2	167.4	86.4
189	64.5	163.4	84.0
190	84.6	163.8	89.1
191	79.8	186.5	86.1
192	71.5	173.8	94.4
193	67.9	172.9	92.6
194	73.0	182.5	98.5
195	72.0	176.7	90.0
196	73.2	183.0	84.7
197	80.9	177.9	90.2
198	73.7	179.1	92.6
199	89.9	187.2	97.3
200	69.9	165.2	85.5
201	64.5	170.1	87.5
202	95.6	199.5	101.1
203	77.0	178.8	88.0
204	95.0	184.2	102.0
205	88.5	184.6	90.2
206	74.7	174.1	90.8

Table Z^3 Raw Data (n = 206) Hydrostatic weighing trials

Participant N°	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10
001	3.31	3.64	3.82	3.62	3.94	3.95	-	-	-	-
002	2.64	2.89	3.26	3.76	3.70	3.81	-	-	-	-
003	4.47	4.38	4.37	4.48	-	-	-	-	-	-
004	3.24	3.60	3.53	3.56	3.55	3.22	-	-	-	-
005	3.72	3.72	3.63	3.91	4.13	4.10	4.16	-	-	-
006	4.83	5.35	5.34	5.37	3.78	5.41	-	-	-	-
007	1.65	2.77	3.32	3.13	3.68	3.69	-	-	-	-
008	4.26	4.24	4.23	4.32	4.18	-	-	-	-	-
009	3.15	3.30	3.24	3.18	3.11	3.14	-	-	-	-
010	4.38	4.64	4.62	4.76	4.56	4.38	-	-	-	-
011	4.80	4.71	4.84	4.83	4.94	4.66	-	-	-	-
012	3.74	3.70	3.76	3.75	3.90	3.69	-	-	-	-
013	4.19	4.10	4.34	4.22	4.28	4.31	-	-	-	-
014	5.63	4.57	4.55	4.65	4.53	4.55	-	-	-	-
015	2.92	3.14	2.99	3.13	3.05	-	-	-	-	-
016	4.22	4.35	4.73	4.20	3.11	-	-	-	-	-
017	1.26	4.34	4.32	4.15	4.32	-	-	-	-	-
018	5.83	6.23	5.65	5.79	5.79	4.26	-	-	-	-
019	4.22	4.21	4.28	4.18	4.18	4.23	-	-	-	-
020	4.18	4.16	4.20	4.18	4.26	-	-	-	-	-
021	3.87	3.88	3.88	3.89	-	-	-	-	-	-
022	3.72	3.82	3.97	4.01	3.82	4.01	-	-	-	-
023	3.91	4.11	4.17	4.29	4.37	4.31	-	-	-	-
024	3.52	3.76	4.45	3.72	4.40	3.87	4.41	-	-	-
025	2.21	2.47	3.52	3.70	3.74	3.64	3.70	3.61	-	-
026	1.72	3.11	3.42	3.64	-	-	-	-	-	-
027	2.87	2.91	3.34	3.38	3.37	-	-	-	-	-
028	2.51	2.54	2.62	2.58	2.62	2.61	2.52	-	-	-
029	4.22	4.30	4.32	4.44	4.42	4.40	-	-	-	-
030	1.98	1.93	2.18	2.07	2.24	2.47	2.38	-	-	-
031	2.91	3.03	3.19	3.22	3.15	-	-	-	-	-
032	3.22	3.48	3.91	4.10	4.14	3.92	4.12	4.02	3.98	-
033	3.87	3.91	4.06	4.01	4.10	4.12	3.88	-	-	-
034	1.72	2.42	2.74	2.83	2.92	2.81	2.99	2.44	-	-
035	4.32	4.51	4.29	4.60	-	-	-	-	-	-
036	4.21	4.24	4.17	4.36	4.37	4.29	4.36	-	-	-
037	2.42	2.51	2.66	2.55	2.64	2.72	3.01	-	-	-
038	2.90	3.10	3.00	3.10	3.60	3.85	3.84	3.96	-	-
039	5.00	4.95	5.02	5.60	5.70	5.65	5.60	-	-	-
040	2.50	2.51	2.52	2.50	2.52	2.47	-	-	-	-
041	3.51	3.68	3.76	3.74	3.74	3.78	3.69	-	-	-
042	4.27	4.28	4.33	4.33	4.33	-	-	-	-	-
043	3.08	3.24	3.70	3.81	3.74	3.69	3.71	3.58	-	-
044	3.01	3.12	3.18	3.27	3.28	3.20	-	-	-	-
045	3.82	4.22	4.55	4.51	4.40	4.52	4.42	-	-	-
046	3.91	4.07	4.28	4.12	4.21	4.31	-	-	-	-
047	1.97	2.19	3.50	2.98	3.41	3.12	3.45	-	-	-
048	3.21	3.37	3.41	3.53	3.51	3.43	3.55	3.11	3.07	-
049	4.16	4.28	4.22	4.37	4.41	4.32	-	-	-	-
050	3.31	3.42	3.48	3.54	3.52	3.41	3.54	-	-	-

051	4.42	4.48	4.52	4.54	4.54	-	-	-	-	-
052	4.01	4.08	4.18	4.30	4.27	4.31	4.10	-	-	-
053	4.00	4.10	4.12	4.12	4.15	4.13	-	-	-	-
054	3.10	3.32	3.42	3.49	-	-	-	-	-	-
055	3.27	3.32	3.45	3.44	3.31	3.47	3.38	-	-	-
056	3.12	3.18	3.21	3.40	3.37	3.28	3.45	3.18	3.12	-
057	3.94	4.07	4.22	4.31	4.12	4.20	4.17	-	-	-
058	3.99	4.24	4.38	4.21	4.32	4.28	-	-	-	-
059	3.92	4.07	4.12	4.30	4.44	4.38	4.21	-	-	-
060	1.97	2.91	4.38	4.18	4.07	4.30	4.21	4.41	-	-
061	2.42	2.87	2.69	3.21	-	-	-	-	-	-
062	2.47	3.03	3.14	3.19	3.12	3.24	3.30	-	-	-
063	3.86	4.14	4.38	4.45	4.81	-	-	-	-	-
064	3.07	3.22	3.31	3.12	3.38	3.30	3.71	-	-	-
065	2.91	3.01	3.07	3.34	3.34	3.30	-	-	-	-
066	2.08	2.27	2.15	3.42	3.40	2.81	3.44	2.74	-	-
067	4.49	4.48	4.50	4.65	4.57	4.55	-	-	-	-
068	4.24	4.32	4.62	4.38	4.71	4.47	4.51	4.74	-	-
069	4.28	4.24	4.40	4.48	4.57	4.60	-	-	-	-
070	3.20	3.30	3.21	3.34	3.30	3.38	3.31	-	-	-
071	4.07	4.45	4.49	4.58	4.60	4.63	4.63	-	-	-
072	4.12	4.30	4.25	4.20	4.17	4.20	4.24	-	-	-
073	3.17	3.54	3.67	3.92	3.97	3.96	3.94	-	-	-
074	3.01	3.12	2.28	3.31	3.36	3.41	3.34	-	-	-
075	3.09	3.47	3.42	3.51	3.52	-	-	-	-	-
076	4.70	4.78	4.79	4.78	-	-	-	-	-	-
077	4.18	4.24	4.36	4.31	4.34	-	-	-	-	-
078	4.95	5.07	5.18	5.20	4.91	4.63	5.01	5.10		
079	5.75	5.74	5.74	5.76	-	-	-	-	-	-
080	7.80	7.81	7.80	7.83	-	-	-	-	-	-
081	7.17	7.27	7.34	7.30	-	-	-	-	-	-
082	4.01	4.27	4.29	4.31	4.27	-	-	-	-	-
083	6.09	6.10	6.40	6.38	6.45	6.43	-	-	-	-
084	2.45	2.95	3.00	3.07	3.10	-	-	-	-	-
085	3.29	3.87	4.09	3.92	4.03	4.06	3.99	-	-	-
086	3.17	4.58	4.72	5.24	4.98	5.31	5.00	5.21	4.87	-
087	3.29	3.38	3.24	3.52	3.58	3.50	-	-	-	-
088	3.71	3.97	4.12	4.00	4.12	4.10	-	-	-	-
089	4.74	4.81	5.80	5.90	5.91	-	-	-	-	-
090	4.00	4.10	4.08	4.04	-	-	-	-	-	-
091	4.12	4.24	4.22	4.28	-	-	-	-	-	-
092	3.03	3.21	3.24	3.80	3.89	3.92	-	-	-	-
093	3.58	4.12	4.52	4.52	4.61	4.80	4.60	-	-	-
094	3.87	4.39	4.28	4.34	4.42	-	-	-	-	-
095	3.17	4.02	4.32	4.33	4.12	4.38	-	-	-	-
096	3.23	4.21	3.82	4.02	4.44	4.44	4.49	-	-	-
097	1.97	1.86	4.02	4.41	1.92	4.45	3.72	3.12	-	-
098	2.41	4.07	4.15	4.09	-	-	-	-	-	-
099	3.28	4.02	4.35	4.41	4.32	4.51	-	-	-	-
100	4.19	4.22	4.54	4.59	4.51	-	-	-	-	-
101	1.87	3.10	3.25	3.52	3.61	3.21	3.65	3.59	3.14	-
102	3.02	3.11	3.18	3.30	3.30	3.34	-	-	-	-
103	2.41	2.68	2.72	2.63	-	-	-	-	-	-
104	3.28	3.51	3.12	3.58	3.60	-	-	-	-	-
105	3.23	3.47	3.60	3.59	3.68	3.42	-	-	-	-

106	3.98	4.03	4.07	4.21	4.35	4.30	4.31	-	-	-
107	3.07	3.13	3.41	3.49	3.24	3.38	-	-	-	-
108	4.32	4.64	4.60	4.58	-	-	-	-	-	-
109	3.31	3.60	3.42	3.63	3.58	-	-	-	-	-
110	3.47	3.49	3.99	3.82	3.90	3.41	3.95	3.58	-	-
111	2.97	3.11	3.03	3.41	3.49	3.45	-	-	-	-
112	2.94	3.18	3.41	3.97	4.02	3.62	4.10	-	-	-
113	3.28	3.79	4.10	3.84	4.21	4.28	3.98	3.92	-	-
114	4.21	4.74	4.72	4.90	4.81	4.95	4.98	-	-	-
115	3.90	4.00	4.30	4.30	4.32	-	-	-	-	-
116	3.92	3.91	4.07	4.21	4.19	4.15	4.20	4.10	-	-
117	4.21	4.37	4.24	4.80	4.89	4.91	2.75	-	-	-
118	3.02	3.12	3.39	3.36	3.40	3.48	-	-	-	-
119	2.75	2.89	3.72	4.43	4.54	4.71	4.82	-	-	-
120	1.02	3.50	3.50	3.54	-	-	-	-	-	-
121	3.03	3.48	3.42	3.68	3.61	3.12	3.70	-	-	-
122	3.28	3.21	3.61	3.64	3.60	-	-	-	-	-
123	2.91	3.68	3.75	3.99	-	-	-	-	-	-
124	2.19	2.75	2.31	3.10	2.95	2.87	-	-	-	-
125	4.24	4.16	4.62	4.70	4.65	-	-	-	-	-
126	1.02	3.97	4.12	4.31	4.30	4.35	4.16	-	-	-
127	3.10	2.87	4.00	4.12	3.62	4.10	4.22	4.17	4.20	-
128	3.24	3.24	3.30	3.36	3.30	3.38	-	-	-	-
129	2.73	3.18	3.51	3.47	3.60	-	-	-	-	-
130	2.92	3.18	3.32	3.39	3.40	3.41	-	-	-	-
131	2.84	3.10	3.21	2.17	3.48	3.21	3.49	3.58	3.67	-
132	1.24	3.17	3.24	3.28	3.88	3.90	3.24	3.84	-	-
133	3.18	3.12	3.19	3.22	3.20	-	-	-	-	-
134	1.97	3.42	3.90	3.67	3.79	3.81	3.87	-	-	-
135	2.17	2.03	3.12	4.42	4.50	3.47	4.42	3.32	4.57	-
136	3.70	2.12	3.24	3.50	3.41	3.60	-	-	-	-
137	2.75	2.20	3.10	3.28	3.42	-	-	-	-	-
138	3.60	3.65	3.75	3.75	3.97	-	-	-	-	-
139	1.24	3.20	4.00	3.70	-	-	-	-	-	-
140	4.15	4.42	4.51	4.50	4.54	-	-	-	-	-
141	2.13	4.00	4.10	4.12	4.10	4.10	-	-	-	-
142	3.64	3.70	3.67	3.78	3.95	3.98	3.92	-	-	-
143	4.48	4.50	4.54	4.53	-	-	-	-	-	-
144	1.18	3.60	3.47	3.41	3.40	-	-	-	-	-
145	3.13	3.17	3.42	3.52	3.42	3.53	-	-	-	-
146	3.22	3.25	3.42	3.38	3.29	3.55	-	-	-	-
147	4.92	5.12	5.16	5.12	5.13	-	-	-	-	-
148	7.01	7.24	7.06	7.03	7.02	-	-	-	-	-
149	3.70	4.42	4.49	4.33	4.35	4.51	-	-	-	-
150	6.02	6.08	6.10	5.99	6.10	-	-	-	-	-
151	3.53	3.50	3.65	3.62	3.57	3.51	-	-	-	-
152	3.95	4.42	4.25	4.25	4.30	-	-	-	-	-
153	3.96	4.33	4.26	4.30	4.31	4.44	-	-	-	-
154	3.14	3.37	3.27	3.30	3.27	-	-	-	-	-
155	2.91	3.73	4.32	4.23	3.93	4.27	-	-	-	-
156	1.48	1.34	2.58	2.82	2.19	2.74	2.18	-	-	-
157	4.45	4.75	4.61	4.43	4.71	4.71	-	-	-	-
158	5.06	5.23	5.25	5.36	5.34	-	-	-	-	-
159	1.31	2.65	2.44	1.24	-	-	-	-	-	-

160	3.24	3.34	3.36	3.33	3.28	-	-	-	-	-
161	4.27	4.29	4.25	4.23	4.43	-	-	-	-	-
162	3.98	4.05	4.12	4.06	4.13	4.12	-	-	-	-
163	3.76	3.72	3.78	3.98	3.96	4.16	4.09	-	-	-
164	4.71	4.81	4.76	4.67	4.65	-	-	-	-	-
165	3.73	4.35	4.27	3.91	4.11	-	-	-	-	-
166	3.72	4.05	4.02	4.03	4.06	-	-	-	-	-
167	3.51	3.66	4.01	4.12	4.00	4.10	-	-	-	-
168	3.26	2.33	3.34	3.34	3.46	-	-	-	-	-
169	3.28	3.10	2.93	3.11	2.95	3.11	-	-	-	-
170	4.01	4.10	4.20	4.25	4.25	4.22	-	-	-	-
171	2.27	3.97	4.28	4.39	4.52	4.27	4.38	4.51	-	-
172	1.20	3.02	3.47	3.31	3.22	3.28	-	-	-	-
173	2.12	2.79	3.16	4.07	4.52	4.70	3.72	4.61	4.80	-
174	2.74	3.02	3.10	3.14	3.12	-	-	-	-	-
175	4.20	4.20	4.22	4.23	4.20	-	-	-	-	-
176	3.71	3.24	3.92	4.30	3.70	4.30	4.52	4.37	-	-
177	4.40	4.38	4.42	4.44	4.45	-	-	-	-	-
178	3.12	3.80	3.89	3.42	3.91	3.99	-	-	-	-
179	4.07	4.28	4.21	4.29	4.27	-	-	-	-	-
180	3.24	4.01	4.10	4.30	4.40	4.27	4.30	4.12	-	-
181	2.51	2.47	2.53	2.51	2.57	2.48	-	-	-	-
182	1.87	3.27	3.49	3.42	3.45	-	-	-	-	-
183	3.10	3.24	3.38	3.27	3.12	3.37	3.40	-	-	-
184	3.27	3.60	3.64	3.62	-	-	-	-	-	-
185	2.74	4.20	4.05	4.01	4.02	-	-	-	-	-
186	2.17	3.80	4.34	3.74	4.32	4.37	4.42	-	-	-
187	4.38	4.38	4.40	4.41	-	-	-	-	-	-
188	1.29	2.12	3.31	3.27	3.40	2.74	-	-	-	-
189	2.81	3.45	3.17	3.40	3.50	3.43	-	-	-	-
190	4.07	4.15	4.20	4.20	4.23	-	-	-	-	-
191	1.17	3.10	3.62	3.24	3.46	3.48	3.40	-	-	-
192	4.10	3.70	4.20	4.60	4.30	4.60	4.55	-	-	-
193	2.72	3.15	2.89	3.40	3.70	4.50	5.10	5.01	5.09	-
194	2.72	3.40	3.46	3.49	3.44	-	-	-	-	-
195	2.30	2.75	3.01	3.27	3.51	3.50	3.55	3.52	-	-
196	3.99	4.22	3.93	3.85	3.97	-	-	-	-	-
197	0.43	0.36	3.52	3.39	3.43	3.94	3.54	-	-	-
198	2.91	1.06	1.94	1.34	1.99	2.20	1.73	-	-	-
199	1.89	3.05	3.07	2.59	2.58	2.71	-	-	-	-
200	0.69	1.63	1.13	1.12	1.06	1.14	-	-	-	-
201	4.92	4.88	4.43	4.66	4.60	-	-	-	-	-
202	1.24	2.18	1.67	1.56	1.95	1.42	-	-	-	-
203	3.39	3.53	4.01	4.14	4.31	3.95	-	-	-	-
204	0.13	0.43	0.10	2.74	2.81	2.61	2.63	-	-	-
205	5.83	3.88	4.34	3.82	3.86	3.93	3.98	-	-	-
206	3.14	1.04	3.05	3.34	3.30	1.23	-	-	-	-

Table Z^4 Raw Data (n = 206) Forced Vital Capacity and Residual Lung Volume

Participant N°	Forced Vital Capacity	Residual Lung Volume
001	4.483	1.08
002	4.379	1.23
003	6.098	1.71
004	5.137	1.44
005	4.977	1.39
006	6.451	1.81
007	5.212	1.46
008	4.486	1.26
009	5.506	1.54
010	6.638	1.86
011	5.538	1.55
012	5.247	1.47
013	3.481	0.97
014	4.560	1.28
015	4.323	1.21
016	4.709	1.32
017	6.421	1.80
018	3.625	1.01
019	5.528	1.55
020	4.805	1.35
021	4.587	1.28
022	4.249	1.19
023	4.236	1.19
024	5.891	1.65
025	4.569	1.28
026	4.827	1.35
027	4.332	1.21
028	4.666	1.31
029	5.031	1.41
030	3.601	1.01
031	4.635	1.30
032	5.105	1.43
033	5.479	1.53
034	5.287	1.48
035	4.251	1.19
036	4.720	1.32
037	4.826	1.35
038	4.773	1.34
039	4.852	1.36
040	4.779	1.34
041	5.200	1.46
042	6.461	1.81
043	4.429	1.24
044	4.547	1.27
045	4.977	1.39
046	4.753	1.33
047	4.208	1.18
048	4.817	1.35
049	5.443	1.52
050	4.112	1.15

051	4.509	1.26
052	4.989	1.40
053	5.225	1.46
054	3.838	1.07
055	4.644	1.30
056	5.020	1.41
057	4.496	1.26
058	5.831	1.63
059	4.966	1.39
060	6.344	1.78
061	4.082	1.14
062	4.592	1.29
063	5.116	1.43
064	4.717	1.32
065	4.408	1.23
066	5.148	1.44
067	4.894	1.37
068	5.762	1.61
069	5.440	1.52
070	5.493	1.54
071	5.063	1.42
072	5.321	1.49
073	4.762	1.33
074	4.408	1.23
075	5.799	1.62
076	4.624	1.29
077	5.468	1.53
078	5.959	1.67
079	5.772	1.62
080	4.528	1.27
081	4.186	1.17
082	6.332	1.77
083	6.117	1.71
084	5.622	1.57
085	5.105	1.43
086	4.050	1.13
087	5.081	1.42
088	4.624	1.29
089	4.936	1.38
090	3.927	1.10
091	4.239	1.19
092	4.074	1.14
093	4.666	1.31
094	5.257	1.47
095	5.526	1.55
096	4.096	1.15
097	5.870	1.64
098	3.752	1.05
099	3.440	0.96
100	4.569	1.28
101	5.105	1.43
102	5.586	1.56
103	5.105	1.43
104	4.496	1.26
105	5.244	1.47

106	4.208	1.18
107	4.018	1.13
108	4.966	1.39
109	4.998	1.40
110	5.860	1.64
111	4.166	1.17
112	5.060	1.42
113	5.257	1.47
114	4.967	1.39
115	5.225	1.46
116	4.849	1.36
117	5.212	1.46
118	5.081	1.42
119	3.519	0.99
120	4.135	1.16
121	4.387	1.23
122	3.763	1.05
123	4.094	1.15
124	4.966	1.39
125	4.520	1.27
126	4.114	1.15
127	4.064	1.14
128	5.622	1.57
129	4.870	1.36
130	2.105	0.59
131	5.751	1.61
132	4.018	1.13
133	4.964	1.39
134	5.148	1.44
135	4.936	1.38
136	5.816	1.63
137	5.139	1.44
138	5.212	1.46
139	4.336	1.21
140	5.081	1.42
141	5.113	1.43
142	5.177	1.45
143	4.936	1.38
144	4.291	1.20
145	4.353	1.22
146	4.800	1.34
147	3.279	0.92
148	5.160	1.44
149	5.182	1.45
150	7.321	2.05
151	6.128	1.72
152	4.069	1.14
153	4.411	1.24
154	4.709	1.32
155	6.183	1.73
156	4.820	1.35
157	4.883	1.37
158	5.569	1.56
159	4.569	1.28
160	5.128	1.44

161	4.816	1.35
162	4.526	1.27
163	6.257	1.75
164	4.635	1.30
165	4.902	1.37
166	5.511	1.54
167	5.233	1.47
168	4.603	1.29
169	3.742	1.05
170	5.304	1.49
171	3.647	1.02
172	4.956	1.39
173	4.257	1.19
174	5.837	1.63
175	6.291	1.76
176	4.753	1.33
177	3.678	1.03
178	5.200	1.46
179	4.492	1.26
180	5.386	1.51
181	5.139	1.44
182	5.319	1.49
183	3.995	1.12
184	4.769	1.34
185	5.274	1.48
186	4.186	1.17
187	3.826	1.07
188	3.837	1.07
189	4.450	1.25
190	4.236	1.19
191	5.160	1.44
192	4.461	1.25
193	5.429	1.52
194	5.300	1.48
195	4.924	1.38
196	4.603	1.29
197	3.784	1.06
198	4.773	1.34
199	3.896	1.09
200	4.397	1.23
201	3.204	0.90
202	5.407	1.51
203	4.816	1.35
204	4.911	1.38
205	4.122	1.15
206	3.948	1.11

Table Z^5 Raw Data (n = 206) Air Displacement Plethysmograph

Participant N^o	Body Volume (L)	Body Density (kg/L)
001	68.6	1.080
002	75.2	1.070
003	76.9	1.080
004	73.2	1.060
005	70.6	1.080
006	93.2	1.060
007	75.2	1.070
008	67.8	1.080
009	80.0	1.070
010	80.7	1.070
011	74.4	1.080
012	71.1	1.060
013	58.9	1.080
014	65.2	1.080
015	67.0	1.080
016	77.0	1.080
017	79.9	1.070
018	60.2	1.070
019	69.9	1.070
020	67.9	1.080
021	68.1	1.080
022	68.7	1.070
023	80.2	1.070
024	88.3	1.070
025	71.8	1.070
026	72.4	1.070
027	74.2	1.060
028	75.1	1.060
029	81.7	1.070
030	87.9	1.070
031	73.2	1.070
032	82.9	1.070
033	67.1	1.080
034	80.6	1.070
035	77.1	1.070
036	79.3	1.070
037	64.4	1.070
038	68.2	1.070
039	76.5	1.070
040	74.8	1.050
041	83.0	1.082
042	81.1	1.070
043	72.8	1.070
044	79.7	1.070
045	82.6	1.070
046	84.2	1.070
047	74.5	1.060
048	69.1	1.070
049	82.7	1.070
050	80.2	1.060

051	60.8	1.070
052	83.6	1.070
053	76.6	1.070
054	76.2	1.070
055	74.8	1.060
056	74.1	1.060
057	80.1	1.070
058	81.8	1.070
059	82.2	1.070
060	84.8	1.070
061	81.3	1.070
062	77.2	1.060
063	81.3	1.070
064	74.6	1.060
065	75.2	1.060
066	76.3	1.060
067	81.6	1.070
068	82.4	1.070
069	80.5	1.070
070	74.6	1.060
071	72.4	1.070
072	70.6	1.070
073	72.9	1.070
074	76.2	1.070
075	75.7	1.070
076	78.9	1.080
077	79.2	1.070
078	74.2	1.080
079	89.1	1.070
080	88.7	1.080
081	89.1	1.080
082	80.2	1.070
083	84.9	1.080
084	75.8	1.070
085	68.3	1.060
086	88.1	1.080
087	69.7	1.070
088	75.1	1.070
089	83.2	1.080
090	75.9	1.070
091	70.3	1.070
092	86.2	1.070
093	63.3	1.080
094	88.4	1.070
095	80.5	1.070
096	80.3	1.070
097	76.7	1.070
098	74.5	1.060
099	88.7	1.070
100	65.1	1.060
101	80.4	1.060
102	74.4	1.060
103	73.7	1.050
104	75.7	1.070
105	76.1	1.070

106	76.8	1.070
107	74.2	1.060
108	80.5	1.070
109	73.3	1.060
110	70.2	1.070
111	72.9	1.060
112	70.7	1.060
113	70.1	1.070
114	63.8	1.080
115	77.3	1.070
116	70.2	1.070
117	78.3	1.080
118	72.0	1.070
119	62.2	1.070
120	72.4	1.070
121	71.8	1.070
122	79.7	1.070
123	68.9	1.070
124	72.7	1.070
125	70.4	1.070
126	80.2	1.070
127	68.3	1.070
128	71.8	1.070
129	69.3	1.070
130	74.0	1.060
131	74.1	1.060
132	77.6	1.060
133	73.2	1.060
134	76.2	1.060
135	61.3	1.070
136	68.3	1.070
137	74.6	1.060
138	77.4	1.070
139	76.1	1.070
140	62.3	1.070
141	70.6	1.070
142	64.8	1.060
143	59.2	1.070
144	72.8	1.070
145	68.5	1.070
146	65.6	1.090
147	63.1	1.090
148	89.6	1.080
149	88.1	1.070
150	86.8	1.080
151	71.9	1.070
152	72.2	1.080
153	70.4	1.090
154	71.9	1.070
155	88.3	1.070
156	72.5	1.080
157	76.1	1.080
158	78.9	1.080
159	88.4	1.070
160	74.1	1.060

161	69.2	1.090
162	63.5	1.090
163	73.3	1.080
164	72.7	1.090
165	75.5	1.070
166	78.5	1.070
167	74.7	1.080
168	68.3	1.080
169	72.6	1.070
170	78.0	1.070
171	58.4	1.070
172	72.0	1.070
173	76.0	1.080
174	72.8	1.070
175	78.2	1.070
176	80.0	1.070
177	82.6	1.070
178	68.9	1.070
179	70.1	1.070
180	88.4	1.070
181	74.4	1.050
182	74.0	1.060
183	73.9	1.060
184	73.2	1.060
185	78.6	1.070
186	79.8	1.070
187	82.1	1.070
188	74.6	1.060
189	82.7	1.060
190	77.9	1.070
191	74.0	1.060
192	65.2	1.080
193	63.7	1.090
194	66.9	1.090
195	66.1	1.090
196	66.6	1.090
197	75.5	1.070
198	67.9	1.080
199	83.5	1.070
200	65.8	1.060
201	60.0	1.070
202	87.9	1.090
203	76.4	1.090
204	88.1	1.08
205	82.6	1.07
206	68.8	1.09

Table Z[6] Raw Data (n = 206) anthropometric skinfolds

Participant Nº	Triceps	Sub scapular	Biceps	Iliac Crest	Supra spinale	Ab dominal	Anterior Thigh	Medial Calf
001	6.2	8.0	3.9	15.2	10.2	15.1	13.8	5.4
002	5.1	9.4	3.2	21.0	11.8	16.2	13.7	4.5
003	7.0	8.0	3.9	10.7	6.3	9.5	11.1	5.8
004	6.0	10.2	2.9	19.8	8.9	15.1	15.1	9.8
005	8.8	8.3	3.5	16.2	9.3	13.7	12.1	5.8
006	11.2	13.4	4.3	8.5	15.0	21.1	13.3	8.3
007	4.3	6.9	2.5	12.0	9.8	21.8	11.2	4.8
008	5.7	13.0	3.4	14.7	8.9	15.8	12.5	4.8
009	8.3	7.8	4.0	19.9	13.9	23.1	15.4	9.1
010	8.3	10.1	4.4	10.9	5.7	11.3	12.1	8.3
011	4.8	7.1	3.7	10.5	7.9	10.9	11.5	3.7
012	6.7	9.3	5.6	24.4	14.8	20.5	13.8	6.4
013	4.6	8.0	2.7	11.5	7.0	9.1	9.8	4.3
014	3.9	7.0	2.8	8.1	6.2	7.7	7.4	4.5
015	7.3	10.5	4.9	5.1	12.9	5.3	15.2	6.8
016	7.8	10.0	7.2	23.3	9.9	22.0	17.9	5.2
017	5.9	9.1	3.4	10.7	6.1	12.2	11.1	6.1
018	5.8	7.1	2.9	8.3	5.4	7.3	7.3	4.5
019	7.9	8.1	3.8	11.3	7.9	14.1	15.0	7.7
020	4.0	6.8	2.8	7.2	5.8	7.5	6.4	4.0
021	6.7	10.1	4.3	18.6	10.8	22.5	11.1	6.0
022	5.5	10.1	4.5	26.9	11.5	26.6	11.6	4.2
023	9.2	11.0	5.6	17.2	9.8	22.7	15.1	7.0
024	13.3	9.2	5.5	14.5	7.1	9.1	20.7	15.7
025	4.4	8.9	3.8	12.7	7.0	12.0	7.1	5.8
026	7.1	11.0	5.1	26.0	12.1	29.9	10.0	4.5
027	8.2	14.4	3.8	25.5	17.5	32.8	11.4	5.6
028	8.4	10.5	5.0	22.0	11.1	20.1	16.0	6.3
029	9.5	7.7	3.4	21.9	12.1	13.3	20.4	6.3
030	7.1	9.5	3.7	20.5	8.0	16.5	18.0	6.3
031	8.5	8.3	3.1	16.8	9.8	15.3	8.7	3.1
032	9.9	11.8	4.3	21.9	16.9	16.2	17.9	6.1
033	4.1	6.2	2.9	7.5	4.8	7.5	7.0	4.1
034	10.5	9.0	3.1	11.5	6.8	12.5	14.1	6.4
035	6.8	10.3	3.0	11.5	7.0	10.4	8.0	6.9
036	4.9	10.7	4.0	28.3	14.8	20.9	5.9	4.6
037	13.7	11.1	4.8	18.2	10.1	13.1	12.7	8.0
038	8.3	8.7	4.5	18.9	9.7	14.5	16.0	4.9
039	12.6	10.8	6.2	17.2	10.8	16.7	16.4	10.5
040	12.1	16.4	5.5	27.9	20.1	29.1	11.4	8.3
041	5.2	11.5	5.0	6.7	10.1	14.8	9.8	9.1
042	9.5	17.5	6.5	34.0	18.0	34.4	10.7	6.8
043	12.0	11.1	4.1	15.6	7.1	11.5	11.4	6.5
044	6.4	10.8	3.1	19.1	7.8	13.1	11.6	5.4
045	9.4	11.3	3.6	17.0	8.6	16.1	12.6	6.0
046	14.7	12.8	4.5	26.8	8.9	19.7	19.2	11.9
047	13.1	9.5	4.5	18.6	9.4	20.3	19.7	7.7
048	7.7	8.6	4.1	12.2	8.3	14.6	18.8	6.4
049	8.4	8.5	3.7	10.7	7.3	12.0	12.2	4.8
050	11.1	10.6	4.2	14.8	6.4	11.9	15.2	8.5

051	6.9	9.1	3.0	11.8	6.5	11.2	9.0	4.5
052	13.6	14.0	9.9	23.8	14.7	22.0	14.0	12.2
053	10.1	13.4	8.6	16.2	11.3	14.1	16.8	10.5
054	12.7	12.3	11.0	15.9	12.3	18.1	16.4	11.8
055	11.1	12.1	8.2	18.4	11.7	18.0	11.1	9.0
056	9.9	14.0	8.6	16.6	11.1	13.9	11.3	9.4
057	13.0	12.9	9.5	16.2	12.0	14.5	17.1	13.4
058	15.5	17.7	10.1	21.7	19.8	32.2	16.4	14.2
059	13.0	16.6	9.5	27.3	18.5	31.2	16.1	14.3
060	13.1	13.1	8.6	15.2	12.1	17.2	13.8	10.0
061	15.9	16.1	9.8	25.0	13.5	19.2	17.1	12.7
062	10.3	14.7	9.1	22.0	12.4	17.4	10.4	9.5
063	13.2	14.5	9.0	23.3	16.0	19.4	15.0	13.8
064	12.9	15.0	8.3	25.0	12.5	22.9	19.2	10.0
065	13.0	12.8	9.8	16.8	12.6	17.8	16.0	10.8
066	15.9	13.7	9.1	18.9	12.0	13.2	16.1	13.1
067	8.4	13.9	4.3	19.5	10.9	25.8	12.0	8.4
068	8.7	11.5	2.8	20.3	9.5	17.9	16.2	8.4
069	12.6	15.1	3.8	39.2	17.5	28.4	27.0	10.8
070	13.9	14.5	8.5	38.1	24.4	31.0	22.2	8.3
071	6.9	8.5	3.7	9.2	7.1	11.1	13.4	4.8
072	7.9	7.9	3.1	10.0	6.5	8.5	8.4	6.8
073	10.2	10.4	3.3	20.1	11.4	17.6	10.7	7.1
074	13.8	10.5	3.4	20.1	9.3	19.0	16.9	9.5
075	16.0	10.1	5.0	18.2	11.0	16.0	19.1	11.0
076	8.1	11.4	3.8	19.2	10.3	18.4	8.7	4.4
077	8.4	8.7	3.8	17.3	9.0	12.0	12.4	10.1
078	5.1	8.3	3.1	6.7	5.3	8.5	7.5	5.4
079	3.9	8.3	5.1	9.7	5.8	7.2	7.7	5.6
080	5.9	11.3	3.1	10.3	7.3	10.3	7.4	5.1
081	6.3	9.9	3.4	15.8	8.3	11.7	6.2	3.1
082	7.8	15.6	6.2	25.1	16.4	24.3	15.8	9.9
083	10.0	10.2	6.8	19.9	12.2	22.8	19.7	7.7
084	8.2	10.0	3.4	14.1	9.0	14.1	15.1	6.1
085	6.5	9.5	2.8	15.1	11.1	14.0	10.4	5.8
086	4.6	8.1	3.1	9.5	5.3	9.0	7.1	4.6
087	4.7	6.1	3.0	7.2	6.3	6.5	6.7	5.5
088	7.3	7.7	3.0	11.6	9.3	11.9	11.0	6.0
089	4.7	8.0	3.3	16.1	9.8	14.0	8.1	4.5
090	5.3	8.9	2.8	12.6	8.2	9.4	9.9	5.8
091	5.1	9.2	3.4	10.9	7.2	9.8	6.3	6.2
092	7.9	10.7	4.5	15.5	11.3	15.1	7.1	6.1
093	5.1	8.3	3.3	9.1	6.3	9.4	6.3	6.4
094	4.7	7.7	2.8	12.8	7.7	11.9	6.7	5.4
095	8.5	10.1	4.0	13.2	8.5	13.0	10.5	8.4
096	7.1	14.7	3.3	21.2	14.8	24.3	15.5	8.8
097	7.4	11.0	3.6	14.6	9.5	14.4	8.7	5.5
098	7.4	10.0	3.6	10.7	9.3	11.1	11.2	7.2
099	8.4	10.9	3.4	13.9	10.2	15.7	14.8	9.0
100	4.5	7.8	3.1	6.0	4.1	7.4	8.2	4.7
101	7.2	11.0	3.2	14.6	10.0	25.3	11.4	6.1
102	10.9	10.3	2.6	14.3	9.7	10.6	12.1	6.6
103	6.1	15.5	3.1	18.0	13.1	15.5	8.0	8.7
104	9.0	10.1	2.5	14.3	7.1	11.5	13.6	3.9
105	7.2	9.0	3.8	10.8	8.5	12.4	13.5	7.1

106	8.4	9.9	3.6	11.2	8.8	12.5	11.9	4.4
107	12.4	12.5	5.3	20.1	12.4	15.9	16.5	8.1
108	10.1	14.5	6.0	12.4	9.8	22.1	16.3	5.0
109	10.0	9.0	5.1	16.7	5.9	13.0	7.5	6.2
110	7.9	10.2	4.9	15.2	11.2	9.8	13.3	7.7
111	12.1	11.1	7.1	22.9	15.3	19.4	15.0	10.3
112	8.4	8.5	3.2	13.0	8.5	11.1	8.5	5.0
113	6.8	10.5	3.8	14.2	7.0	12.9	10.7	7.0
114	8.0	6.1	3.0	7.5	5.0	6.7	10.0	4.5
115	10.6	11.5	3.7	16.1	8.6	12.5	8.3	7.0
116	8.0	7.8	4.0	10.0	7.4	9.8	8.4	6.1
117	11.4	14.0	4.2	23.7	11.6	24.1	9.6	10.0
118	6.7	7.3	2.8	8.1	6.0	7.3	9.5	8.0
119	5.2	7.9	2.8	9.9	5.4	6.6	6.0	4.1
120	12.6	9.9	4.3	15.0	8.2	13.9	8.1	7.2
121	6.5	7.8	3.1	12.8	6.5	9.8	9.6	4.8
122	6.8	9.5	3.5	11.7	6.3	14.1	12.0	7.1
123	6.5	8.0	3.7	15.1	7.2	11.2	8.9	7.6
124	8.7	9.2	4.1	13.0	6.7	10.7	11.5	7.5
125	7.4	9.3	3.8	13.2	8.0	12.5	7.1	5.1
126	8.3	8.6	3.8	11.9	7.1	13.2	10.5	8.1
127	5.0	7.8	3.3	7.7	4.6	7.1	7.0	4.1
128	5.6	7.8	2.8	11.8	8.3	12.4	9.7	5.5
129	9.2	7.2	5.6	17.3	7.4	12.1	8.3	6.7
130	17.1	14.2	8.5	30.0	20.1	32.5	29.5	13.9
131	12.0	12.0	5.0	19.6	15.9	12.4	20.5	11.3
132	10.5	11.9	7.9	11.0	10.0	10.8	12.4	9.4
133	11.0	10.0	6.2	18.4	13.1	12.2	14.9	8.1
134	10.5	11.5	7.2	14.4	9.6	11.1	11.0	8.9
135	6.8	8.7	3.3	9.5	6.8	8.7	9.9	6.9
136	8.5	9.6	3.9	17.3	7.5	13.1	17.7	8.0
137	12.8	11.7	9.9	24.1	12.2	22.5	24.0	13.1
138	7.9	11.4	4.9	19.4	7.2	13.1	11.9	6.9
139	8.3	10.7	4.8	20.4	9.8	16.0	17.2	7.1
140	10.1	7.3	4.6	8.7	5.1	8.9	17.2	10.8
141	9.1	7.9	4.0	9.3	5.5	10.2	10.4	7.1
142	7.1	9.0	2.7	9.6	6.8	7.8	7.3	5.5
143	4.2	6.9	3.9	7.3	5.0	8.8	6.7	4.1
144	4.3	8.2	2.5	8.8	6.2	9.2	8.5	5.3
145	5.1	7.7	2.1	15.8	8.3	14.9	14.8	5.4
146	6.7	7.9	3.8	9.7	5.5	12.1	8.1	6.5
147	4.8	8.9	3.5	5.1	4.5	5.6	6.8	4.1
148	5.9	9.6	3.1	8.6	5.7	9.8	11.6	7.8
149	12.2	10.2	4.1	15.8	9.8	18.1	14.5	9.2
150	7.7	9.9	3.2	13.5	8.5	6.0	9.5	4.1
151	10.8	8.7	2.9	17.1	9.5	14.7	22.7	5.7
152	4.4	8.3	3.5	11.3	5.8	13.1	6.7	5.0
153	5.4	8.3	2.6	11.0	7.0	11.4	6.4	3.0
154	6.2	10.9	3.0	19.1	10.5	19.9	11.3	5.5
155	11.2	10.3	2.8	20.0	8.7	17.5	12.6	5.5
156	5.6	13.0	3.5	18.1	8.5	15.2	12.6	9.5
157	7.3	8.9	4.1	17.4	9.7	19.2	11.1	6.4
158	5.2	7.5	3.5	3.8	6.2	10.1	8.9	5.6
159	7.9	10.4	2.7	20.8	15.3	18.4	9.1	4.7
160	5.4	14.6	4.7	21.3	14.1	21.8	10.9	6.0

161	9.4	7.5	3.9	10.1	5.5	12.0	16.5	5.1
162	6.2	8.1	4.0	18.9	8.9	16.3	12.3	5.4
163	6.5	8.0	2.3	9.1	5.5	11.8	9.7	5.2
164	4.9	7.9	3.8	10.9	5.9	7.7	6.7	5.1
165	6.8	9.0	3.1	12.4	7.9	11.7	20.0	10.9
166	18.1	16.0	9.7	22.1	19.4	10.7	16.3	10.2
167	5.6	10.8	5.5	17.9	11.8	11.5	10.1	7.1
168	8.5	7.5	3.0	8.7	5.8	7.6	20.1	8.9
169	13.3	14.5	3.7	25.1	15.9	23.3	23.7	13.8
170	6.9	9.6	3.9	10.9	26.5	17.2	7.7	4.1
171	12.5	12.8	5.5	15.3	12.8	6.3	13.1	5.5
172	9.5	9.5	3.3	12.3	8.7	9.8	12.7	5.5
173	4.0	6.6	3.2	5.0	4.4	5.1	4.5	3.9
174	5.3	9.0	2.7	21.4	14.2	22.5	9.2	6.3
175	9.6	11.4	3.1	22.3	13.1	20.4	12.3	6.8
176	5.8	7.5	2.5	13.4	7.0	11.8	15.3	5.7
177	9.1	10.5	4.1	10.9	6.8	9.9	8.0	4.9
178	8.0	10.9	3.2	11.9	7.1	15.6	11.7	6.8
179	5.5	6.8	2.7	7.5	4.4	6.8	5.9	4.5
180	7.9	11.8	3.5	21.1	12.0	14.9	15.4	9.0
181	7.9	12.1	4.6	21.4	13.3	17.9	11.9	5.2
182	8.4	9.9	6.4	20.2	13.0	14.5	10.0	6.5
183	11.6	9.2	4.7	18.6	11.3	9.3	14.8	6.3
184	11.7	15.3	7.5	22.3	11.2	18.6	10.8	7.3
185	7.6	12.5	5.0	20.2	8.1	14.7	13.0	7.1
186	7.6	11.0	5.5	19.3	11.4	13.6	15.6	6.6
187	12.4	12.1	3.8	19.8	12.1	16.7	11.4	5.4
188	6.5	8.0	3.9	9.9	6.4	9.4	8.9	5.8
189	8.4	10.9	3.1	4.7	11.1	20.3	12.8	4.9
190	4.3	9.1	4.0	5.7	5.4	6.9	5.8	4.1
191	16.4	13.1	10.0	18.0	12.7	16.3	19.8	11.1
192	5.5	7.7	3.1	8.9	6.4	6.0	6.9	5.2
193	3.9	6.9	2.3	9.3	5.9	11.2	9.1	7.5
194	6.3	6.9	3.5	8.1	4.7	5.6	8.7	4.7
195	5.4	6.5	2.7	12.3	5.3	8.9	5.1	5.2
196	5.3	7.1	3.0	7.4	5.1	8.8	6.9	5.5
197	9.5	9.7	5.7	15.8	11.5	17.0	11.8	7.6
198	4.8	11.3	4.9	14.4	10.8	15.9	12.8	7.6
199	6.8	8.9	3.9	16.3	12.2	12.7	9.5	5.5
200	12.3	9.6	3.9	25.5	15.7	18.0	11.2	7.3
201	3.8	9.0	11.5	17.5	8.0	9.5	13.6	9.9
202	8.4	10.3	4.0	11.3	7.8	13.6	13.2	6.4
203	3.7	6.8	2.7	5.9	4.3	6.5	5.3	3.5
204	7.9	12.8	3.7	15.6	10.9	15.0	6.9	5.5
205	6.7	11.8	4.5	26.9	19.7	17.5	10.7	8.3
206	4.3	7.7	2.7	9.3	5.2	10.5	5.2	3.9

Table Z[7] Raw Data (n = 206) anthropometric girths

Participant Nº	Neck	Arm (relax)	Arm (flex)	Fore Arm	Wrist	Chest	Waist	Hip	Thigh	Calf	Ankle
001	37.0	32.4	34.4	28.2	16.9	100.1	87.2	93.3	51.1	38.1	21.2
002	38.2	32.5	35.9	28.8	16.8	100.6	88.0	90.5	54.1	37.5	22.4
003	37.4	32.0	35.4	28.0	17.6	98.7	79.3	86.7	55.4	38.4	23.5
004	39.4	35.7	39.5	26.4	18.1	101.6	85.4	92.2	56.9	38.3	25.7
005	38.5	34.3	37.0	28.0	16.8	101.3	82.2	95.7	53.3	38.1	22.5
006	44.0	35.5	38.3	32.5	19.0	104.3	90.2	104.1	61.8	42.3	25.1
007	40.1	35.2	37.6	28.5	18.4	105.7	79.6	86.6	57.4	40.5	24.8
008	38.4	31.3	33.7	28.0	16.5	97.9	80.0	94.9	56.4	38.8	22.7
009	38.8	32.4	35.2	28.4	17.2	102.3	88.0	99.1	58.0	37.6	22.6
010	39.6	32.6	36.4	29.8	19.1	103.3	88.1	99.3	58.1	39.0	24.0
011	39.4	37.0	40.2	29.4	18.4	101.1	87.6	98.4	58.5	39.6	24.6
012	35.2	30.3	36.2	28.0	17.4	90.7	81.2	95.4	54.1	35.0	21.2
013	38.4	28.5	32.5	26.5	15.7	92.7	77.8	87.1	55.7	36.7	21.0
014	38.5	31.4	34.6	27.5	18.6	100.1	90.3	97.9	60.3	38.7	22.6
015	38.0	32.0	37.6	28.0	18.0	101.4	87.3	94.5	57.6	39.6	25.0
016	39.5	34.5	36.8	30.8	18.2	101.1	83.2	95.8	55.5	38.8	24.1
017	39.5	32.8	36.4	27.6	18.9	101.5	85.1	93.3	57.5	40.2	22.4
018	37.5	31.0	33.7	26.7	17.9	97.3	83.3	90.1	56.0	41.0	24.5
019	38.6	32.4	34.1	28.3	18.3	98.1	87.4	92.9	58.7	39.7	23.8
020	35.8	28.8	30.8	26.2	16.2	98.8	74.9	85.3	50.5	36.4	22.2
021	38.2	31.3	33.3	28.0	17.4	102.1	80.6	90.8	54.3	36.6	23.0
022	37.0	31.6	32.6	28.2	16.4	98.3	81.7	91.6	53.7	38.5	21.9
023	39.0	31.5	32.8	28.1	18.0	100.4	84.7	98.5	58.3	40.5	24.7
024	39.8	37.7	38.7	29.2	18.5	102.4	87.2	102.1	51.4	42.2	25.4
025	39.7	31.2	33.9	28.3	17.8	102.5	78.5	92.9	53.0	37.2	23.2
026	38.2	32.1	34.3	28.5	17.8	98.9	80.2	93.0	54.5	37.7	23.6
027	37.4	29.8	30.9	27.3	17.4	100.6	83.3	95.8	53.6	39.0	22.1
028	40.4	35.5	38.3	30.0	17.8	104.1	85.3	100.8	59.9	41.0	24.1
029	37.1	31.5	31.6	27.3	17.1	97.6	85.6	95.5	60.2	39.4	23.0
030	39.8	35.5	36.5	30.4	17.8	100.6	82.4	99.9	63.3	39.5	23.5
031	37.7	32.4	34.1	27.3	17.2	98.3	80.7	92.7	55.0	38.8	24.0
032	38.2	32.0	33.7	30.0	17.8	99.7	78.2	92.5	54.3	38.5	24.5
033	38.8	33.0	35.5	30.7	18.1	100.6	84.7	98.1	58.1	39.4	25.1
034	39.7	34.9	36.8	31.1	18.4	100.2	84.1	99.0	58.8	40.2	25.8
035	37.9	32.1	35.0	29.5	17.7	97.6	80.0	96.3	56.7	37.3	23.5
036	38.2	33.7	36.2	30.3	18.0	100.8	84.4	99.1	58.0	38.4	25.0
037	37.9	30.0	33.5	27.2	17.1	96.2	80.7	90.4	53.4	36.0	21.6
038	37.9	28.5	31.2	26.4	16.1	100.1	78.9	96.1	53.7	34.8	21.5
039	38.2	32.0	35.9	30.2	18.3	100.6	82.2	97.4	55.3	35.1	23.0
040	38.5	31.2	33.7	26.6	16.4	87.7	98.2	95.6	51.7	36.5	22.4
041	42.3	36.1	38.0	31.2	18.1	100.9	94.3	103.0	53.6	37.6	22.5
042	43.8	33.9	34.6	29.8	18.3	107.1	95.5	106.4	59.6	39.4	25.5
043	40.0	33.2	34.5	29.0	17.6	98.6	81.7	95.7	57.8	38.3	25.4
044	38.6	35.9	37.2	30.8	18.1	105.5	85.7	102.0	58.3	39.6	23.7
045	41.0	35.7	36.3	29.2	17.7	101.3	84.3	92.9	57.7	41.5	23.4
046	38.1	34.5	34.2	28.1	17.7	109.2	92.5	98.7	61.0	42.2	25.1
047	36.8	30.4	31.9	25.6	17.2	90.7	77.8	95.4	52.7	35.9	23.5
048	37.9	30.6	31.8	26.0	16.2	95.8	79.1	89.9	54.4	38.6	22.9
049	38.0	31.7	33.1	28.5	18.1	100.9	83.1	96.3	57.3	40.1	23.0
050	37.6	30.1	32.0	27.4	17.3	107.5	79.1	93.7	55.0	38.3	22.3

051	37.3	29.7	30.5	25.7	16.7	92.6	77.2	87.8	55.7	38.2	21.2
052	39.0	32.5	35.1	29.2	18.8	103.3	88.4	98.4	56.6	38.7	24.0
053	36.8	31.7	31.2	28.0	16.8	92.2	75.7	91.7	54.8	36.4	23.1
054	37.3	30.9	33.0	27.4	17.2	97.4	79.4	88.5	54.9	39.4	23.6
055	40.1	32.2	34.0	28.5	17.1	106.8	86.5	92.9	56.3	39.3	23.1
056	39.9	34.0	35.5	29.0	18.2	103.0	79.3	91.9	55.2	38.5	25.1
057	37.6	30.0	33.1	27.2	17.0	92.4	74.8	90.1	55.0	37.0	22.6
058	40.0	34.6	35.8	29.4	17.1	105.2	85.5	97.1	55.9	38.4	24.0
059	37.0	31.8	32.8	27.4	17.0	102.5	82.4	99.4	55.6	36.1	22.0
060	40.6	33.9	36.1	30.4	17.6	107.5	84.9	102.1	59.1	42.2	25.5
061	39.1	33.2	35.3	28.9	17.6	99.9	81.1	99.5	58.5	38.4	22.9
062	37.8	29.9	32.6	26.8	16.2	96.5	93.9	96.8	48.7	34.7	20.9
063	40.9	32.9	34.7	29.3	17.8	100.4	82.3	98.2	54.3	37.8	26.0
064	38.6	30.1	32.1	27.8	16.0	101.7	82.4	92.2	56.2	38.9	21.5
065	39.2	29.4	32.5	27.0	16.9	97.4	80.1	94.1	53.8	35.2	22.4
066	37.9	30.4	32.7	28.0	17.0	95.1	79.1	91.2	53.6	38.2	23.7
067	37.2	29.7	34.3	27.1	17.2	100.4	81.1	97.3	54.1	37.0	21.4
068	36.5	30.7	33.1	28.4	18.1	97.4	80.4	91.8	56.3	36.9	19.7
069	38.1	32.1	35.4	27.6	17.7	102.2	84.0	92.2	58.3	38.2	22.8
070	39.0	33.5	36.2	30.5	18.6	99.4	82.0	90.0	57.4	36.7	18.9
071	36.4	31.4	33.1	29.5	18.8	98.5	81.6	90.7	57.3	38.3	22.5
072	38.0	32.0	36.1	29.1	18.2	100.4	84.3	91.9	57.3	38.9	23.0
073	37.0	30.0	32.0	27.3	17.3	100.1	84.1	90.1	56.3	37.9	21.2
074	39.8	33.1	35.5	28.1	17.4	98.5	81.2	90.6	57.8	38.0	20.5
075	38.3	31.7	33.4	27.6	17.0	107.1	90.1	100.1	59.4	39.2	22.0
076	38.7	32.3	35.6	28.4	18.0	105.1	90.3	92.9	58.9	37.0	19.8
077	38.9	33.0	35.1	28.9	18.6	105.3	91.6	92.2	58.7	38.9	23.7
078	39.5	34.1	37.4	27.4	17.3	104.5	91.0	92.1	58.5	40.1	24.1
079	37.3	29.7	32.3	27.1	17.0	108.2	90.4	100.4	60.8	37.8	21.0
080	39.4	32.6	33.8	28.0	17.2	97.4	80.7	91.5	58.7	37.1	21.7
081	36.7	30.2	33.0	28.2	18.1	100.1	84.5	91.3	56.3	38.7	23.8
082	38.0	33.1	35.6	27.6	17.5	103.2	80.1	92.7	57.5	39.5	24.0
083	37.1	30.5	33.3	27.0	16.9	104.7	86.5	93.0	58.1	37.3	21.8
084	37.1	29.6	32.4	27.4	17.5	102.0	81.4	95.1	54.5	39.8	24.4
085	35.6	28.9	30.7	26.3	15.8	93.9	77.6	90.8	52.4	37.3	22.2
086	39.4	34.3	38.5	29.8	18.3	109.7	85.7	97.2	60.5	38.3	24.2
087	37.2	32.5	34.8	28.3	16.9	102.9	80.9	90.0	53.7	36.4	21.4
088	38.9	28.5	31.3	28.0	17.4	100.3	84.7	94.5	56.8	38.2	24.1
089	37.5	32.2	33.2	27.3	16.7	100.4	84.2	95.1	57.0	39.7	23.5
090	40.0	30.8	34.4	28.8	17.0	109.2	91.5	94.6	55.8	38.4	23.4
091	38.1	30.0	31.4	26.9	19.9	99.1	77.4	92.1	52.7	36.0	23.2
092	41.3	34.4	37.6	30.8	18.1	100.4	87.0	100.1	60.4	42.3	24.6
093	38.9	30.5	33.0	29.6	18.3	99.6	80.6	95.2	52.9	38.5	24.6
094	38.7	34.4	36.5	30.6	18.5	104.7	81.1	99.8	56.8	40.0	24.0
095	41.1	31.5	35.1	29.1	18.2	105.1	88.3	101.0	60.5	42.0	25.3
096	37.9	31.2	33.5	27.6	17.8	96.7	81.9	91.8	57.4	39.2	23.6
097	40.9	31.1	34.1	29.5	18.6	102.1	84.0	92.7	58.1	37.9	24.1
098	37.0	31.7	34.4	28.7	17.2	98.2	79.5	90.1	54.0	36.4	22.8
099	39.4	32.5	35.0	29.0	18.4	105.0	86.5	101.1	59.4	40.7	24.3
100	39.2	28.1	31.4	26.1	17.0	92.1	76.1	89.4	55.8	38.0	23.1
101	38.3	32.4	34.3	27.3	16.5	99.9	82.5	92.8	57.0	38.0	22.6
102	38.8	28.6	29.6	26.5	16.2	99.7	84.3	95.3	53.8	35.5	22.1
103	38.7	30.6	33.0	27.3	16.6	101.7	83.3	97.2	59.3	37.5	23.0
104	39.0	33.8	36.2	28.4	17.2	101.2	78.4	75.0	55.6	37.7	22.8
105	39.1	32.9	38.1	27.2	16.7	100.9	86.3	97.0	55.7	40.3	21.4

106	37.8	29.6	32.8	26.8	17.0	94.8	76.2	93.2	56.4	37.6	23.7
107	37.2	32.8	34.4	28.0	16.7	97.0	76.1	87.2	58.6	39.9	24.8
108	41.2	35.0	35.8	30.3	18.0	102.2	78.3	91.2	56.8	38.8	22.5
109	40.0	33.3	34.0	26.5	17.4	100.1	77.9	90.4	55.8	37.4	21.4
110	37.8	29.6	30.2	27.0	17.4	101.2	78.3	93.1	55.0	37.9	21.4
111	37.2	31.4	32.0	26.9	16.5	97.8	80.2	90.7	54.3	36.6	23.5
112	37.4	31.6	32.9	28.1	17.0	100.8	80.5	90.5	55.8	38.1	24.1
113	38.1	32.7	34.8	28.4	18.3	102.1	80.3	90.2	56.9	37.5	21.3
114	39.7	34.1	37.5	30.3	19.1	100.0	78.6	90.0	58.2	36.0	23.6
115	37.0	31.9	32.3	26.3	16.8	98.1	76.4	89.8	59.7	40.2	24.0
116	36.9	31.7	32.7	27.7	17.3	99.4	81.1	93.5	55.1	37.4	21.6
117	39.1	33.8	36.4	30.2	19.0	103.8	85.5	100.4	59.0	37.2	21.1
118	37.0	31.8	34.8	29.9	18.0	99.3	84.2	93.1	58.1	39.0	23.9
119	38.2	33.0	35.0	26.6	17.3	98.3	78.9	95.8	59.6	39.1	22.8
120	39.3	33.5	35.3	28.8	18.8	98.9	83.8	93.1	55.6	36.7	22.2
121	36.9	32.7	36.1	28.2	18.2	100.3	77.5	97.0	56.5	37.8	21.5
122	38.7	34.1	38.2	27.0	17.7	99.6	83.6	95.3	59.5	29.7	23.5
123	38.1	33.8	37.7	26.1	17.5	99.1	84.2	90.3	57.0	38.4	22.8
124	37.4	31.9	33.9	26.7	17.1	99.5	85.0	87.3	55.1	37.5	21.3
125	38.5	34.2	36.9	28.5	18.7	87.1	75.8	85.2	59.2	36.6	23.5
126	37.7	31.5	33.2	28.7	18.0	98.2	84.1	96.0	56.0	38.0	22.1
127	38.9	32.1	35.7	27.1	19.2	99.6	86.2	96.6	55.1	39.8	23.8
128	36.8	28.1	30.8	26.7	16.8	94.0	76.5	93.4	52.0	36.4	23.1
129	36.0	30.4	32.2	27.5	17.9	99.1	77.2	90.2	56.9	39.0	24.7
130	37.2	31.8	33.7	27.9	17.8	100.1	79.4	97.1	59.5	38.4	23.9
131	36.7	28.9	32.5	26.7	17.4	98.0	86.4	93.2	58.1	38.0	23.7
132	37.2	29.7	31.6	27.8	16.3	86.4	71.3	85.2	52.8	36.3	21.7
133	34.4	27.7	29.4	24.1	15.6	86.0	74.6	88.1	51.2	34.4	21.0
134	38.2	30.4	32.1	26.7	16.6	94.4	76.5	92.5	55.5	38.5	23.7
135	36.4	29.0	30.8	26.1	17.0	96.5	76.5	91.6	51.5	33.9	21.7
136	36.6	28.5	30.0	27.0	16.9	93.1	75.7	90.1	49.9	33.9	21.6
137	39.0	31.8	34.6	27.7	18.1	96.6	76.7	91.2	56.1	39.5	24.7
138	38.0	29.1	30.8	27.0	16.6	94.6	76.1	89.6	50.2	38.6	23.0
139	40.1	32.5	34.8	28.2	17.8	100.3	82.9	92.1	56.3	37.4	24.1
140	36.2	28.7	30.4	26.1	17.5	91.1	79.3	88.1	51.7	34.5	22.6
141	37.0	29.7	31.8	28.2	17.5	97.6	74.4	92.9	53.2	37.0	22.8
142	36.4	27.9	29.5	26.0	17.3	85.2	70.8	92.3	49.6	35.0	21.7
143	36.6	28.0	30.3	26.0	16.6	92.7	72.4	85.3	48.9	35.2	22.4
144	37.4	31.9	34.5	29.1	18.4	97.9	77.5	90.1	55.3	39.6	24.5
145	35.3	29.5	32.7	27.2	17.1	96.5	98.6	88.5	53.5	38.7	23.5
146	37.4	28.4	29.8	25.6	16.0	94.4	78.3	83.1	53.1	34.4	21.5
147	37.6	31.7	35.3	39.4	16.7	97.9	75.0	84.4	55.0	35.0	21.2
148	42.1	34.6	38.7	32.7	18.5	106.3	83.6	102.0	63.0	41.9	24.9
149	39.1	34.9	36.5	30.7	18.5	102.1	85.2	96.3	57.7	40.5	24.9
150	40.7	34.2	37.5	30.6	19.3	105.1	84.8	99.7	55.8	39.0	24.1
151	36.9	27.7	30.0	27.4	17.2	94.2	76.7	93.5	52.5	34.9	22.8
152	36.8	32.6	34.4	28.0	17.1	90.2	74.3	92.5	54.8	38.6	22.3
153	38.4	30.8	34.1	27.8	17.4	94.1	76.1	94.9	53.0	38.4	21.4
154	38.7	31.6	36.8	27.5	16.0	94.6	84.7	93.3	51.5	35.7	21.7
155	36.9	32.7	36.5	28.6	18.2	105.7	84.3	106.9	62.5	40.1	24.9
156	39.2	28.5	30.7	27.0	17.3	97.1	79.7	94.5	51.4	36.7	21.5
157	39.2	33.0	36.1	29.3	18.4	103.9	86.3	97.1	54.8	39.5	24.5
158	40.2	35.5	36.7	29.5	17.5	102.2	86.3	97.2	54.7	37.2	22.0
159	41.3	34.5	36.3	29.4	18.2	108.3	86.7	102.2	59.5	41.3	23.7
160	38.6	31.2	33.9	28.2	17.0	100.1	84.7	97.0	55.4	38.4	22.3

161	36.9	32.4	36.3	29.2	17.3	101.7	79.6	95.8	52.8	36.5	23.0
162	37.0	31.6	34.2	28.7	17.5	96.7	79.2	92.2	58.2	41.0	22.0
163	38.9	31.1	33.8	28.4	17.7	103.0	74.9	85.8	55.9	38.2	24.3
164	38.9	32.6	34.9	29.2	17.6	98.7	81.0	94.7	56.5	38.5	23.5
165	37.1	31.8	32.5	27.5	17.4	96.2	75.2	94.2	55.8	39.4	22.7
166	39.1	33.6	35.8	28.6	17.0	98.9	79.1	96.1	56.7	39.2	22.0
167	37.2	31.4	33.6	28.3	16.3	97.6	83.7	92.9	54.3	37.0	22.1
168	38.4	34.6	37.6	28.1	17.6	93.5	78.6	92.7	57.4	38.6	23.4
169	38.9	35.4	38.0	27.4	17.2	99.4	84.9	94.4	58.4	38.4	23.8
170	37.5	32.7	32.5	27.5	17.7	97.6	84.4	97.1	57.4	42.0	23.7
171	38.2	36.4	38.1	29.1	18.3	100.3	83.7	98.3	56.9	38.8	24.0
172	39.8	37.4	39.4	29.7	18.9	103.3	87.4	100.4	60.5	39.8	24.5
173	43.2	32.9	35.7	29.7	16.9	98.8	78.8	97.1	58.7	38.5	24.0
174	38.8	32.8	34.2	28.2	18.0	92.1	80.4	91.1	56.2	39.3	25.1
175	37.5	30.9	34.2	29.5	17.5	97.9	82.6	96.7	57.9	41.3	23.8
176	37.3	34.0	33.1	28.4	17.3	97.1	82.1	93.8	57.7	40.4	23.3
177	40.1	30.7	34.5	28.8	17.9	103.9	86.2	98.1	59.4	41.2	24.3
178	36.4	31.8	32.9	27.6	17.1	96.0	76.4	90.4	54.3	37.4	22.8
179	37.2	32.2	36.7	29.9	18.0	98.1	75.7	93.1	54.4	39.9	24.6
180	43.0	33.5	36.0	30.7	18.9	106.7	86.8	99.1	58.7	37.6	24.1
181	41.8	34.6	37.1	29.4	17.3	109.1	89.2	98.3	59.6	41.3	23.2
182	40.1	33.1	36.3	30.5	18.4	100.3	84.1	96.1	57.8	41.0	22.4
183	35.4	31.0	32.6	26.2	15.8	94.2	84.2	96.7	53.0	33.0	19.6
184	36.0	31.2	33.2	27.0	16.0	98.5	86.7	98.1	53.2	37.4	22.0
185	36.4	32.6	34.5	28.7	18.2	98.3	86.4	98.1	58.3	41.2	24.3
186	38.8	33.4	34.6	27.8	17.2	98.5	87.3	98.2	55.0	29.9	23.0
187	38.2	32.1	35.7	27.1	18.2	98.1	85.9	94.1	54.7	40.1	23.4
188	37.7	32.7	36.0	29.4	18.8	102.1	74.9	87.1	55.2	39.7	24.1
189	36.7	27.1	31.1	25.5	15.7	94.2	77.7	88.1	53.2	36.0	20.4
190	36.2	32.7	35.9	28.9	17.3	104.2	83.8	95.3	58.1	38.2	22.5
191	38.8	32.4	34.1	29.1	17.6	100.3	80.5	95.8	57.4	38.2	23.2
192	37.8	31.4	34.9	29.3	17.6	95.6	77.4	91.8	54.5	37.8	25.8
193	36.9	30.0	31.9	28.8	16.9	93.5	74.9	93.5	52.2	35.0	21.7
194	37.2	29.3	32.4	38.4	17.6	101.8	78.2	88.5	49.8	36.5	23.0
195	37.2	30.7	33.4	28.2	16.3	92.7	82.3	93.5	48.9	34.4	21.8
196	37.5	30.0	31.1	27.1	16.2	87.5	79.7	88.1	49.7	36.2	24.6
197	37.6	32.1	31.2	28.0	17.2	99.9	89.5	96.3	55.0	36.8	23.7
198	37.2	29.8	32.5	27.0	18.4	94.9	78.6	92.8	50.1	35.2	22.0
199	38.4	34.9	38.6	29.1	17.1	92.7	82.2	98.2	58.3	40.2	23.1
200	37.7	32.3	34.6	26.7	16.0	89.9	79.9	89.0	54.3	34.4	22.0
201	35.8	28.0	31.2	24.8	15.4	82.5	74.5	92.3	47.8	35.5	21.5
202	42.5	31.5	33.3	29.1	18.1	90.9	84.2	103.0	52.1	40.7	25.6
203	38.6	32.6	31.5	28.9	16.5	87.5	77.2	90.1	55.5	38.9	22.1
204	42.8	32.0	34.1	29.1	17.7	97.4	87.4	101.7	56.1	39.5	23.7
205	42.6	34.8	37.0	30.2	17.3	99.6	87.3	97.2	59.2	38.5	21.8
206	38.2	28.4	31.3	27.7	16.1	88.1	78.4	92.1	51.9	34.5	21.2

Table Z[8] Raw Data (n = 206) anthropometric breadths, depths and widths

Participant N°	Biacromial Breadth	Biliocristal Breadth	Transverse Chest Depth	A-P Chest Depth	Humerus Width	Femur Width
001	42.1	28.4	30.0	21.6	7.2	8.8
002	42.5	30.5	29.9	18.9	7.5	9.4
003	41.6	27.4	28.1	22.0	7.6	10.0
004	43.5	31.5	31.3	21.1	7.1	9.8
005	41.8	28.9	29.0	20.4	7.0	9.3
006	43.9	31.2	32.4	22.8	7.9	10.1
007	46.5	28.5	32.8	20.2	7.0	9.1
008	44.0	26.3	29.4	19.9	6.9	9.2
009	44.3	31.4	31.3	18.8	7.5	9.2
010	46.5	31.2	31.2	20.4	8.2	9.8
011	44.9	31.2	32.1	21.5	7.7	9.8
012	42.9	31.0	30.1	19.6	7.3	9.3
013	39.7	25.5	28.5	19.9	6.2	9.2
014	44.5	31.7	32.3	21.1	7.1	9.3
015	45.3	30.3	30.1	20.0	7.5	9.1
016	43.5	29.8	29.2	20.8	8.4	9.5
017	45.2	28.6	29.3	20.5	7.0	9.2
018	40.8	28.0	28.7	19.9	7.1	9.9
019	41.5	28.5	29.4	18.7	7.6	10.1
020	41.6	26.3	28.1	17.6	7.0	8.9
021	44.9	29.6	30.8	21.5	6.7	9.6
022	43.9	30.0	31.4	19.9	6.9	9.4
023	41.7	30.7	30.7	23.7	6.9	10.0
024	45.0	31.9	32.3	22.9	7.6	10.2
025	44.7	30.8	29.1	22.3	7.3	9.0
026	43.4	29.6	32.1	20.5	7.4	9.5
027	44.2	30.2	29.8	22.7	7.0	9.3
028	43.9	31.4	31.8	21.9	7.2	9.6
029	44.2	30.9	32.2	19.4	7.3	9.9
030	43.8	27.8	30.7	20.6	7.0	9.8
031	40.4	28.3	30.1	21.1	7.0	9.9
032	40.8	29.7	30.7	18.7	7.2	10.2
033	41.5	31.1	30.1	21.7	7.1	9.8
034	41.2	31.7	30.0	18.9	7.6	10.2
035	41.0	31.1	30.2	21.5	7.0	9.9
036	41.7	31.5	30.5	18.8	7.1	9.9
037	42.1	26.8	27.1	20.3	7.0	8.8
038	41.6	28.3	38.1	18.7	7.3	9.3
039	42.7	29.2	29.4	22.5	9.6	9.2
040	41.0	31.6	31.4	22.0	6.3	9.2
041	44.5	31.6	33.7	22.8	8.0	9.6
042	44.1	33.8	34.7	24.3	7.5	10.7
043	43.1	29.3	30.7	20.1	7.0	9.7
044	46.4	30.7	31.6	20.9	7.6	10.2
045	43.6	28.6	29.4	22.0	7.5	9.9
046	42.9	30.3	31.7	24.8	7.1	10.3
047	39.7	30.5	26.2	19.9	6.8	9.2
048	40.8	27.3	29.5	20.4	6.4	9.3
049	44.9	30.0	29.6	21.0	7.2	10.5
050	41.4	28.3	28.1	20.2	9.7	6.9

051	40.6	26.2	29.4	17.5	6.6	9.5
052	44.6	32.6	31.2	22.9	7.5	10.4
053	42.8	28.3	30.1	19.5	7.1	9.9
054	40.8	28.7	29.1	21.2	6.7	10.0
055	44.7	30.5	34.6	21.0	6.8	9.5
056	45.2	28.6	30.6	19.9	6.9	9.9
057	41.2	27.2	29.1	19.4	6.9	10.3
058	44.2	30.2	32.1	20.2	6.7	9.9
059	44.0	30.7	31.3	21.8	7.4	10.1
060	47.4	32.5	35.6	23.5	7.8	10.2
061	45.3	29.7	32.3	18.9	7.0	10.7
062	41.9	27.4	31.3	19.3	7.0	9.3
063	44.0	32.5	32.5	19.0	6.8	9.7
064	44.9	28.8	31.7	21.9	7.1	9.8
065	40.6	29.0	30.4	19.3	6.8	9.9
066	40.5	27.6	30.3	18.8	7.5	9.4
067	41.3	30.2	32.0	22.8	7.6	9.0
068	42.4	29.4	30.8	20.9	8.0	9.8
069	42.1	30.1	31.1	20.9	6.7	9.2
070	41.6	29.6	29.0	20.7	6.9	10.1
071	40.8	29.3	29.1	23.7	8.0	9.9
072	41.8	30.3	30.8	21.0	7.1	9.2
073	41.5	30.0	31.8	22.0	6.8	9.1
074	42.8	29.6	30.2	19.1	7.6	9.4
075	45.1	30.8	33.1	20.5	10.1	10.4
076	45.1	30.6	32.1	23.7	6.8	9.2
077	45.5	31.0	32.7	21.3	7.1	9.3
078	44.2	31.1	31.4	24.1	7.1	9.2
079	45.3	31.5	35.2	19.5	6.9	9.4
080	40.7	30.0	28.8	19.1	10.3	9.4
081	42.3	30.7	31.1	19.9	6.7	8.9
082	44.1	30.8	32.4	20.1	7.6	9.0
083	44.9	31.1	32.6	21.4	7.0	8.9
084	44.4	30.3	33.0	22.8	7.6	10.1
085	39.9	27.4	28.1	19.1	6.2	8.5
086	48.4	29.9	31.2	24.4	7.4	9.8
087	42.9	30.0	31.1	21.5	7.2	9.0
088	43.5	29.3	29.5	21.5	7.1	9.6
089	44.0	29.9	31.2	21.0	6.5	9.5
090	46.4	30.3	34.7	21.8	8.0	10.2
091	42.9	27.7	30.3	19.8	7.2	9.5
092	46.9	31.5	31.3	22.7	8.1	9.2
093	43.0	30.4	28.6	25.5	7.0	9.8
094	45.2	30.6	30.5	21.9	7.0	10.4
095	44.8	31.4	31.3	23.6	7.4	9.8
096	42.1	29.8	30.0	21.4	6.7	9.5
097	43.5	29.1	31.0	20.9	7.7	9.5
098	41.7	27.5	28.8	21.7	6.9	9.4
099	44.4	30.8	31.4	22.5	10.1	7.7
100	42.9	26.6	29.2	19.6	7.0	9.4
101	43.0	30.4	31.9	20.2	7.2	9.3
102	43.2	31.3	32.0	20.4	7.6	10.0
103	42.1	29.3	31.1	22.6	6.9	9.9
104	45.5	30.4	30.9	21.1	6.9	9.2
105	42.9	30.1	30.8	20.1	7.2	10.0

106	40.7	31.4	31.1	19.8	7.5	9.7
107	44.7	30.1	31.2	20.3	7.5	9.6
108	45.3	32.1	31.2	20.5	7.7	9.5
109	43.5	30.6	36.3	20.0	7.4	10.0
110	43.9	30.0	31.8	20.2	7.1	9.5
111	42.9	31.5	30.9	19.4	7.4	9.5
112	43.6	31.2	31.0	19.7	7.0	9.6
113	43.9	31.1	31.2	20.1	7.4	10.5
114	44.1	29.9	30.9	19.0	6.7	8.5
115	44.9	30.0	31.9	20.4	7.1	9.3
116	45.5	32.0	32.4	21.5	8.0	10.6
117	44.9	31.4	31.0	22.4	7.0	9.6
118	44.0	32.0	30.5	19.7	7.6	10.0
119	45.1	32.4	31.4	22.1	7.4	10.1
120	42.1	30.6	31.6	20.7	7.1	9.5
121	44.5	27.9	32.7	22.3	7.5	10.3
122	44.0	31.4	30.5	20.6	6.7	8.7
123	43.8	31.1	30.1	19.5	7.5	10.0
124	44.1	31.2	30.6	21.7	7.1	9.4
125	43.6	29.9	30.0	19.4	7.0	9.0
126	44.0	31.2	30.1	22.0	7.0	8.5
127	45.2	32.0	32.7	20.5	7.4	9.6
128	44.2	29.5	30.6	18.0	6.8	9.6
129	43.5	29.9	32.2	17.8	7.5	10.1
130	41.9	27.8	30.6	21.8	6.9	10.0
131	41.7	27.4	30.4	20.4	6.9	10.9
132	41.5	26.1	28.1	16.0	7.0	9.8
133	40.1	27.5	28.3	16.4	6.4	9.0
134	45.4	29.6	29.9	20.4	7.0	9.7
135	43.9	29.6	30.6	18.5	6.8	9.6
136	44.1	30.7	30.6	16.8	7.2	9.5
137	43.2	31.1	30.1	20.6	7.1	10.0
138	42.1	30.7	30.7	17.7	7.2	9.5
139	42.2	29.5	32.5	19.4	7.4	9.7
140	40.0	26.6	28.0	18.3	7.1	9.1
141	43.3	27.3	30.3	20.1	6.9	9.8
142	45.4	26.4	28.1	18.3	7.1	9.5
143	42.0	25.0	28.1	21.7	6.5	9.1
144	43.7	28.7	29.4	21.1	7.1	9.7
145	41.8	27.4	30.8	18.6	6.7	9.6
146	43.5	29.8	30.0	20.0	6.3	9.5
147	41.0	25.1	28.6	18.9	6.5	9.5
148	49.9	30.1	33.7	21.8	7.3	10.2
149	44.3	30.9	33.2	21.2	7.4	10.1
150	45.6	30.5	32.7	21.3	7.3	9.5
151	43.2	31.0	29.4	19.6	7.2	10.0
152	44.0	26.3	28.5	19.5	6.4	9.4
153	43.1	30.5	29.4	19.4	7.3	10.5
154	40.7	30.5	31.0	19.8	7.4	9.1
155	46.0	30.8	32.4	21.0	7.3	10.2
156	46.1	29.9	31.3	19.0	6.9	9.5
157	44.7	31.9	32.0	21.8	6.8	9.8
158	46.9	31.2	33.3	20.6	6.5	9.8
159	45.9	32.1	33.4	24.0	7.0	10.4
160	43.1	30.7	33.1	23.6	7.2	10.3

161	44.2	30.9	31.4	19.4	7.0	9.9
162	42.0	26.9	29.9	20.7	7.1	9.4
163	47.5	28.8	33.7	20.0	6.9	10.1
164	43.7	29.9	31.9	20.0	7.0	9.5
165	41.5	28.9	28.5	20.1	7.0	9.8
166	44.5	31.7	31.1	21.3	6.7	9.5
167	44.6	27.9	30.6	20.7	7.2	9.4
168	41.2	28.8	28.7	22.3	7.0	9.1
169	42.5	29.9	29.2	18.8	6.8	8.9
170	42.9	30.7	30.3	19.6	7.6	10.9
171	41.3	26.6	34.6	22.3	7.0	9.0
172	45.4	30.4	35.3	21.6	7.3	9.1
173	47.4	28.8	33.1	19.5	7.1	10.2
174	42.6	29.8	29.6	21.4	7.1	9.8
175	33.8	30.9	31.0	22.7	7.0	10.1
176	44.6	29.2	30.9	21.1	7.2	10.9
177	45.2	30.4	33.0	20.2	7.3	10.2
178	44.2	29.0	29.9	21.0	7.1	9.7
179	42.4	27.9	31.4	20.4	10.2	6.9
180	45.3	30.7	34.6	21.6	7.4	9.6
181	44.8	30.3	33.1	22.4	10.0	7.4
182	45.7	30.0	34.5	21.5	7.4	8.5
183	41.4	26.1	30.2	20.0	6.4	8.9
184	41.2	29.0	31.5	20.1	7.0	9.2
185	43.3	30.4	31.5	19.8	7.7	10.6
186	44.2	30.5	31.8	19.7	7.4	10.0
187	41.7	29.3	31.3	20.5	9.9	10.0
188	43.1	30.6	31.7	19.7	7.2	9.7
189	40.6	26.0	28.3	31.3	9.5	9.5
190	44.8	31.1	32.0	19.0	7.4	9.9
191	42.9	29.9	33.1	18.6	6.7	9.6
192	42.6	29.5	29.9	21.5	7.2	9.5
193	41.7	26.8	27.8	18.2	7.1	10.1
194	45.0	27.7	32.7	20.0	7.1	9.4
195	42.6	27.8	29.1	18.7	7.3	9.4
196	43.1	27.1	29.7	18.7	7.4	8.8
197	43.3	30.0	30.9	20.1	6.7	9.6
198	41.0	28.6	29.2	21.5	9.0	6.6
199	44.8	26.8	29.9	20.1	6.8	10.0
200	43.1	29.1	30.7	18.8	6.9	9.3
201	39.6	25.4	27.7	17.9	6.4	9.3
202	46.8	31.5	31.9	21.6	7.3	10.0
203	45.8	27.3	28.3	19.7	6.5	9.0
204	41.9	31.0	32.0	24.3	7.5	9.8
205	47.1	29.4	32.3	21.3	7.4	9.8
206	41.2	26.8	28.7	20.8	7.1	9.2