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**PHYSIQUE CHARACTERISTICS OF ELITE CAUCASIAN
AND POLYNESIAN RUGBY UNION ATHLETES**

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ABSTRACT

Rugby union (RU) is an international full-contact team sport characterised by short bursts of high intensity running, heavy tackling, and substantial body contact events. It requires a unique combination of physiological attributes, which are position specific, with an athlete's morphology considerably influencing their on-field position. Forwards are in continual close contact with opposition players, and need to be strong and powerful to gain and retain possession of the ball. Backs control possession of the ball once obtained by the forwards, and are required to accelerate away from opposition players to create scoring opportunities, whilst providing cover in defence. Speed and endurance are among the most important physical attributes for backs. Substantial morphological differences between forwards and backs exist, with forwards possessing more lean mass (LM), and greater absolute and proportional fat mass (FM) compared to backs. There are well established links between the mass of RU athletes and success, with "supersized" athletes highly sought after at the professional level. With physique traits having the potential to influence performance, being able to monitor and manipulate body composition in elite RU athletes is beneficial. As such, physique traits are routinely assessed in elite RU populations, with the most common techniques utilised being surface anthropometry (SA) and dual-energy X-ray absorptiometry (DXA).

RU has been described as Darwinian in nature, in that only the "fittest" reach the highest level of competition. This has widened the international search for athletes with the morphology to succeed. Anecdotally, there is an increasing proportion of RU athletes at the elite level of Polynesian descent, indicating the evolving physical demands of the sport may now be better complemented by the morphology of Polynesian athletes. Compared to Caucasians, Polynesian individuals have been shown to have higher proportions of absolute and relative LM. However, this has not previously been explored in the context of elite athletes, nor have differences in response to training stimuli based on ethnicity.

Polynesians have also been shown to exhibit more abdominal adiposity compared to Caucasians, along with some of the highest worldwide rates of obesity and cardiometabolic disease. The relationship between ethnicity and disease risk markers, including visceral adipose tissue (VAT), which is an established marker of cardiometabolic complications, has not previously been documented in an elite RU population. Furthermore, with the increasing number of Polynesian participants at the elite level, an understanding of whether, and how, ethnicity needs to be considered when interpreting body composition assessment in this population of athletes would be of value to sport science practitioners. This body of work was designed to explore the influence ethnicity has on physique traits, health status, adaptations to training, and body composition assessment in elite RU athletes.

In study one, body composition characteristics of elite Australian RU athletes were investigated, according to playing position and ethnicity. Thirty-seven international Australian RU athletes, including 27 Caucasians (15 forwards, 12 backs) and 10 Polynesians (5 forwards, 5 backs), underwent body composition assessment via SA and DXA. Forwards were significantly taller, heavier and had a greater total FM and LM than backs. Backs displayed a higher proportional LM, and lower sum of seven skinfolds (S7SF) and body fat percent (BF%). While no whole body composition differences were seen between ethnicities, significant regional differences were observed. In the peripheral (arm and leg) regions, Polynesians had a greater proportion of FM (53.1% vs. 51.3%, $P = 0.052$, $d = 0.5$) and LM (49.7% vs. 48.6%, $P = 0.040$, $d = 0.9$), while in the trunk region a lower proportion of FM (37.2% vs. 39.5%, $P = 0.019$, $d = 0.7$) and LM (45.6% vs. 46.8%, $P = 0.020$, $d = 1.1$) was observed. In contrast to DXA, SA indicated that Polynesians had a larger proportion of FM in their trunk (56.2% vs 50.7%, $d > 0.8$). Given the majority of trunk anthropometry measures are taken around the abdomen, it was postulated that VAT may also differ between ethnicities. It was found that elite Polynesian RU athletes have different distribution patterns of FM and LM compared to Caucasians, which may influence their suitability for particular positions and play a role in their selection at the elite level. Furthermore, given the sheer size of RU forwards, and ethnicity specific

differences in regional adiposity, detailed investigations looking at VAT levels in this athlete population was considered necessary.

Study two followed on from study one, further exploring differences in abdominal adiposity based on ethnicity. Thirty (19 Caucasian, 11 Polynesian) elite male RU athletes underwent assessment of VAT via a single slice at the L4/L5 level using magnetic resonance imaging (MRI) at the start of a pre-season period. This was complemented with DXA estimates of VAT. MRI VAT did not differ between ethnicities (Caucasian $92.7 \pm 26.7 \text{ cm}^2$; Polynesian $86 \pm 27.3 \text{ cm}^2$; $P = 0.52$), however, there was a trend for forwards ($96.7 \pm 25.0 \text{ cm}^2$) to have higher VAT than backs ($81.7 \pm 27.3 \text{ cm}^2$; $P = 0.13$). Thirty-seven percent of athletes were found to be at an increased risk of cardiometabolic complications with a VAT surface area $>100 \text{ cm}^2$. No athlete had a VAT $>160 \text{ cm}^2$, indicative of high risk. However, these thresholds were derived from older and obese populations, therefore their application to this group of athletes is questionable. A moderate association was found between MRI VAT and DXA VAT ($r = 0.46$, $P = 0.01$), with slight differences noted in the ability of DXA VAT to predict MRI VAT based on ethnicity. Given the size of RU athletes is increasing in the pursuit of improved performance outcomes, further investigations into VAT and other cardiometabolic complications in this population was deemed warranted.

With the established differences in morphology based on both playing position and ethnicity, studies three and four evaluated the application of commonly utilised body composition assessment techniques in elite RU populations. Study three assessed the ability of available skinfold regression equations, based on SA measures, to estimate absolute body composition in elite RU athletes. The development of sport-specific, ethnicity-sensitive equations was also pursued. Forty-three male international Australian RU athletes of Caucasian ($n = 26$) and Polynesian ($n = 17$) descent underwent SA and DXA assessment. BF% was estimated using five previously developed equations and compared to DXA measures. Novel sport and ethnicity-sensitive prediction equations were developed using forward selection multiple regression analysis. Existing skinfold equations provided unsatisfactory estimates of BF% in elite RU athletes, with all

equations demonstrating a 95% prediction interval in excess of 5%. The equations tended to underestimate BF% at low levels of adiposity, whilst overestimating BF% at higher levels of adiposity, regardless of ethnicity. The novel equations created explained a similar amount of variance to those previously developed. Given this, the use of skinfold equations, including the newly created ones, could not be supported to estimate absolute body composition. Until a population-specific equation is established that can be validated to precisely estimate body composition and accurately track longitudinal change, the use of raw skinfold data is advocated when using SA, in conjunction with proven methods such as DXA when absolute measures of LM and FM are desired.

Study four investigated the association between DXA and SA when assessing longitudinal changes in fat-free mass (FFM; LM + bone mineral content) and FM in elite RU athletes. Thirty-nine elite male RU athletes of Caucasian (17 forwards, 9 backs) and Polynesian (6 forwards, 7 backs) ethnicity underwent assessment via DXA and SA multiple times over three consecutive international seasons. Changes in the anthropometric based lean mass index (LMI), an empirical measure of proportional variations in FFM, showed a large correlation with changes in DXA FFM ($r = 0.54$, $SEE = 1.5\%$, $P < 0.001$), with the strength of association greater amongst forwards ($r = 0.63$) compared to backs ($r = 0.38$). Changes in the SA derived S7SF showed a very large correlation with changes in DXA FM ($r = 0.73$, $SEE = 5.8\%$, $P < 0.001$), with a meaningful difference based on ethnicity (Caucasians $r = 0.75$; Polynesians $r = 0.62$). The LMI and S7SF predicted the direction of change in FFM and FM, respectively, 86% and 91% of the time when DXA change was >1 kg. SA measures were found to provide a robust indication of the direction of FM and FFM change, although caution was recommended when interpreting the magnitude of change, particularly with FM.

An auxiliary study was completed to assist in the interpretation of true and meaningful body composition changes in the final two studies, with the precision of DXA assessed in a group of 21 resistance trained individuals. Two DXA scans were undertaken back-to-back on a single morning, in addition to one scan either

the previous or subsequent morning, all following best practice protocols. Least significant change 95% confidence interval (LSC-95% CI) values for consecutive day scans incorporating both technical error and biological variations for FM (1261 g) and LM (2083 g) were established. These values were wider than those found for same day scans measuring technical error alone (FM 660 g; LM 617 g). This indicated that despite best practice protocols being used by the participants regarding how they presented for the scans, there was still considerable biological variation over a 24 hour period. It was advocated when interpreting meaningful change via DXA, as might occur when monitoring body composition over a pre-season period in an elite RU population, to use values incorporating both technical error and biological variation as this provided a more valid insight in to true body composition adaptation.

The final two studies sought to quantify physique and cardiometabolic health related adaptations over a pre-season training period. In study five DXA derived body composition changes were assessed. Twenty-two Caucasian (6 forwards, 5 backs) and Polynesian (5 forwards, 6 backs) elite RU athletes undertook DXA assessment at the beginning and conclusion of a high-volume high-intensity 11-week pre-season training program (~15 hours per week), in addition to a 2-week unsupervised maintenance block (i.e. Christmas), which fell approximately half way through the pre-season period. After accounting for baseline body composition, Caucasians gained significantly more LM than Polynesians during the pre-season ($F = 5.3$, $P = 0.03$). Significant physique changes were noted over the pre-season for whole body and all regional measures with FM decreasing ($F = 31.1$ – 52.0 , $P < 0.01$), and LM increasing ($F = 12.0$ – 40.4 , $P < 0.01$). Seventeen athletes (9 Caucasian, 8 Polynesian) had a reduction in FM, and 8 (6 Caucasian, 2 Polynesian) had an increase in LM greater than the LSC-95% CI, with significantly more Caucasians increasing LM compared to Polynesians (55% vs 18%). The use of the individualised LSC method of analysis provided great insight into the adaptations of elite RU athletes over a pre-season period, with future work exploring physique changes during the off-season recommended to add value to the interpretation of results in the subsequent pre-season.

Finally, study six was designed to explore the relationship between ethnicity, body composition, and blood biochemical cardiometabolic disease risk markers in elite RU athletes, incorporating analysis of the impact a pre-season training program had on these measures. Twenty-two Caucasian ($n = 11$) and Polynesian ($n = 11$) elite RU athletes undertook a high-volume high-intensity 11-week pre-season training program as described in study five, with pre- and post-assessments of body composition via SA, DXA, and a volumetric MRI examination of the abdominal cavity. A fasted blood test was also undertaken at the same time points. Polynesians had a significantly higher waist to height ratio (WHt; 0.50 ± 0.03 vs 0.47 ± 0.02 ; $P = 0.019$), android FM percentage ($19.4 \pm 5.0\%$ vs $14.5 \pm 3.8\%$; $P = 0.020$) and greater amount of VAT ($771 \pm 609 \text{ cm}^3$ vs $424 \pm 235 \text{ cm}^3$; $P = 0.043$), plus triglyceride (TG; $1.0 \pm 0.9 \text{ mmol/L}$ vs $0.6 \pm 0.2 \text{ mmol/L}$; $P = 0.050$), and low-density lipoprotein cholesterol concentrations (LDL-C; $3.1 \pm 0.9 \text{ mmol/L}$ vs $2.3 \pm 0.7 \text{ mmol/L}$; $P = 0.019$), whilst also trending towards a higher total cholesterol concentration (TC; $5.1 \pm 0.9 \text{ mmol/L}$ vs $4.4 \pm 0.8 \text{ mmol/L}$; $P = 0.057$) and greater amount of abdominal subcutaneous adipose tissue (SAT; $3424 \pm 1529 \text{ cm}^3$ vs $2279 \pm 1014 \text{ cm}^3$; $P = 0.068$). Over the pre-season period, Polynesians had greater reductions in waist circumference (WC; $-2.8 \pm 1.6 \text{ cm}$ vs $-0.7 \pm 1.2 \text{ cm}$; $F = 9.208$, $P = 0.007$) and WHt (-0.020 ± 0.009 vs -0.004 ± 0.006 ; $F = 7.206$, $P = 0.015$), whilst Caucasians had greater reductions in TC concentration ($-0.13 \pm 0.32 \text{ mmol/L}$ vs $-0.08 \pm 0.68 \text{ mmol/L}$; $F = 5.543$, $P = 0.029$). Twenty-one out of 22 (95%) athletes decreased (exceeding LSC-95% CI) VAT and skinfolds over the pre-season period, whilst 19 (86%) decreased SAT and android FM percent. Overall, Polynesians recorded higher values for VAT and several lipid profile markers, although in most cases the overall risk profile remained in normal ranges. However, 2 Polynesians (18%) recorded high TC ($>6.0 \text{ mmol/L}$), and 6 (55%) elevated LDL-C concentration ($>3.0 \text{ mmol/L}$). Although participants of both ethnicities were able to make meaningful reductions to VAT over the pre-season period, Polynesian athletes may be predisposed to naturally higher levels of VAT, which may have implications post-career given the genetic predisposition for increased cardiometabolic disease risk. This warrants future consideration.

In conclusion, this is the first series of studies to explore the role ethnicity plays in the physique and health status of this population of elite athletes, many of whom are “supersized” to elicit improved performance. RU athletes of Polynesian descent exhibit unique morphology, particularly in regards to regional FM and LM distribution. However, as the desire to increase the size of elite RU athletes continues, consideration needs to be given to the short- and long-term health status of the athletes, particularly amongst Polynesians given their propensity for elevated VAT and blood lipid profiles. As such, coaches and sport science practitioners need to prudently interpret results at both a group and individual level. In summary, this thesis identified a number of issues pertinent to physique assessment and management within elite RU populations previously unidentified, specifically recognising the uniqueness of Polynesian athletes within the sport. The findings will assist coaches and sport science practitioners in the preparation and management of elite RU athletes, and provide researchers with a basis for future ethnicity-specific investigations in elite sport relative to both performance and health.

DECLARATION OF ORIGINALITY

I, Adam J. Zemski, hereby declare that this thesis is my own work and does not, to the best of my knowledge, contain material from other sources unless due acknowledgement is made.

This thesis is submitted to the University of the Sunshine Coast in fulfillment of the requirements for the degree of Doctor of Philosophy, under the guidelines of the Faculty of Science, Health, Education and Engineering, and has not previously been submitted for an award at this or any other higher education institution.

Where explicitly acknowledged in each experimental chapter, and otherwise, a number of individuals have contributed to the research presented in this thesis:

- Assoc Prof Gary Slater Research design, data collection, manuscript review
- Dr Elizabeth Broad Research design, manuscript review
- Dr Shelley Keating Research design, data analysis, manuscript review
- Damian Marsh Data collection, manuscript review
- Dr Karen Hind Manuscript review
- Dr Janet Chaseling Statistical analysis
- Kylie Walters Data collection
- Assoc Prof Fiona Pelly Research design

I declare that I contributed to the majority of the work in the design, data collection, analysis and interpretation of the results, composition and editing, and manuscript preparation of all research contained within this thesis.

Adam Zemski
Candidate

20/09/2018

Associate Professor Gary Slater
Primary Supervisor

20/09/2018

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“Success is a journey, not a destination. The doing is often more important than the outcome.” – Arthur Ashe (1943–1993)

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LIST OF ACRONYMS AND ABBREVIATIONS

η_p^2	Partial eta squared
%CV	Percent coefficient of variation
μSv	Micro-Sievert
3D	Three-dimensional
4C	Four compartment
95% PI	95% prediction interval
a	Acceleration
ADP	Air displacement plethysmography
AFL	Australian rules football, Australian Football League
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
ARU	Australian Rugby Union
BD	Body density
BF%	Body fat percent
BIA	Bioelectric impedance analysis
BM	Body mass (BM = FFM + FM; BM = BMC + LM + FM)
BMC	Bone mineral content
BMD	Bone mineral density
BMI	Body mass index
BODPOD	Air displacement plethysmography (equipment used)
CAC	Coronary artery calcium
CI	Confidence interval
cm	Centimeters
CT	Computed tomography
CV	Coefficient of variation
D1S1	Day 1 scan 1
D1S2	Day 1 scan 2
D2S1	Day 2 scan 1
D&W	Durnin and Womersley skinfold equation

<i>d</i>	Cohan's effect size
DXA	Dual-energy X-ray absorptiometry
DXA-BF%	Dual-energy X-ray absorptiometry derived body fat percent
F	Force (Newton's laws); F-statistic (statistical analysis)
FFM	Fat-free mass (FFM = BM – FM; FFM = BMC + LM)
FFMI	Fat-free mass index
FM	Fat mass
FMI	Fat mass index
FOV	Field of view
g	Grams / g-force
HDL-C	High-density lipoprotein cholesterol
HIIT	High-intensity interval training
ICC	Interclass correlation coefficient
IQR	Inter-quartile range
IRB	International Rugby Board
ISCD	International Society of Clinical Densitometry
kg	Kilograms
lbs	Pounds
LDL-C	Low-density lipoprotein cholesterol
LM	Lean mass
LMI	Lean mass index
LSC	Least significant change
LSC-95% CI	Least significant change 95% confidence interval
m	Meters
M	Mass
mm	Millimeters
MRI	Magnetic resonance imaging
n	Number
NFL	American (gridiron) football, National Football League
NHANES	National Health and Nutrition Examination Survey
P	P-value
PhD	Doctor of Philosophy
R ²	Coefficient of determination

r	Correlation coefficient
RMS	Root-mean-square
RMS-SD	Root-mean-square standard deviation
ROI	Region of interest
RU	Rugby union
RWC	Rugby World Cup
S7SF	Sum of seven skinfolds
SA	Surface anthropometry
SAT	Subcutaneous adipose tissue
SD	Standard deviation
SEE	Standard error of the estimate
T2DM	Type 2 diabetes mellitus
TC	Total cholesterol
TEM	Technical error of measurement
TG	Triglycerides
VAT	Visceral adipose tissue
VAT:SAT	Visceral adipose tissue to subcutaneous adipose tissue ratio
WC	Waist circumference
WHO	World Health Organisation
WHR	Waist to hip ratio
WHt	Waist to height ratio

PUBLICATIONS ARISING FROM CANDIDATURE

PEER REVIEW PUBLICATIONS ARISING DIRECTLY FROM THIS THESIS

Zemski AJ, Slater GJ, and Broad EM. Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity. *Journal of Sports Sciences*. 2015; 33: 970-978.

Zemski AJ, Broad EM, and Slater GJ. Skinfold prediction equations fail to provide an accurate estimate of body composition in elite rugby union athletes of Caucasian and Polynesian ethnicity. *International Journal of Sport Nutrition and Exercise Metabolism*. 2018; 28: 90-99.

Zemski AJ, Keating SE, Broad EM, and Slater GJ. Longitudinal changes in body composition assessed using DXA and surface anthropometry show good agreement in elite rugby union athletes. *International Journal of Sports Nutrition and Exercise Metabolism*. 2018; 14: 1-25 [Epub ahead of print].

Zemski AJ, Keating SE, Broad EM, Marsh, DJ, Hind K, and Slater GJ. Pre-season body composition adaptations in elite Caucasian and Polynesian rugby union athletes. *International Journal of Sports Nutrition and Exercise Metabolism*. 2018; 14: 1-24 [Epub ahead of print].

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Zemski AJ, Keating SE, Broad EM, Marsh, DJ, Hind K, Walters KJ, and Slater GJ. Differences in visceral adipose tissue and biochemical cardiometabolic risk markers in elite rugby union athletes of Caucasian and Polynesian descent. *Sports Medicine*. (To be submitted, September 2018).

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Presented as a poster presentation at the International Sport and Exercise Nutrition Conference in Newcastle, United Kingdom, 13–15 December 2012.

Zemski AJ, Slater GJ, Broad EM, and Chaseling J. Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity.

Presented as a poster presentation at the Sports Dietitians Australia Conference in Melbourne, Australia, 19 October 2013.

Keating SE, **Zemski AJ**, Broad EM, Marsh DJ, and Slater GJ. Ethnic differences in visceral adipose tissue and markers of cardiometabolic risk in elite rugby union athletes.

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PUBLISHED PEER REVIEW ABSTRACTS ARISING FROM THIS THESIS

Zemski AJ, Slater GJ and Broad EM. Estimating body composition in elite rugby union athletes using surface anthropometry. *International Journal of Sport Nutrition and Exercise Metabolism*. 2013; 23: S7-8.

Keating SE, **Zemski AJ**, Broad EM, Marsh DJ, and Slater GJ. Ethnic differences in visceral adipose tissue and markers of cardiometabolic disease risk in elite rugby union athletes. *Journal of Science and Medicine in Sport*. 2017; 20: 62.

NON-RELATED PEER REVIEW PUBLICATIONS DURING CANDIDATURE

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NON-RELATED BOOK CHAPTERS DURING CANDIDATURE

Zemski AJ. Physiology of sports: Practical tips. In: LM Burke & V Deakin (eds), *Clinical Sports Nutrition* (5th ed.). Sydney, Australia: McGraw Hill Education.

Zemski AJ. Spirulina. In: LM Castell, SJ Stear, & LM Burke (eds), *Nutritional supplements in sport, exercise and health; an A-Z guide*. London, England: Routledge.

CHAPTER ONE – INTRODUCTION

Rugby union (RU) is a full contact team sport characterised by short bursts of high intensity running and heavy tackling, with substantial and frequent intense body contact events [14, 163]. It requires a unique combination of strength, skill, speed and endurance from the athletes [17, 165]. Teams consist of 15 players on the field, with positions split into two main packs: forwards and backs. Forwards contest possession in set-pieces such as scrums, rucks, mauls and line-outs, with strength and power needed to gain and retain possession on the ball [403, 449, 465]. Backs control possession of the ball, gain territory, score points, and provide cover in defence to prevent the opposition scoring. Agility, speed and acceleration are required for backs to out-manoeuvre opponents [26, 136, 163]. Given the distinctive positional roles, physique traits differ significantly. Forwards benefit from being heavier and taller, and possess higher levels of both fat mass (FM) and lean mass (LM) compared to backs, as well as greater relative FM [163, 333].

RU has been described as Darwinian in nature, in that only the “fittest” reach the highest level of participation [409]. Indeed, body mass (BM), a key physique characteristic strongly linked with successful performance [416, 496], has been increasing over time at the elite level, with distinctive differences identified across playing levels [163, 454]. As such, it has become increasingly difficult to find athletes of the size and shape required to compete at the highest level, with the recruitment of foreign players in professional leagues increasing in recent years [416, 497].

Polynesian individuals possess greater proportions of LM in comparison to Caucasians of comparable size [479, 538], which may predispose them to success in RU. However, they also exhibit greater stores of abdominal fat in both absolute and relative terms [480], which is associated with a gamut of cardiometabolic diseases [145, 146, 187]. Further, Polynesians have been shown to have some of

the highest global rates of obesity [402] and type 2 diabetes mellitus (T2DM) [98, 390], suggesting they may be genetically predisposed to cardiometabolic diseases and their associated complications.

There is a comprehensive range of assessment techniques available for the measurement of body composition, both for the assessment of health status [579], and the measurement of physique traits pertaining to athletic performance [2]. These methods vary in complexity, cost, and availability, with some of the techniques requiring different reference ranges to be applied based on the ethnic group being assessed [95, 122, 123, 469]. The selection of suitable assessment tools is imperative in elite athletic populations to ensure programs and interventions are prescribed to the athletes appropriately.

STATEMENT OF THE PROBLEM

Despite an abundance of research reporting body composition in male RU athletes, there is no published literature within which physique traits have been differentiated based on ethnicity. Given the number of Polynesian athletes participating in RU at the elite level, and the body composition differences identified between Polynesians and Caucasians in the general population, exploration into this area is warranted. Presently, practitioners rely on body composition data derived from Caucasian and/or mixed populations when profiling athletes and planning individual programs, which may not be providing an accurate indication of absolute and relative changes in body composition across ethnicities. With the results of these assessments used across a range of areas, including in the identification of individuals at risk of cardiometabolic disease, and in the adjustment of training and/or dietary interventions based on responses, an appreciation of differences based on ethnicity would be valuable. Further, the literature is scarce regarding the quantification of athlete body composition adaptations to pre-season training stimulus, with nothing pertaining to regional adaptations using advanced assessment methodologies, or differences in adaptations based on ethnicity.

It is well established that a large proportion of elite RU athletes are classified as overweight or obese using traditional measures such as relative mass (body mass index; BMI) [242, 333]. In other sports with similar “supersized” athletes, noteworthy associations have been made between the size of athletes and their abdominal adiposity levels, with cardiometabolic disease complications, both during and post career [380, 561]. To date, there is no scientific literature exploring abdominal adiposity levels in elite RU athletes, nor the cardiometabolic health status of this population. This would appear particularly pertinent in Polynesian athletes, given their propensity to store more of their adipose tissue abdominally, and the increased incidence of cardiometabolic disease within this population. Indeed, there is no scientific literature looking specifically at visceral adiposity in any Polynesian populations using advanced imaging techniques.

Regression equations derived from anthropometric data are often used to estimate absolute body composition. However, none have been specifically created for, or validated within, RU populations. Dual-energy X-ray absorptiometry (DXA) and surface anthropometry (SA) are often used concurrently within elite groups, yet little is understood regarding the relationship between these two assessment tools. Finally, although DXA is now able to estimate visceral adiposity, with this having been validated in general populations [100, 399], the appropriateness of these estimates has not been explored within a group of elite athletes, some of which may be “supersized” to elicit optimal performance outcomes.

AIMS OF THE THESIS

The specific aims of the studies undertaken as part of this thesis can be separated into three sub-categories as listed below:

Quantification of body composition traits in modern day elite rugby union athletes

- Describe the body composition traits of modern-day elite RU athletes.
 - Compare the morphology between forwards and backs, and between Caucasian and Polynesian athletes.
 - Identify differences in regional distribution of FM and LM, in absolute and relative terms.
- Investigate levels of visceral adipose tissue (VAT) in elite RU athletes, incorporating comparisons based on ethnicity.

Body composition assessment methods in elite rugby union

- Assess the ability of currently available skinfold regression equations to estimate body composition relative to DXA in an elite RU population of different ethnic backgrounds.
- Derive ethnicity-sensitive skinfold regression equations for predicting body composition in RU athletes.
- Investigate the association between DXA and raw SA data when measuring changes in fat-free mass (FFM; FFM = bone mineral content +LM) and FM in elite RU athletes, and to explore whether differences exist due to the physique traits of the athletes based on ethnicity and/or position.

- Assess the ability of DXA to estimate VAT compared to the criterion magnetic resonance imaging (MRI) in a population of elite RU athletes.

Assessment of cardiometabolic disease risk markers and pre-season adaptations in elite rugby union athletes

- Explore the relationship between ethnicity, VAT, and cardiometabolic disease risk markers in elite RU athletes of Caucasian and Polynesian descent.
- Identify pre-season team and individual athlete DXA derived body composition adaptations in elite RU athletes, with sub-group analysis to compare changes between Polynesian and Caucasian athletes.
- Assess the impact of a pre-season training program on VAT and biochemical markers of cardiometabolic disease risk, in a population of elite RU athletes of Caucasian and Polynesian descent.

SPECIFIC HYPOTHESES

The hypothesised findings from the studies undertaken as part of this thesis, separated into the three sub-categories identified previously, are as follows:

Quantification of body composition traits in modern day elite rugby union athletes

- Polynesian athletes will possess a greater proportion of LM, and lower proportion of FM, in comparison to Caucasian athletes.
- Forwards will possess greater amounts of FM and LM, and a greater proportion of FM, in comparison to backs, similar to what has been observed previously in elite RU athlete populations.
- Polynesian athletes will exhibit differences in regional body composition distribution in comparison to Caucasian athletes, similar to the regional distribution patterns observed in non-athletic populations.
- VAT levels in elite RU athletes will not exceed general population thresholds for increased risk of cardiometabolic disease complications.
- VAT levels in elite RU forwards will be elevated in comparison to backs.
- VAT levels in elite Polynesian RU athletes will be elevated in comparison to Caucasian athletes.

Body composition assessment methods in elite rugby union

- No currently available skinfold regression equations will be appropriate to apply to an elite RU athlete population.
- RU and ethnicity specific skinfold regression equations, which are to be developed, will provide a more valid estimate of body fat percent (BF%) in an elite RU athlete population in comparison to previously developed equations.
- Raw SA data will provide an appropriate proxy for measuring longitudinal body composition change in elite RU athletes.
- DXA will provide a general indication of VAT levels in elite RU athletes.

Assessment of health status and pre-season adaptations in elite rugby union athletes

- Elite Polynesian RU athletes will exhibit elevated levels of VAT, and blood biochemical cardiometabolic disease risk markers, in comparison to Caucasian athletes. However, these measures will remain within normal ranges.
- Elite RU forwards will exhibit elevated levels of VAT, and blood biochemical cardiometabolic disease risk markers, in comparison to backs. However, these measures will remain within normal ranges.
- Significant increases in LM, and decreases in FM, will occur during the pre-season period, with minimal differences in the adaptations observed between Caucasians and Polynesians.
- A pre-season training program will effect small, yet significant changes in VAT and biochemical markers of cardiometabolic disease risk in elite RU athletes.

SIGNIFICANCE OF THE THESIS

The findings of this thesis will have a direct and practical application in the assessment and interpretation of body composition data in elite RU populations. Importantly, this series of studies will present data describing the physique traits of elite Polynesian athletes for the first time in the literature. This improved understanding of the physique traits of individual athletes will assist high performance staff in prescribing more personalised dietary and training programs, thus increasing the likelihood of eliciting the desirable adaptations.

The exploration of abdominal adiposity using criterion measures in elite athletes of different ethnicities will add considerably to the literature. The novel findings will provide practitioners with valuable information pertaining to visceral adiposity and cardiometabolic health status, particularly of the more “supersized” forwards, using criterion measures. Further, associations between abdominal adiposity, cardiometabolic disease risk markers, and RU athletes will guide sport science and sports medicine practitioners from a health status perspective, and possibly drive changes in during and end-of-career athlete management and education.

THESIS SYNOPSIS

This thesis consists of nine chapters. Chapter Two provides an in-depth review of the literature, and is separated into three main sections. Firstly, a comprehensive overview of RU, with a particular focus placed on the physique characteristics and physical requirements of the sport. Secondly, an exploration into the role ethnicity plays in RU, physique traits, and cardiometabolic disease risk. Finally, an overview of body composition assessment, with a focus on the techniques commonly utilised in RU is presented.

Chapters Three and Four are investigational studies which explore the physique traits of modern-day elite RU athletes, in which a particular emphasis is placed on exploring the regional body composition differences between athletes of Caucasian and Polynesian descent. The following two chapters (Chapters Five and Six) investigate the application of commonly used body composition assessment methods used in RU, and their association. Chapters Seven and Eight explore the role that ethnicity plays in cardiometabolic disease risk in an elite RU population. Additionally, the changes that occur in body composition and biochemical markers of cardiometabolic disease risk in elite RU athletes over the course of a pre-season period are investigated. Finally, Chapter Nine provides a summary of the findings from the investigations and examines the implications of these in practice. Relevant appendices follow the conclusions, including conference presentations and abstracts, and an auxiliary study which was undertaken as part of the research.

Each research based chapter (Chapter Three to Chapter Eight) is presented in manuscript format as they have been submitted to, or accepted by, peer reviewed scientific journals. Consequently, there is some repetition between chapters contained within the thesis. Furthermore, for the benefit of the reader, all chapters have been formatted consistently, meaning they may deviate slightly from the published manuscripts. Specifically, there are some additional headings that have been added, abbreviations and terminology have been made consistent throughout the chapters, and references have been consolidated at the end of the

thesis. Finally, due to the word count limitations in published manuscripts, a detailed description of the methods was not always able to be provided. As such, a full explanation of the data collection methodologies have been provided in the appendices. A schematic overview of the thesis structure can be seen in Figure 1.1.

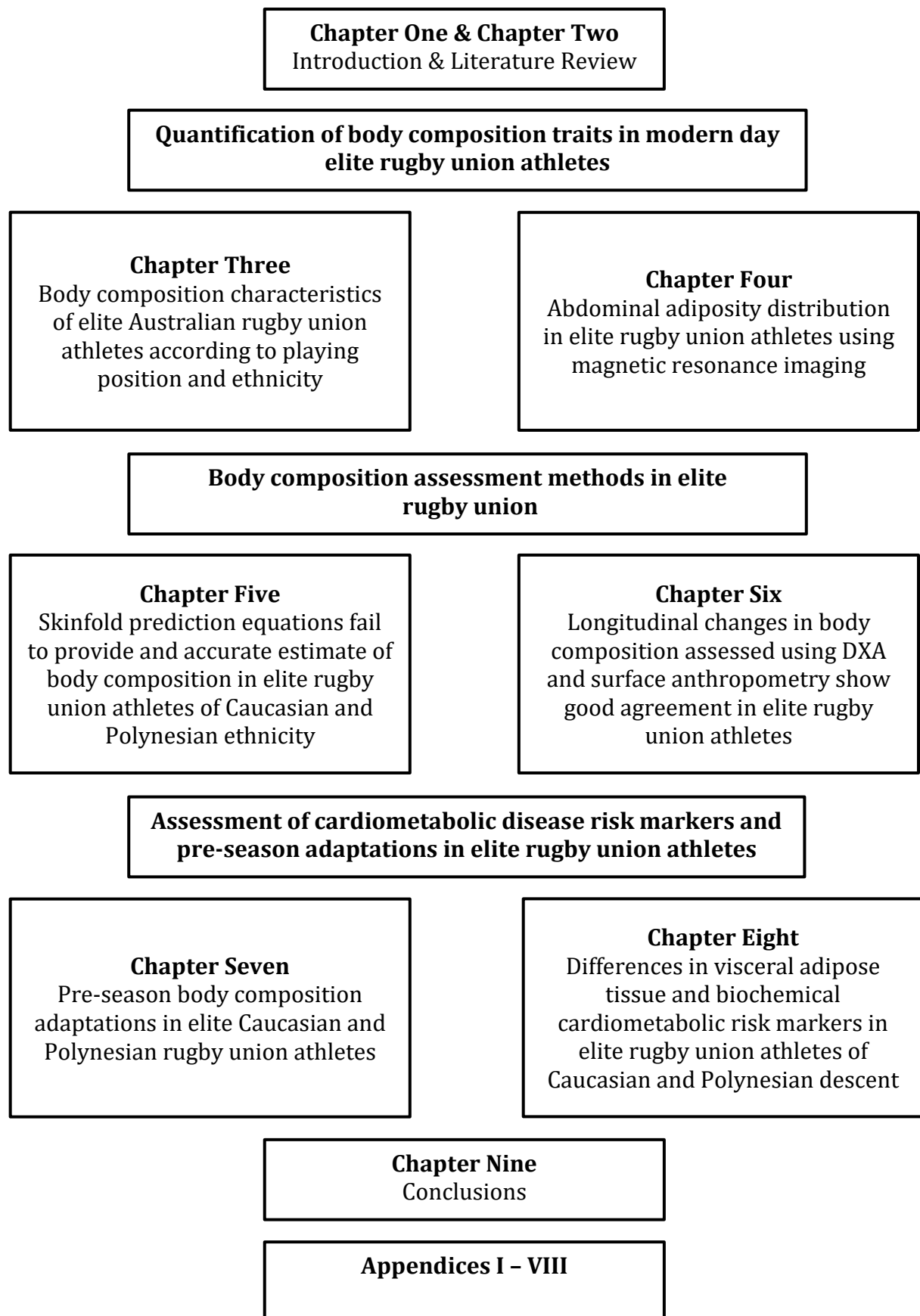


Figure 1.1. Schematic overview of thesis structure.

CHAPTER TWO – REVIEW OF LITERATURE

RUGBY UNION

In 1823 AD, William Webb Ellis, who, with a fine disregard for the rules of football as played at the time, first took the ball in his arms and ran with it, thus originating the distinctive feature of the rugby game.

The brazen undertaking stated above is widely believed to be the “first act” resulting in the distinctive form of RU [159]. In reality, it is a myth, which was used as part of the marketing campaign for the 1991 Rugby World Cup (RWC) [510]. The true origins of RU were far more evolutionary, with a historical timeline of RU through the 19th and 20th Centuries presented in Figure 2.1.

HISTORY AND EVOLUTION OF RUGBY UNION

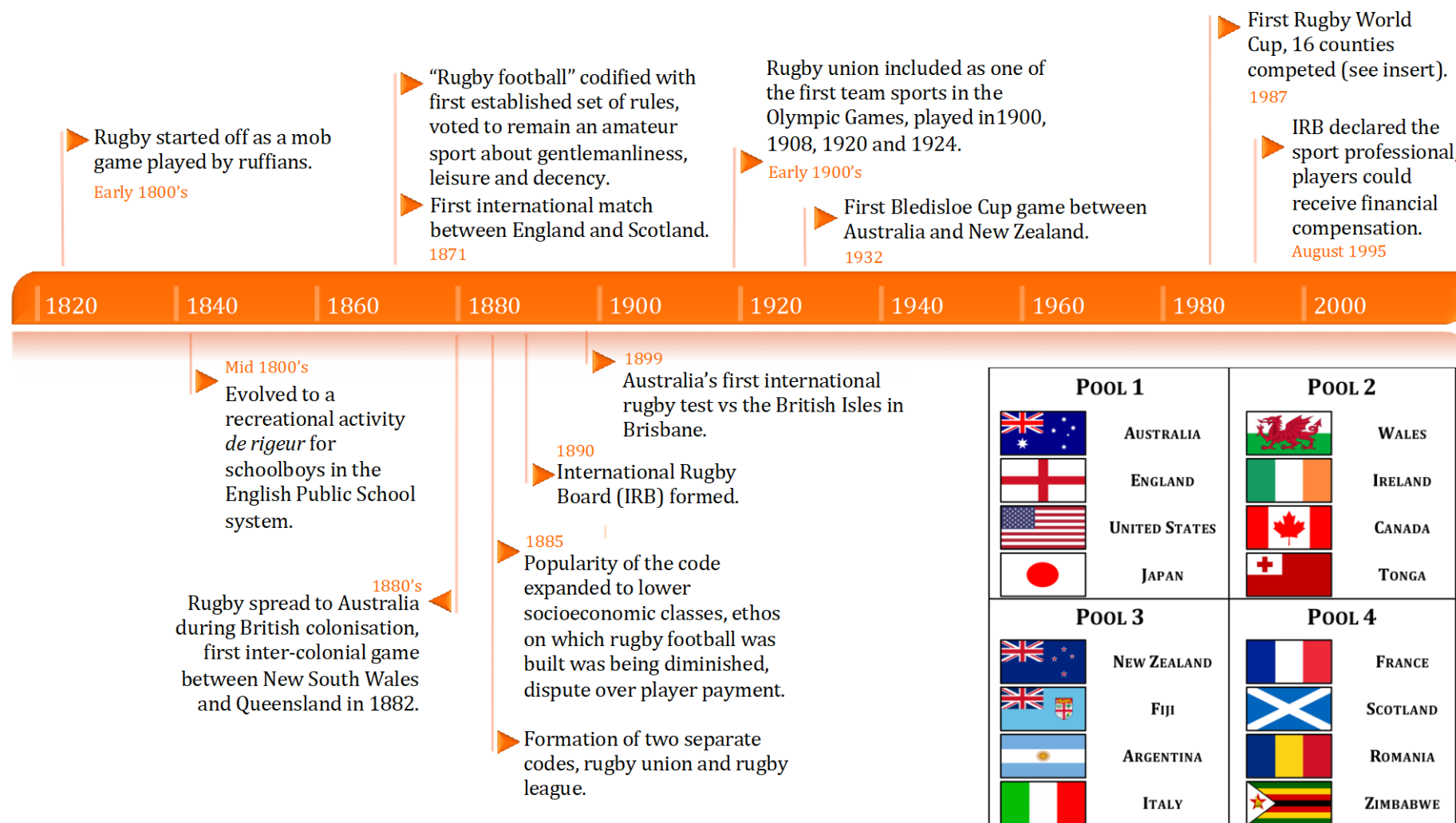


Figure 2.1. Timeline of rugby union prior to professionalism [9, 94, 160, 430, 451, 464, 510].

The sport

RU is a full contact team sport characterised by short bursts of high intensity running and heavy tackling, plus frequent and intense body contact events, interspersed with periods of recovery. Due to its distinctive form, RU athletes require a unique combination of strength, skill, speed and endurance [15, 17, 101, 150, 163, 165, 453]. Since the start of the professional era in 1995, there have been a number of significant changes to the sport to make the game faster, free flowing, safer, and higher scoring to make the game more exciting for spectators [26, 389, 430, 451, 603]. These changes include the lineout law being modified with the jumper being permitted “support” from other members of their team, the number of reserves increasing, non-injury replacements being permitted, and a modification to the “use it or lose it” law which allowed the team in possession at a maul five seconds either to free the ball or restart forward movement prior to the referee calling a scrum [451, 603]. Games in the modern era are played with an oval shaped ball between two teams on a field approximately 144 m long and 70 m wide, with “H-shaped” goal posts on each try-line. In actual gameplay there is a maximum of 100 m between the two try-lines, with anywhere between 10 m and 22 m behind each try-line to serve as the in-goal area. Games are played over two 40 minute halves, with a break of no longer than 10 minutes at half-time. Points are scored through tries (worth five points), try conversions (two points), field goals and penalty goals (three points each), with the object of the game to score more points than the opposition.

In Australia, the professional RU franchise teams compete in the southern hemisphere’s premier competition, Super Rugby. The season typically runs from late-February until early-August. The schedule for national teams varies from year to year; however, the majority of international matches typically take place after the Super Rugby season between August and December. The pre-season period will generally last 8–12 weeks following 3–6 weeks of rest time in the off-season, with a 1–2 week break over Christmas [76]. However, pre-season duration will be dependent on whether the team is involved in finals, and if individuals have earned international selection.

RU teams consist of 15 players on the field, who may be replaced in the case of injury, or substituted for tactical reasons during the match, from a pool of seven or eight (depending on the competition) substitute players. Once a player has been substituted, they cannot return to the field of play. Each player has a designated position and number outlined by the International Rugby Board (IRB) as shown in Table 2.1 [163]. Rugby sevens, which is an abbreviated variant of RU gaining popularity in both participation levels and scientific research, has been identified as a stand-alone sport requiring different physiological requirements to that of RU [193, 241-243, 462, 470, 530, 531], and as such will not be considered in this review. For the purpose of this research, the definition of the term “elite” is based on that presented by Olds [416]. Namely, athletes from the national teams of RWC playing countries, and those competing in the top professional leagues in the world (Super Rugby, Premiership Rugby, The Top 14), and their historical equivalents. Finally, although RU is played at the elite level by both males and females, this review of literature, and thesis, will be focused on male athletes.

The 15 players on the field are categorised into two main groups, the forwards (numbers 1–8), and the backs (numbers 9–15). The primary role of the forwards is to contest possession in set-piece plays such as scrums, line-outs, rucks and mauls. Within the forwards, players 1 to 3 are referred to as the “front row”, players 4 and 5 as the “second row”, and collectively players 1 to 5 are commonly called the “tight five”. The remaining forwards, players 6 to 8, are known as the “back row”, or the “loose forwards” (Table 2.1) [163]. The designations relate primarily to the players position and role in the formation of a scrum. In general, being tall and having a greater BM is advantageous in the forward positions [163, 165, 403, 450, 454]. Specifically, the tight five positions demand strength and power to gain and retain possession of the ball as they are in continual close contact with opposition players, whereas the loose forwards need to be powerful and mobile in open play, with excellent speed, acceleration and endurance [163, 403, 449].

The principle role of the backs is to control possession of the ball once obtained by the forwards, gain territory, and score points. Additionally, when not in possession, backs provide cover in defence and strive to prevent opposition players scoring through tackling. Within the backs, “half backs” are players 9 and 10, the “centers” (or “mid-field backs”) are players 12 and 13, whilst players 11, 14 and 15 are the “outside backs” (Table 2.1) [163]. In general, speed, acceleration and endurance are the key physical attributes of backs [27, 136, 163, 403, 450, 465]. Additionally, the midfield backs also require considerable strength and power as they have a high frequency of contact with the opposition, whilst outside backs need agility, in conjunction with speed and acceleration, to out-manoeuvre opponents [163].

Table 2.1. Rugby union positions, their respective groups/sub-groups, plus playing number.

Number	Position	Sub-Group	Group
1	Loosehead Prop	Front Row*	Forwards
2	Hooker		
3	Tighthead Prop		
4	Left Lock	Second Row*	
5	Right Lock		
6	Blindside Flanker	Loose Forwards (Back Row)	
7	Openside Flanker		
8	Number Eight		
9	Scrum Half	Half Backs	Backs
10	Fly Half		
11	Left Wing	Outside Backs	
12	Inside Centre	Centres	
13	Outside Centre	(Mid-Field Backs)	
14	Right Wing	Outside Backs	
15	Full Back		

*Front row and second row forwards are collectively referred to as the “tight five”.

Physiological requirements

Winning and higher ranked teams have been shown to lose possession less during scrums and line-outs, win more mauls, complete more tackles, and make more line breaks [277, 420, 442, 577, 578]. Therefore speed, and muscular strength and power, are arguably the most important performance characteristics in RU, all of which are closely related to specific physique traits [163, 165].

Speed

On average, professional RU forwards sprint just over 500 m a match, with backs sprinting between 500 m and 1000 m [26, 27]. Backs are faster than forwards [131, 167, 244, 514, 546] with the differences in speed characteristics reflective of explicit positional requirements. Specifically, outside backs are the fastest players, whereas props are the slowest [244].

Explicit links have been established between speed and the execution of on-field skills. Speed over 10 m and 20 m is positively correlated with the number of successful line breaks and tackle breaks [514]. The execution of effective ball carries is also related to maximum sprinting speed [487]. Further, small but significant differences between international level and Super Rugby athletes in 20 m sprint times exist [516], with international forwards and backs proving to be faster (forwards 1.9%, backs 2.2%), illustrating the importance of speed at the elite level.

A number of relationships between speed and body composition have been identified. In a rugby league population, moderate to very large correlations between LM and 20 m sprint time were reported [587]. In studies looking specifically at sprinters, greater muscularity has been closely related with greater acceleration, and also a faster maximal running speed [3, 594]. Although there is a point of diminishing returns where further gains will impair performance, it is clear an association exists between speed and LM.

Strength and power

In RU [18, 226, 516], as well as other contact sports such as rugby league [31-33], American (gridiron) football (NFL) [188], and Australian rules football (AFL) [291], strength and power have been shown to have a strong positive correlation with the playing level of the athlete. Specifically, in RU, muscular strength and power are essential components for success, particularly for forwards in scrums, rucks and mauls [368, 454].

Certain body composition traits have been explicitly linked to strength and power, and RU specific movements, in other contact football codes. In an elite AFL population, changes in upper body LM were found to be related to changes in upper body strength performance (bench press $r = 0.37$, bench pull $r = 0.40$) [64]. Similarly, in NFL athletes it has been suggested that performance in tests of maximal strength and power are strongly related to LM, with a correlation of $r = 0.55$ ($p < 0.001$) found between 1 repetition maximum bench press and lean body mass [239]. In rugby league, moderate to large relationships between LM and vertical jump power were identified [587], with a superior vertical jump acknowledged as a characteristic of selected players over non-selected players at the professional level [197]. The aforementioned relationships between particular physique traits, and specific movements associated with success in contact sports, highlights the importance body composition optimisation plays in RU at the elite level.

Aerobic and anaerobic capacity

Aerobic fitness has long been proposed as an indicator of performance in RU athletes [458]. A high aerobic capacity facilitates the repetition of high-intensity efforts as are required in RU [163, 235, 374]. Backs typically possess greater levels of aerobic fitness than forwards. Indeed, backs are able to complete more shuttles in a maximal multistage 20-m shuttle run test (“beep test”), a proven indicator of aerobic fitness and VO_{2max} [336, 337], than forwards (backs 127.4

vs forwards 108.6; $p < 0.001$) [449, 450]. These advantageous levels of aerobic capacity assists backs in undertaking their specific on-field responsibilities.

Anaerobic capacity is an important attribute for RU athletes to possess given the nature of the explosive work periods undertaken in matches [163]. In sub-elite groups, forwards produce higher absolute peak and mean power outputs compared with backs [53, 367, 463, 564]. However, when expressed relative to BM the results are similar [367], or even favour the backs [546]. Backs outperform forwards in repeated-sprint ability tests, as well as single sprint performance [361], making anaerobic capacity task and position dependent [68, 207]. Given the position specific requirements pertaining to aerobic and anaerobic fitness in RU, backs may benefit from lower levels of relative adiposity to elicit improved sprinting and running performance [163, 165, 242, 333].

Physique characteristics and performance

Interest in physique traits and their relationship to human performance is long standing. Fat content and body composition were being studied as far back as the 1940's as a way to identify individuals most suitable to be deep sea divers in the US Navy [47]. Since then, Norton and Olds [409] affirmed that sport was Darwinian in nature, and that only the “fittest” reach the highest level of participation. Further, they recognised that it has become increasingly difficult to find athletes of the size and shape required to compete at the highest level in some sports, generalising that there was a Darwinian selection pressure directing the perfect body form in specific events [409].

Physique and performance in elite sport

Over time, as sport has increased in professionalism, the body composition of elite athletes has become progressively different from that of the general population. Further, it has become more differentiated between sports and playing levels within the same sport, with specific physique traits having been identified as being strongly related to competitive success in certain athletic

pursuits. Indeed, one or more of the abovementioned occurrences has been observed in the following sports: soccer [534, 611], water polo [11], tennis [92], hammer throw [545], judo and karate [12], wheelchair sports [535], cross-country skiing [324, 405, 528], rowing [295, 503], yachting [401], ironman triathlon [308, 310], running (distances from 100 m to 10,000 m) [335], ultra-marathon [251, 309], gymnastics [105, 154], modern pentathlon [104], handball [379], surfing [38], volleyball [196, 359], luge [133], baseball [250], swimming [504] and alpine skiing [600].

Given the associations identified between body composition and successful sporting outcomes, regular physique assessment is now considered a routine undertaking within the majority of high performance athletic programs. These assessments can be used to evaluate the effectiveness of training and dietary interventions, and/or to make comparisons against normative or reference data, whether that be from a sports performance or health perspective.

Body composition comparison with other team sport athletes

In the majority of professional full contact team sports, such as AFL [64, 66, 216, 580], rugby league [141, 197], and rugby sevens [242, 243, 530], most athletes are relatively homogeneous in regards to body composition traits. Conversely, elite RU athletes are characterised by the heterogeneity of their physical attributes [163]. Likewise, NFL athletes exhibit a range of physiques of comparable heterogeneity to those of RU athletes [73, 268, 364, 447, 559].

NFL defensive linemen, linebackers and tight ends possess similar physique traits to RU forwards (Table 2.2), as do NFL wide receivers and defensive backs in comparison to RU backs [73, 143, 315, 447, 448]. Further, studies in NFL populations indicate a progressive increase in the BM, stature, and BMI of elite athletes over time [143, 230, 315, 417], with greater values for these measures in elite athletes in comparison to sub-elite athletes [305, 369].

Table 2.2. Comparison between body composition characteristics of rugby union forwards and NFL athletes of particular positions.

	Rugby Union [448]		NFL [143]	
	Forwards	Defensive Linesmen	Linebackers	Tight Ends
Stature (cm)	1.89 (1.85 – 1.98)*	190.9 ± 2.9	186.7 ± 3.9	192.9 ± 3.6
Mass (kg)	110.0 (108.0 – 120.0)*	132.9 ± 14.7	109.9 ± 4.3	113.9 ± 4.2
BMI (kg/m²)	30.8#	36.5 ± 4.5	31.6 ± 1.6	30.6 ± 1.6
FM (kg)	19.1 ± 5.4	33.3 ± 12.3	17.9 ± 3.8	18.4 ± 4.5
BF%	17.7 ± 4.3	25.2 ± 7.6	17.0 ± 3.2	16.8 ± 3.8

Mean ± SD; BMI = body mass index; FM = fat mass; BF% = body fat percent.

* Reported in the study as median (IQR).

Calculated from stature and mass medians reported in study.

Physique in rugby union

RU has evolved into the 21st Century as a highly skilled and fast paced sport, with both participation and spectatorship continuing to grow [91, 464]. RU is now a multi-billion dollar business [416], and as with any money making enterprise, the best employees will be sought after, which in the case of professional sport, are the athletes. In RU, the fraction of the population who possess the physical attributes alone to fit the prototype for an elite athlete is minuscule, before even considering the technical skills and psychological qualities required. Indeed, in 2001, only three in 1000 people from the Australian population were both taller and heavier than the average Australian RU forward [416], highlighting the Darwinian nature of RU.

Since the introduction of professionalism there has been significant changes in the patterns of play as a result of new training methods, law changes, technological advancements in game analysis, and developments in sport science practice [18, 26, 169, 192, 416, 451, 496, 603]. This has resulted in marked changes in the physique of athletes, making athletes with a morphology compatible with success a desirable commodity at the elite level. This has also

stimulated research interest pertaining to physique traits, with over 100 papers having been published in the last 25 years reporting some form of body composition measurement on RU athletes [10, 14, 15, 17-19, 26, 34, 36, 41, 48-52, 54-56, 60-62, 76, 79, 80, 91, 94, 97, 112-114, 117-120, 124-126, 128-132, 134, 135, 140, 150, 161, 166, 167, 172-175, 180, 182, 184, 185, 191, 192, 194, 200, 206, 211, 225-227, 242, 252, 253, 271, 297-299, 317, 322, 333, 350, 360, 362, 363, 366, 367, 375, 376, 381, 404, 448, 450, 454, 455, 463, 488, 495-497, 511, 514-517, 520, 541, 550, 563, 572, 576, 588, 593, 596, 598, 599, 602, 605, 608, 614].

Stature

Stature has been identified as an extremely important physique trait of elite RU athletes, with teams comprising taller players performing better in RWC tournaments [40, 416, 496]. Specifically, greater stature allows for extra elevation in line-outs, with successful line-out completion also being correlated with winning teams [277, 420, 488]. Indeed, the higher the level of playing competition, the greater average stature of the athletes [163], with the stature of both forwards and backs at elite and sub-elite levels trending upwards since the inception of professionalism (Figure 2.2). Speculatively, backs may be becoming taller over time given that an athlete with greater stature can carry more LM without compromising sprinting speed due to possessing longer leavers, thus enabling greater stride lengths. Indeed, this has been shown in successful elite sprinters [164, 262, 565, 595, 597].

Given the distinct positional requirements of RU, significant differences in stature exist between forwards and backs (Figure 2.2). In the 2011 RWC, the average stature of forwards was 190.0 ± 7.0 cm (mean $\pm$ SD), in comparison to the backs average stature of $184.0 \text{ cm} \pm 4.0 \text{ cm}$ [40]. Within the forwards, second row players have been identified as the tallest, averaging 198.3 ± 3.2 cm [192].

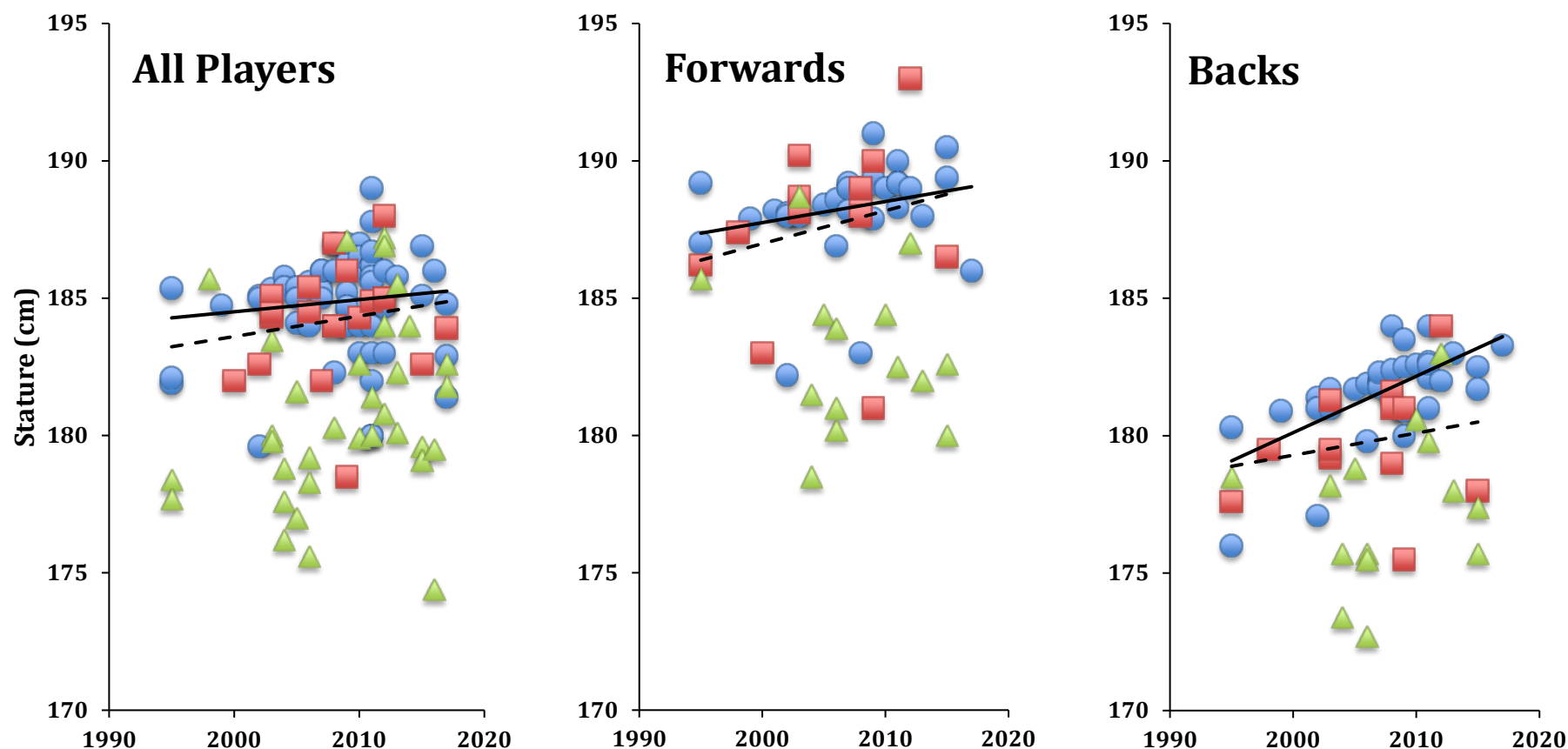


Figure 2.2. Stature of rugby union athletes reported between 1995 and 2017. Elite – blue circles/solid line of best fit; sub-elite – red squares/dashed line of best fit; club level/junior – green triangles [10, 14, 15, 17-19, 26, 36, 41, 52, 54-56, 60-62, 76, 79, 80, 91, 112-114, 117-120, 124-126, 128-132, 134, 135, 140, 150, 161, 166, 167, 172-175, 180, 182, 184, 185, 191, 192, 194, 200, 206, 211, 225-227, 242, 253, 297-299, 322, 333, 350, 360, 362, 363, 375, 376, 381, 404, 448, 454, 455, 488, 495-497, 511, 514-516, 520, 541, 550, 563, 572, 576, 588, 593, 596, 598, 599, 605, 614].

Body mass

As with stature, the BM of RU athletes has progressively increased over the past half century [416, 451, 496, 497], particularly since the introduction of professionalism (Figure 2.3). Indeed, in the early 21st Century the BM of RU forwards was reported to be increasing at a rate 2.6 times secular trends [416]. Higher total BM is associated with greater force production in the RU scrum [454]. Further, with the extremely high number of contact circumstances in a match [452, 515, 572, 573], greater BM, particularly within the forwards, has been shown to have a strong correlation with overall team competitive success [40, 416, 496].

Unlike stature, which is in the most part genetically predetermined, BM is adaptable, and has been increasing in elite populations with the additional attentiveness to nutritional practices and specialised conditioning provided in the professional training environment [163]. This also explains the distinctive differences in BM across playing levels [18, 163, 185, 448, 497, 516], although the BM of sub-elite forwards is increasing towards that of elite forwards (Figure 2.3). Similar trends are shown when BM is expressed relative to stature, i.e. BMI (Figure 2.4) [402].

Given the distinct on-field demands of RU athletes, BM varies considerably based on the requirements of specific positions. The tight five forwards (front row 113.3 ± 7.9 kg; second row 114.2 ± 6.1 kg) are heavier than the back-row forwards (107.3 ± 5.7 kg) [192], reflecting their specific roles in the scrum [454]. Within the backs, centers (97.2 ± 6.9 kg) are the heaviest, followed by outside backs (94.2 ± 7.9 kg), with half backs being the lightest (87.8 ± 6.7 kg) [192].

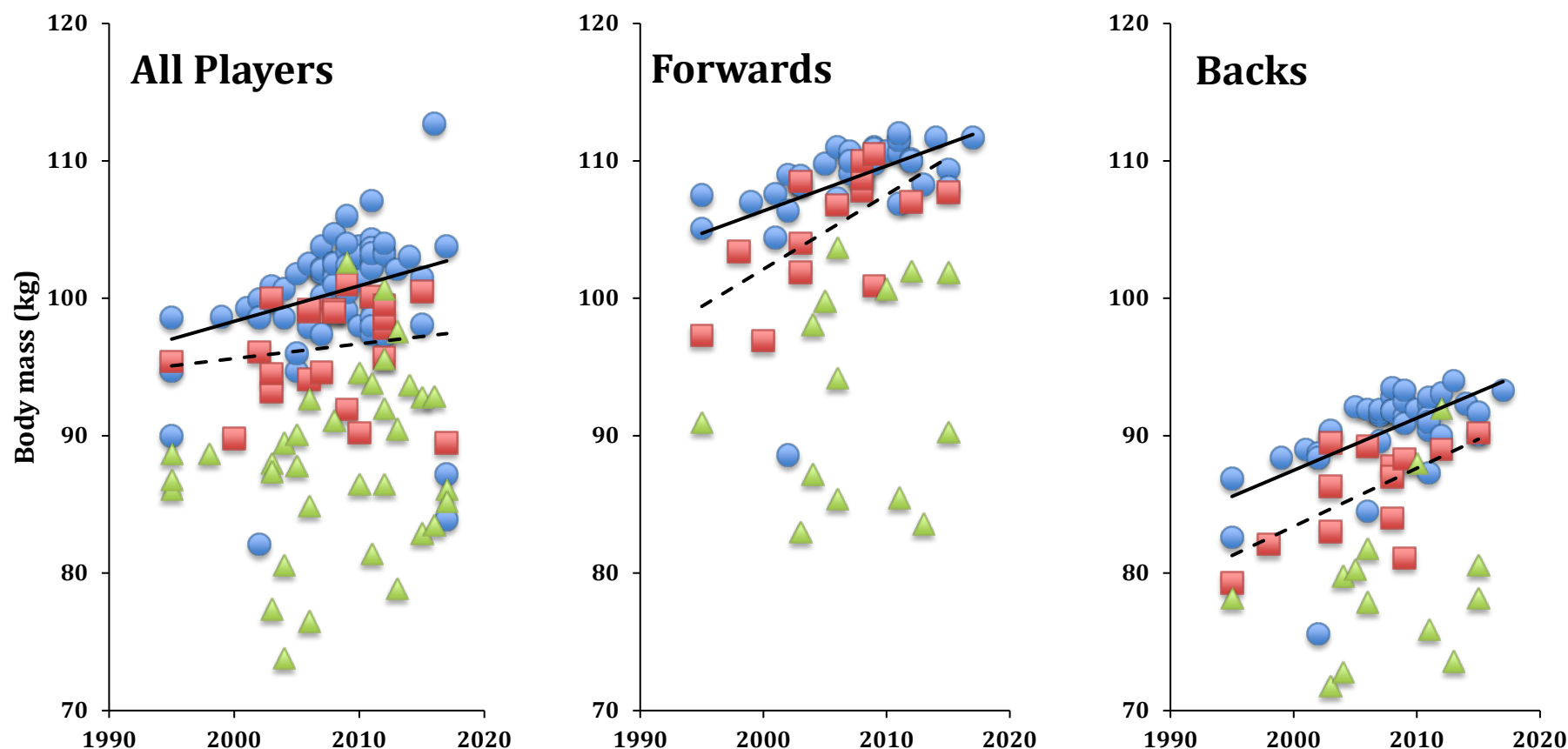


Figure 2.3. Body mass of rugby union athletes reported between 1995 and 2017. Elite – blue circles/solid line of best fit; sub-elite – red squares/dashed line of best fit; club level/junior – green triangles [10, 14, 15, 17-19, 26, 36, 41, 52, 54-56, 60-62, 76, 79, 80, 91, 112-114, 117-120, 124-126, 128-132, 134, 135, 140, 150, 161, 166, 167, 172-175, 180, 182, 184, 185, 191, 192, 194, 200, 206, 211, 225-227, 242, 253, 297-299, 322, 333, 350, 360, 362, 363, 375, 376, 381, 404, 448, 454, 455, 488, 495-497, 511, 514-516, 520, 541, 550, 563, 572, 576, 588, 593, 596, 598, 599, 605, 614].

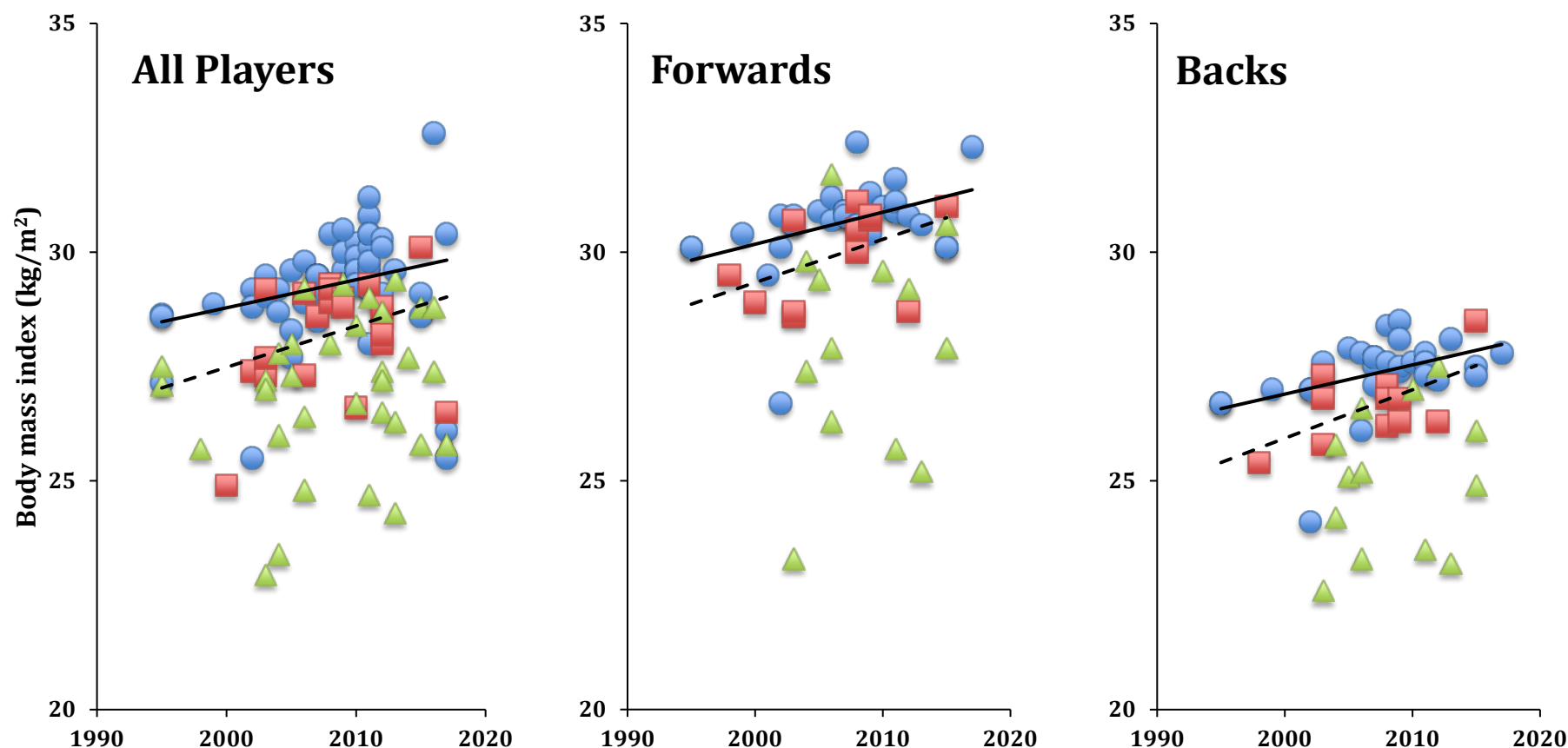


Figure 2.4. Body mass index (BMI) of rugby union athletes reported between 1995 and 2017. Elite – blue circles/solid line of best fit; sub-elite – red squares/dashed line of best fit; club level/junior – green triangles [10, 14, 15, 17-19, 26, 36, 41, 52, 54-56, 60-62, 76, 79, 80, 91, 112-114, 117-120, 124-126, 128-132, 134, 135, 140, 150, 161, 166, 167, 172-175, 180, 182, 184, 185, 191, 192, 194, 200, 206, 211, 225-227, 242, 253, 297-299, 322, 333, 350, 360, 362, 363, 375, 376, 381, 404, 448, 454, 455, 488, 495-497, 511, 514-516, 520, 541, 550, 563, 572, 576, 588, 593, 596, 598, 599, 605, 614].

Body composition – fat mass and lean mass

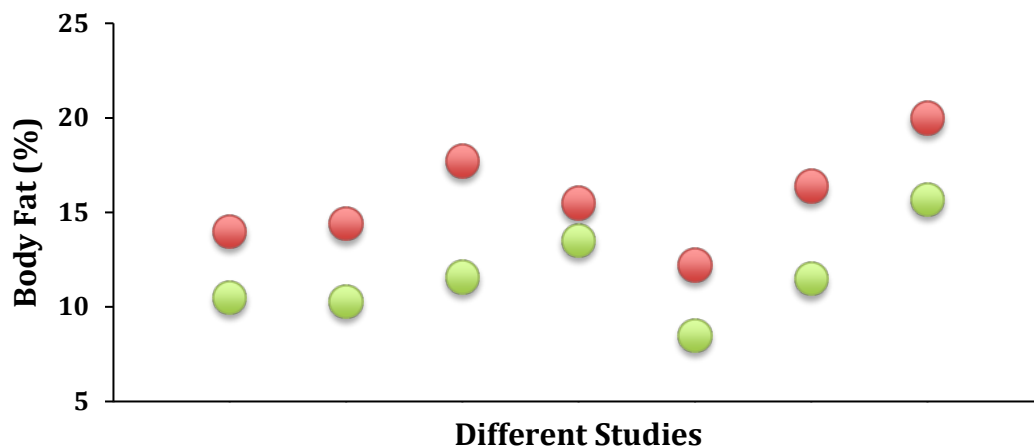
As total BM is comprised of both FM and LM, absolute and relative BM (BMI) may not be the best measures to use when assessing the relationship between body composition and competitive success. Indeed, excess body fat has negative implications for thermoregulation [232, 499], and increases energy expenditure during exercise [165]. Additionally, an increase in FM has the potential to attenuate force production according to Newton's second law of motion ($a = F/M$). Specifically, an increase in FM (M) without a corresponding increase in muscle force (F) will reduce acceleration (a) [165, 242, 333]. This is important given the fundamental role of momentum, and the generation of explosive force, in determining the outcome of tackle contests and other high impact match activities [237, 238]. Conversely, increases in LM have been proposed to improve the power-to-weight ratio of players, thus increasing the ability to generate force and proliferate acceleration, strength, power and speed [55], whilst potentially attenuating the risk of contact injury [198]. For these reasons, the monitoring and modification of body composition in elite RU athletes, beyond simply looking at BM, is important to develop optimal training and nutrition interventions to maximise performance outcomes.

Relative FM (often referred to as BF%) is regularly reported in elite RU athletes [76, 131, 184, 322, 333, 448, 514], with forwards consistently exhibiting a greater BF% (Figure 2.5). Forwards also display higher absolute FM, as indicated by skinfolds, and LM, as indicated by the lean mass index (LMI; skinfold measures adjusted for BM [141, 166, 511]), in comparison to backs (Table 2.3). Additionally, elite backs have been shown to have lower skinfolds compared to sub-elite backs, despite also possessing greater LM [448].

Table 2.3. Sum of seven skinfolds and lean mass index of elite rugby union athletes.

Source	Sum of seven skinfolds (mm)		Lean mass index (kg/mm ^{0.14})	
	Forwards	Backs	Forwards	Backs
Duthie et al., 2006 [166]	84 ± 19	60 ± 13	58.8 ± 3.6	52.4 ± 3.4
Appleby et al., 2009 [14]	71.2 ± 13.9	51.9 ± 6.9	63.4 ± 2.0	52.5 ± 4.4
Pumpa et al., 2012 [448]	70.2	47.4	60.7	51.9
Bradley et al., 2015 [76]	87.6 ± 25.8	63.5 ± 15.7	58.5 [#]	51.2 [#]

Mean ± SD; [#] Calculated from sum of seven skinfolds and body mass averages reported in study.

**Figure 2.5.** Body fat percentage of rugby union athletes between 2008 and 2017. Forwards – red circles; backs – green circles [76, 131, 184, 322, 333, 448, 514].

Regional body composition

With the introduction of new assessment techniques, the reporting of regional body composition in RU has become possible [242, 333, 448]. This includes the reporting of bone mineral content (BMC), LM and FM in arm, leg and trunk regions. Differences in regional body composition have been reported based on position, with forwards exhibiting higher absolute FM and LM, as well as higher relative FM in all regions [242]. Indeed, regional body composition may have implications from a performance perspective, with faster sprinters having lower

relative body fat and greater muscle thickness in the upper thigh than their slower peers [320]. Further, deposition of mass more proximal to the joint may enhance biomechanical efficiency [242, 478].

Regional body composition assessment can also measure adiposity in the android and gynoid regions. Android fat designates the distribution of adipose tissue around the central abdominal region, is more common in males, and is known to be associated with cardiometabolic risk more so than peripheral (arm and leg) fat or gynoid fat [280]. Gynoid fat is distributed around the hips, thighs and bottom and is proportionally higher in females. In elite RU athletes, forwards have been shown to have a substantially larger amount of android fat than backs both proportionally ($16.0 \pm 4.0\%$ vs $12.3 \pm 2.5\%$), and in absolute terms (1165 ± 392 g vs 723 ± 244 g) [242], which may have implications from a cardiometabolic health perspective.

Body composition adaptations

Pre-season conditioning is considered crucial for elite RU athletes, and consists of a high-volume, high-intensity training regime incorporating the multifaceted aspects of physical conditioning [20, 231, 412, 468]. The goals of the pre-season training phase are to increase aerobic and anaerobic fitness, speed, strength and power, which are often accompanied by specific body composition adaptations including increasing LM and decreasing FM [17, 76]. Meaningful reductions in FM and gains in LM have been shown to be achievable over a short yet intense 4-week pre-season program in elite RU athletes, with FM decreasing (1.4 ± 0.4 kg) and FFM (BMC + LM) increasing (2.0 ± 0.6 kg) [17]. Indeed, similar results have been observed over the pre-season in other contact sports such as rugby league [205, 228], AFL [64], and college footballers (NFL) [305, 559]. However, presently there is a paucity of literature pertaining to regional pre-season body composition changes in elite RU athletes.

During the competitive RU season, the main emphasis of the conditioning program is to maintain gains made in strength, power, and LM during pre-season training. This can be difficult, since conditioning volume during the playing season is reduced as the emphasis shifts to skill and tactical training, as well as the increased time spent on recovery and travel [20]. Generally, improvements in specific areas of physical conditioning during the competition phase of training are limited by the brevity of the training blocks [412]. Indeed, favorable pre-season body composition adaptations have been shown to dissipate during the season [333], the reasons for this likely being multi-factorial. As such, having an appreciation of the magnitude of pre-season adaptations possible, particularly from a regional perspective, may assist in the development of in-season programs to limit unfavorable changes.

Physical characteristics and health status in rugby union athletes

Given the well established association between size and success in RU, it can be hypothesised the development of taller, heavier, and more muscular RU athletes is likely to continue. Although this appears to be advantageous from a performance perspective, it is important to take a holistic view, and consider the implications this could have on both the short- and long-term health status of the athletes. Indeed, it has been suggested that after athletes reach a BM of ~114 kg (250 lbs), LM accumulation decreases, whereas FM accumulation increases at a more exponential rate [73].

Given the sheer size of elite RU athletes, the most pertinent health issues to consider are those related to obesity, namely T2DM and cardiovascular disease [145, 383, 525, 544, 607]. In 2010, overweight and obesity were estimated to cause 3.4 million deaths and accounted for 3.9% of years of life lost worldwide [402]. According to the World Health Organisation (WHO) guidelines [270], many elite RU athletes, particularly forwards, are classified as overweight (BMI 25.0 to 29.9 kg/m²) or obese (>30.0 kg/m²). However, given frame size, proportions and muscularity all independently influence BMI, it has been acknowledged as not a true reflection of physique in athletic populations [2].

Consequently, and as in general populations, abdominal adiposity has been identified as an important indicator of health status which may be more pertinent to athletes [73].

VAT, which incorporates fat stored in the intra-abdominopelvic region bounded by the abdominal wall and the pelvic floor [502], is an established marker for cardiometabolic risk independent of subcutaneous abdominal tissue (SAT; external fat) and total body fat [145, 187, 283, 562]. There are distinct anatomical and functional differences that exist between SAT and VAT [263]. Anatomically, SAT is located superficial to the muscle layer and under the dermis [502]. SAT has large storage capabilities, and unlike VAT, the subcutaneous adipocytes can expand the capillary network to match the increased adipocyte diameter [157, 204, 519].

Abdominal obesity plays a significant role in the development of cardiovascular disease and T2DM [567, 568]. Indeed, higher levels of VAT are strongly associated with dysfunctional glucose and lipid metabolism, including hypertriglyceridemia, low levels of high-density lipoprotein cholesterol (HDL-C), increased low-density lipoprotein cholesterol (LDL-C), elevated fasting glucose, and hyperinsulinemia [146-148, 187, 202, 203, 210, 224, 248, 300, 318, 392, 400, 418, 471, 473, 475, 544]. Additionally, isolated lipid measures are associated with cardiovascular disease, insulin resistance, metabolic syndrome, and overall mortality [171, 275, 301, 302, 581]. Further, VAT is an independent predictor of elevated blood pressure, with hypertension being highly prevalent in individuals with obesity [81, 461]. Finally, VAT accumulation appears to be influenced by gender and ethnicity [16, 93, 95, 282, 328, 469, 529]. Individuals are considered to be at an “increased risk” of cardiovascular disease when VAT surface area $>100\text{ cm}^2$, and “high risk” when VAT $>160\text{ cm}^2$ [422, 431]. Furthermore, studies have shown that individuals with VAT $>130\text{ cm}^2$ have distinctive blood and metabolic disorders [144]. The VAT to SAT ratio (VAT:SAT) can also be used as a proxy of disease risk, with a cut-off of 0.4 used as a threshold, above which individuals with obesity are likely to exhibit glucose intolerance and hyperlipidemia [190].

As in RU, a large proportion of elite NFL athletes are considered obese according to the BMI scale [230, 364]. More specifically, the linemen, who are the largest athletes in terms of BM and FM, had significantly greater VAT levels (1.2 ± 0.6 kg) compared to all the other positional groups (0.3 ± 0.2 kg; 0.3 ± 0.1 kg) [73]. Further, it has been proposed that initially excess fat is stored preferentially as SAT, though after 20% body fat is reached, significant VAT accumulation begins [73]. The high adiposity levels reported in NFL populations, particularly in linesmen, have been associated with higher cardiometabolic risk factors during their career [561], and an increased prevalence of metabolic syndrome and cardiovascular disease after they retire [39, 380].

Similar to the findings in NFL populations, “supersized” athletes from other sports have been linked to cardiometabolic complications. Professional Chinese strength sport athletes in the heaviest weight class were found to be at an increased risk of cardiometabolic disease compared with athletes in other weight categories, displaying significantly higher total cholesterol (TC) and triglycerides (TG), and lower HDL-C [220]. However, a population of Sumo wrestlers were found to have a lower VAT:SAT in comparison to obese controls (Figure 2.6), as well as normal plasma glucose, normal TG, and lower TC compared to non-obese controls [365]. Likewise, heavyweight judo athletes were found not to have increased cardiometabolic risk according to blood biochemical markers, despite displaying greater FM and VAT compared to a matched heavyweight football control group [387].

There is a paucity of research on cardiovascular disease risk within RU populations. Larger sub-elite RU athletes have been shown to have higher VAT levels, with VAT stores being significantly correlated with TG levels [614]. Furthermore, over a fifth of these athletes met the criteria for visceral obesity ($\text{VAT} > 100 \text{ cm}^2$) based on general population thresholds [431, 614]. However, given the athletes were not at the elite level, and VAT was measured via a non-criterion and non-validated method [83, 84], the results should be interpreted with caution.

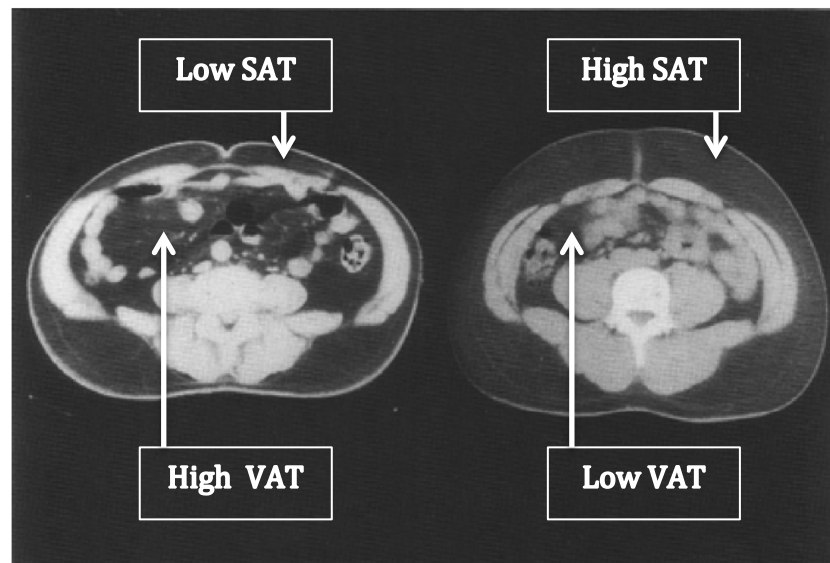


Figure 2.6. Abdominal computed tomography (CT scan of active Sumo wrestler (right) showing a large amount of SAT with relatively little VAT compared with a person of similar overall adiposity (left). Adapted from Matsuzawa et al., 1993 [365].

There have been some studies in which lipid profiles have been reported in non-elite RU athletes [264, 360, 363]. Specifically, one study reported forwards had significantly lower HDL-C than backs, with no significant differences reported in LDL-C or TG [264]. In other sports with “supersized” athletes, males in the unlimited body-weight categories in strength sports were found to have significantly higher TC and TG, and lower HDL-C, compared to athletes in limited body weight classes [220].

Despite some elite RU athletes possessing similar physique characteristics to those in other “supersized” sports, to date there has been no research into the cardiometabolic disease risk in this population from either a visceral adiposity or blood biochemical perspective. As such, investigations are warranted to ensure athlete health is not compromised in the pursuit of improved performance. Further, given the well established association between exercise and reductions in VAT [59, 208, 281, 388, 429, 512, 583] and biochemical markers of cardiometabolic disease risk [287, 288, 467, 569] in non-athletic populations, gaining an appreciation of the impact training stimulus has on these parameters in elite athletes would be valuable in determining potential long-term risk.

Summary

RU is a unique sport characterised by the heterogeneity in body composition traits exhibited by the athletes. The morphology of elite RU athletes has evolved over time, particularly since the introduction of professionalism, with athletes becoming taller, heavier, and more muscular. With the strong correlation between size and success, body composition assessment has become routine within this population, and understanding the physique traits exhibited by the athletes is important for sport science practitioners. This may be particularly pertinent from a regional body composition standpoint, given the potential for regional adaptations to stimulate improved performance. Furthermore, given the sheer size of the individuals at the elite level, particularly forwards, being able to appreciate the health implications for the more “supersized” athletes is of great importance. Presently, there is no published literature investigating the health status of elite RU athletes. Given the established relationship between short-term and post-career cardiometabolic risk in NFL athletes, and the similar morphology and body composition trends of athletes within the respective sports, exploration into this in an elite RU population is warranted.

POLYNESIANS IN RUGBY UNION

It has become increasingly difficult to find athletes of the size and shape required to compete at the highest level... In response to this, various strategies have emerged to widen the net and to make sure that less potential players slip through. One of these strategies is increased globalisation and international recruitment in sport.

International recruitment has become a priority in the search for RU athletes with the required morphology to compete at the elite level [409, 416, 497]. Polynesian athletes are highly sought after given their passion for RU, and anecdotally these athletes are larger and more muscular relative to Caucasian athletes. Indeed, population based research confirms Polynesians are larger and more muscular than Caucasians, although they also have higher levels of abdominal fat [479, 480, 537, 538]. Given there is evidence of a higher rate of lifestyle disease within Polynesian populations [214, 402], the “supersized” status of some of the athletes within this ethnic group may need to be considered from the perspective of potential health implications.

The definition of the term “ethnicity” from a research perspective is the source of ongoing debate, and continues to evolve over time due to political trends [24, 75, 373]. A simple definition of ethnicity proposes people are categorised by their place of birth, culture, traditions and race [115]. However, given the increasing multicultural, and somewhat transient nature of modern society, place of birth, culture, and even traditions may not necessarily provide an accurate portrayal of an individual’s ethnicity. The premise of this thesis is to investigate the role phenotype expression plays in body composition differences, and disease risk, in elite athletes of Caucasian and Polynesian descent. Previous research focused on comparing body composition traits in individuals of different ethnicity has used grandparental heritage as the defining factor [116, 155, 480]. As this research is investigating differences based on phenotype expression, as previously described in sedentary populations [122, 479, 537, 538] grandparental heritage will be used throughout this research series. This thesis will focus on Caucasian and Polynesian athletes as anecdotally these make up the vast majority of elite

RU athletes in Australia where the research was conducted. Polynesian athletes include those with grandparental heritage (at least three out of four) linked to Micronesia, Melanesia, and Polynesia [46, 90, 285, 286, 303, 304, 372, 428, 532, 589, 606, 612]. “Caucasians” will be the term used to describe White Australians, which may also be referred to as White Europeans or simply Whites in other contexts.

Polynesian participation in rugby union

For many Polynesians, RU is more than just a sport. For example, in Fiji, RU is part of their colonial heritage, and was used by British colonists to legitimise their authority over the Fijian people [279, 490]. Undeniably, RU has become an integral part of contemporary Fijian culture [219, 279, 464]. Similarly in Samoa, RU plays an important role in young men’s socialisation as they represent their families and villages in competition for local audiences, including the village chiefs [109]. RU takes place in the context of, and is influenced by *fa’asāmoa* (the Samoan way of being and doing things), and their physical style of playing and aggressiveness is regarded to symbolise Pacific masculinity [109].

Polynesian dominant RU nations have been involved in the RWC since its inception in 1987. In October 2017, Fiji (ranked 9), Tonga (ranked 13) and Samoa (ranked 16) were all ranked in the top 20 of the IRB world rankings, along with Australia (ranked 3) and New Zealand (ranked 1), both of which are comprised of high proportions of Polynesian athletes (data retrieved from www.worldrugby.org on 27 October 2017). This is despite the relatively miniscule populations of these countries compared to the others in the top 20. For example, France (ranked 8) has a population in excess of 66 million, compared to the population of Fiji (ranked 9) of less than 1 million. The increasing popularity of RU in the Pacific may well be due to the distinctive yet natural morphology of Polynesians predisposing them to success and attracting the attention of international recruiters [409], as well as the strong links to their cultural heritage.

Physique traits of Polynesians

Body composition differences between ethnicities have long been reported in the literature [45, 408, 621]. The comparison of physique traits between Caucasian and Polynesian ethnic groups has been well documented over the past 20 years, and has been of particular interest to researchers given that Polynesian people are widely regarded as the largest people in the world [480].

In male populations, it has been established that Polynesians have higher levels of absolute LM than their Caucasian counterparts, with a particular study finding significant differences in a healthy population of New Zealand Polynesians (69.7 ± 7.5 kg) and Caucasians (62.9 ± 6.2 kg) [256, 457, 480]. Further, at any given level of BF%, the BMI of Polynesians was significantly higher than that of Caucasians [481, 537, 538], and likewise for a comparable BMI, BF% for Polynesians was 4% lower in comparison to Caucasians [479]. Additionally, following adjustments for stature and BM, Polynesians continue to display higher levels of FFM, and lower levels of FM [480]. Similarly, BMI's of 25.0 and 30.0 kg/m² in Australian Caucasian men corresponded with 27.5 and 35.8 kg/m² in Tongan men with comparable FM [122], whilst differences in BF% were not found to be significant [123]. For this reason, cut-offs using BMI to define overweight and obesity should differ in Polynesian populations [123, 479-482, 537, 538, 543].

Regionally, LM in peripheral (arm and leg) regions has been shown to be significantly higher in Polynesians compared to Caucasians, both before (26.9 ± 2.8 kg vs 31.7 ± 2.4 kg) and after being adjusted for stature and BM [479]. Indeed, these proportional differences may provide a morphology more compatible with success in RU; however, this is yet to be explored in elite Polynesian athletes. Additionally, Polynesians presented with longer legs than Caucasians, along with higher bone mineral density (BMD) and BMC after adjustments for stature and BM [479]. However, Polynesians have greater stores of abdominal FM than Caucasians both in absolute and relative terms, and as a

percentage of total FM [480], which may infer cardiometabolic health complications.

There is limited literature exploring ethnic physique differences in athletic populations [534], including none in elite Polynesian athletes. However, elite junior rugby league and RU athletes of Polynesian descent are significantly taller, heavier and more muscular than non-Polynesian athletes [99, 316, 425]. Given the significant body composition differences recognised in general Polynesian populations, as well as in youth Polynesian athletes, investigations into the body composition traits of elite Polynesian athletes are warranted, which may offer insight into the trainability of these physique traits.

Disease risk in Polynesians

There has been significant research undertaken looking at differences in disease risk markers across different ethnic populations [6, 29, 63, 82, 93, 142, 168, 345, 529]. In the Pacific region, T2DM and cardiovascular related issues were rare in most countries until about 60 years ago [622]. Since then, diabetic abnormalities in Polynesian people have been rapidly on the rise [445, 622], and the prevalence of T2DM is among the highest recorded worldwide [98, 213, 390]. In Nauru, age-standardised prevalence of T2DM was non-existent in 1952, yet occurred in 41.0% of the population in 2002 [151], and in Tonga the prevalence of T2DM doubled to 15.1% in the last quarter of the 20th Century [110].

Unquestionably, the high prevalence of obesity through the Pacific is contributing to the incidence of T2DM in Polynesians.

The proportion of overweight and obese adult males in Samoa (83.0% overweight, 45.9% obese) and Tonga (83.5% overweight, 52.4% obese) far exceeds rates elsewhere in the world using traditional BMI cut-offs [402]. Indeed, the increasing rate of obesity through the Pacific has been highlighted as a concern by the WHO [592]. Cardiovascular disease risk in males is significantly higher in Samoans and Tongans in comparison to Caucasians [533], whilst elevated microalbuminuria, a marker of increased risk for cardiovascular

morbidity and mortality [556], is 2.5 fold more common among Polynesians compared to Caucasians [278].

In a study undertaken in Wallis and Futuna, an isolated island in the South Pacific between Fiji and Samoa (population ~15,000), between 1980 and 2009 in males 25–64 years of age, the prevalence of T2DM increased from 2.3% to 12.2%. In addition, increases were noted in BMI >32.0 kg/m² from 14.1% to 45.4%, TC >5.2 mmol/L from 6.8% to 20.7%, TG >1.7 mmol/L from 2.0% to 32.1%, and mean cholesterol increased from 3.9 mmol/L to 4.4 mmol/L [344]. The isolated nature of the population suggests the changes in the health status of Polynesians over the past quarter century are due to social, cultural, and environmental changes, which has resulted in the increased availability of convenience food and activities promoting sedentary behaviour [98, 423, 466, 592, 622]. Indeed, this supports the Thrifty Genotype Hypothesis, which proposes that the high prevalence of T2DM and cardiometabolic disease in Polynesians is caused by the disjunction between genes and environment, specifically the genes which facilitated survival during times of famine by allowing more efficient energy storage [67, 151, 390, 391, 397, 398, 622]. The Thrifty Gene Hypothesis remains a highly contentious issue [28, 57, 214, 234, 391, 414, 421, 440, 500, 521, 526], with no definite scientific conclusions having been drawn. However, given that the rapid escalation of obesity rates in the Pacific far exceeds changes possible in the genetic pool alone, it is likely a combination of lifestyle changes and genetics that contribute to the emerging health issues in Polynesian individuals [313].

The rapid industrialisation and urbanisation of the Pacific, along with the genetics of Polynesians, all appear to be causative factors to the high prevalence of cardiometabolic disease in Polynesian populations, with T2DM, hypertension and cardiovascular disease accounting for three quarters of all deaths throughout the Pacific [592]. Additionally, and of most concern, is that Polynesians demonstrate greater health vulnerability [549] with the life expectancy of Polynesians not increasing at the same rate as the Western world. Fijian life expectancy, as an example, having not increased since 1985 [96, 542].

Indeed, there are huge health disparities between Polynesians and Caucasians, and important differences in cardiovascular disease risk profiles and T2DM incidence [533]. The prevalence of these health complications is projected to continue to rise, driven by the underlying problem of obesity [342]. However, given the established protective effects of exercise against cardiometabolic related complications, highly trained individuals are a unique population which may be safeguarded against these risks, making Polynesian athletes an important population to explore in the context of cardiometabolic disease risk.

Summary

The number of Polynesian athletes participating in RU at the elite level is increasing due to their genetic predisposition to possess a morphology compatible with success. However, Polynesians also possess greater abdominal adiposity which is closely related to an increased risk of cardiometabolic complications. It is unknown whether this is well managed within an elite sporting environment; but regardless, risk may present when exercise stimulus is removed, for example at the end of an athletes playing career. Little is known about the interrelationship between these variables, and as such targeted investigations in a population of “supersized” Polynesian athletes is warranted. The results of such investigations may aid sport science and sport medicine practitioners in the development of appropriate interventions for these athletes, from both a performance and a health standpoint.

BODY COMPOSITION ASSESSMENT IN RUGBY UNION

Upon taking a bath, Archimedes (c.287–212 B.C.) observed that the buoyant force on a submerged object equals the mass of the water it displaces, enabling the calculation of its specific gravity. He took to the streets, naked, crying “Eureka”.

The findings of Archimedes sparked an interest in human body composition assessment, which today is routinely undertaken on elite athletes, primarily from a performance perspective. When measuring body composition in athletic settings a range of assessment techniques are utilised. The choice of assessment tool is based on a number of factors, including cost, risk, how the equipment facilitates the athletes based on their size, availability, expertise needed to take the measure, burden placed on the athletes, and what outcome measures are required [2]. The ability of athletes to present rested, fasted and well-hydrated [152, 393, 566] also needs to be considered with a number of assessment tools, such as air displacement plethysmography (ADP; BODPOD) [332, 560], hydrodensitometry [47, 78, 85], bioelectrical impedance analysis (BIA) [44, 102, 321, 351], and DXA, as these have been shown to be highly influenced by athlete presentation [152, 181, 233, 393, 433, 477, 547]. In contrast, SA is not influenced by athlete presentation [293]. Special consideration also needs to be given to the assumptions underpinning the measurement tool being used, and the impact this may have on athletic individuals in which the assumptions may be violated [85, 293, 508, 609].

In addition to the body composition assessment techniques mentioned above, ultrasound [311, 386, 435, 436], 3D photonic scanning [590], and medical imaging techniques (MRI and computed tomography [CT]) [474] have also been used to assess physique in athletic populations. The reference method for body composition assessment is the four compartment (4C) model. This combines a number of assessment techniques in order to minimise assumptions and maximise accuracy [591, 610], is both time consuming and expensive, and generally confined to use in research settings [2, 609]. A summary of the assessment methods utilised in athletic populations is provided in Table 2.4.

In Oceania the most commonly used body composition assessment techniques in athletes of all playing standards, including elite athletes, are SA (using International Society for the Advancement of Kinanthropometry [ISAK] techniques) and DXA [377]. SA using skinfolds is the most frequently used method of body composition assessment in RU populations, with data having been reported in elite [14, 17, 76, 80, 94, 131, 166, 184, 185, 367, 375, 448, 511, 514, 550, 593], sub-elite [10, 126, 130, 173, 184, 185, 206, 211, 253, 271, 350, 361, 368, 404, 448, 495, 515, 516], and junior [161, 362, 368] populations. The use of DXA on RU athletes is now common practice in many professional clubs, and there have been numerous instances of research being undertaken using this technology [55, 112, 140, 172, 174, 242, 322, 333, 448].

Table 2.4. Features of body composition assessment methods. Adapted from Ducker et al. 2018 and Ackland et al. 2012 [2, 158].

Technique	Best Used For	Advantages	Limitations
Surface anthropometry (SA)	- Tracking changes in physique over time - Assessing body size and shape	- Relatively low cost equipment and training - Portable and convenient for field based data collection - Reliable measures with trained technicians	- Requires a skilled and certified (ISAK) technician - Unable to estimate absolute body composition values
Dual-energy X-ray absorptiometry (DXA)	- Whole and regional body composition - Estimate of VAT	- Fast and easy for participant - Regional body composition assessed - VAT estimates available	- Small radiation dose – may limit number of scans per annum - Bed size may not accommodate athletes - Availability and cost may limit consistent use
Medical imaging – magnetic resonance imaging (MRI) and computed tomography (CT)	- Research where high accuracy is needed - Criterion measures of VAT	- No radiation (MRI) - VAT measurement - Very accurate	- Expensive and not readily available - High radiation (CT) - Long scan times and analysis

Air displacement plethysmography (ADP; BODPOD)	Assessing body density and volume	- Fast tests - Minimal subject burden - Does not require water confidence (like hydrodensitometry does)	- Relies on suitable room to house unit - Sensitive to participant attire and body hair - Uses invalid assumptions in athletic populations
Ultrasound	- Assessing SAT - Tracking change over time	- Non-invasive - Minimal subject involvement - More objective than surface anthropometry	- Samples of SAT deposits only - Considerable operator skill needed - Relatively new method not fully validated - Significant analysis required
3D photonic scanning	- Assessing body shape, surface area and volume - Can be used to assess segment lengths	- Minimal subject involvement - Quick scan times - Can assess surface area and segment lengths	Hair and clothing will affect results
Bioelectric impedance analysis (BIA)	Assessing body composition where low cost, easy access, and low operator skill are the priorities	- Minimal subject involvement - Portable in field - Quick, cheap and widely available	- Poor accuracy - Hydration status affects results

4-compartment (4C) model	• Research settings	• Highly accurate	• Time consuming • Expensive • High subject burden • Limitations of the techniques it is derived from
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Surface anthropometry

SA is the scientific study of the measurement and proportions of the human body. It encompasses measurements of an individual's BM, stature, skinfold thickness, girths, bone lengths and breadths at specific body landmarks [357, 410, 527]. SA provides a simple, relatively inexpensive, and non-invasive method for estimating body composition that can be applied both in the laboratory and the field [2]. Standardised techniques have been developed to assess anthropometric parameters to ensure valid measurements [267, 357], including ISAK techniques which are used as the primary methodology of collection in the southern hemisphere.

The BMI has widely been condemned for use in RU populations, as the proportions and muscularity possessed by the athletes independently skews the BMI results, often reporting lean athletes as overweight or obese [2, 143, 364]. Given that the BMI has been shown not to be predictive of VAT in adults [418], and is not a consistent health measure across ethnicities [95, 122, 123, 469, 479, 480, 537, 538], it has little application in RU from a performance or health standpoint.

Waist circumference (WC) has been recommended in clinical guidelines [5] to assess obesity-associated cardiometabolic risk, with a WC ≥ 102 cm in men being associated with T2DM and cardiovascular issues [307, 327, 615]. Although generally accepted and implied as an indirect measure of VAT [418], WC has been shown to have stronger correlations with SAT [74]. Furthermore, WC does not reflect the same VAT levels across different ethnicities [382, 469]. As such, similar to the BMI, its application in elite RU populations is questionable due to the unique morphology of the athletes. Of note is that the waist to hip ratio (WHR; ratio of WC [cm] to hip circumference [cm]), has been abandoned as a measure of health status. It was found to be the least predictive anthropometric measure of cardiovascular disease risk [69, 148, 579], and did not independently contribute to the prediction of SAT [107] or VAT [107, 418].

The waist to height ratio (WHt; ratio of WC [cm] and stature [cm]), is a simple screening tool for cardiometabolic disease risk that is more sensitive than the BMI [257, 424], can be used on males and females of all ages [343, 371, 486, 543], and allows the same boundary values (≥ 0.5 for “take care” and ≥ 0.6 for “take action”) for different ethnicities [23, 343, 486]. However, the use of this measure as an indicator of risk in “supersized” athletes has not been explored.

Skinfold measures, which are the thickness of a double fold of skin and compressed SAT [358], are the principal anthropometric variable that allows for the approximation of adiposity [170, 201] and fat distribution [106]. Qualified technicians are required for reliable data to be collected [89, 138, 260], and the use of correctly calibrated and consistent equipment is also required [212, 218, 349, 491, 513, 621]. Using doubly indirect methods, anthropometry can provide absolute estimates of FM and FFM. Indeed, over 100 regression equations have been created and reported in the literature for this purpose [106]. However, inconsistencies with fat compressibility and skin thickness [106, 162, 358], along with differences in fat patterning based on ethnicity amongst other factors [479, 480] has meant the underlying assumptions are not always validated [356, 358, 483].

There have been a number of studies completed within high-level athletic populations attempting to create skinfold prediction equations to estimate BF% in athletes [179, 459, 608]. Despite some of these showing promise to translate SA data into absolute measures within very specific populations, none have been strongly validated. However, it has also been postulated that equations created specific to a population and used within that population may have some merit if they can be validated. To date no specific equations have been created for use within elite RU populations. Additionally, no sport specific equation has previously differentiated between ethnicities, which is a variable pertinent to RU. Presently, it is recommended to use raw skinfold data, not estimates of body composition derived from regression equations, to measure relative changes in adiposity over time [2, 106, 459].

Dual-energy X-ray absorptiometry

In the context of RU populations, DXA is becoming a more commonly used method of body composition assessment over time as the technology becomes more affordable and commercially available [2, 86]. It provides a number of advantages in that it is fast, non-intrusive, and able to provide estimates of regional body composition. However, despite this, there have been no studies to date which have assessed pre-season body composition changes in elite RU athletes using DXA.

DXA is based on the differential attenuation of transmitted photons at two energy levels, as this can determine the mass and composition of any two known materials [290, 370, 432]. Originally developed to measure BMC and BMD [272], and used in the diagnosis of osteopenia and osteoporosis [4, 338], DXA is considered the reference technique for such assessments [70, 338]. DXA is also able to estimate whole and regional distribution of bone, fat and lean tissue [195, 240, 370]. As only two tissues can be estimated at one time from the two different photon energies emitted [13, 325, 407, 432], DXA first separates pixels into those with soft tissue only (FM and LM), and those with soft tissue plus BMC. Subsequently, in the pixels with BMC, soft tissue is not separately analysed and the equipment assumes the FM content of the adjacent area [432, 483].

Although DXA is able to produce detailed body composition information, there are a number of limitations of the technology which need to be considered, particularly in athletic populations. Firstly, differences in body composition estimates are produced between pencil-beam [348, 552] and fan-beam technologies [217, 406, 415, 552, 554, 555] even from the same manufacturer [108, 259, 265], different manufacturers [446, 518, 555], different machines [415, 555] and different software versions [306]. DXA technology assumes a hydrated constant in its partitioning of tissue into FM and LM [325, 437], meaning that non-euhydrated presentation of individuals may be the cause of some error [290, 348]. The “beam hardening” effect is another concern. This is the term used to describe the preferential loss of lower energy photons relative

to high-energy photons as a result of increasing body thickness [312, 443]. This may be a concern for assessment in RU populations given the morphology of the athletes. A few studies found DXA to overestimate FM as thickness increased [273, 326, 443]; however, this was not the unanimous outcome [274].

Regardless, manufacturers have claimed to improve software to overcome this issue [13, 312, 325], and good agreement has been shown with the reference 4C model [552].

Significant issues have been identified related to the validity [2, 348, 384, 396, 485, 507, 610], and reliability due to the subject presentation [209, 255, 325, 340, 393, 394, 433, 437, 547] and positioning [312, 323, 346, 396, 443] for the scan. The majority of these issues can be overcome with a standardised scanning protocol, which has now been established, well documented, and proven to decrease error [88, 292, 393, 394, 396].

Another limitation is that the size of the scanning area on DXA machines. Typically 60–66 cm wide and 193–198 cm long [395], this scanning bed size does not always accommodate large individuals, which is a potential concern for RU forwards who often exceed this stature and/or breadth [448]. However, solutions have been proposed for this with varying levels of success [178, 395, 484, 505]. Finally, DXA exposes subjects to a small dose of radiation. Typically this is minimal, approximately 0.5 μSv per scan [441, 552], which is the equivalent to approximately 1/100th of the radiation dose from a chest X-ray, or a single day's exposure of background radiation [441]. Although the radiation dose is small, this does mean most facilities will have limitations on the number of scans able to be completed annually on an individual [2]. Hence if DXA is purely relied upon for assessment in RU populations, there may be less opportunity for further personalisation of training and diet. In practice, DXA is often used to track longer term changes (such as over the competitive season), and complemented by SA measures at regular intervals during the season, thereby reducing their radiation exposure.

Relationship between surface anthropometry and DXA

In many elite sporting populations, including RU, both SA and DXA measures are routinely taken, often concurrently. As such, having an appreciation of the relationship between the techniques is important. In non-athletic populations the two assessment methods have shown good agreement in estimating body composition [319]. It is, however, important to recognise that although equations are able to provide good comparisons between techniques on a group or population level, significant differences remain when examining the equations on an individual level, or when tracking changes longitudinally [319, 489, 506].

In specific athletic populations, including elite climbers [176], professional soccer players [459], and participants in Gaelic games [153], it has been shown that generalised anthropometric equations are not able to be used to predict DXA derived BF%. A number of other studies agree with these findings, concluding that although individual skinfold measures are positively associated with DXA-BF% [177], generalised anthropometric models provide lower BF% estimates compared to DXA in both female [434] and male [35] athletes. As such, given the frequency that DXA and SA are used in the same group of RU athletes, investigations into the relationship between these two assessment techniques when tracking longitudinal changes is justified. Indeed, a study of professional rugby league players found that the LMI was able to offer an adequate and practical alternative for assessing FFM change over time when compared to DXA [141]. However, given the homogeneity of rugby league players compared to RU athletes from both a physique and ethnicity perspective, it is unlikely the application of these results is applicable across codes.

Magnetic resonance imaging

CT and MRI are considered the criterion measures of VAT, with coefficients of variation (CV) for repeated measures of approximately 2% [249, 498, 502, 585]. CT was the first method validated for directly quantifying VAT [72, 186, 215, 524, 548], with MRI later validated as an alternative to determine VAT that did not use ionizing radiation [186, 524]. The use of MRI in body composition assessment is generally confined to quantifying internal body fat, particularly VAT. MRI is a non-invasive technology which provides 3D visualisations of the anatomy, has immense flexibility in tissue contrast mechanisms, and is safely repeatable across longitudinal studies without restriction [186, 524]. The complex physics of MRI and the differences between approaches are beyond the scope of this review; however, can be found elsewhere [221, 584].

Most studies using MRI only measure and report a single slice of VAT area attributed to the increased cost, and increased time commitment in the analysis process to measure multiple slices and/or whole volumes [501]. Measures obtained in studies sampling a single slice have been observed to be affected by ethnicity and gender [142], and not found to be a reliable method for determining longitudinal changes in abdominal regional fat during weight loss [7, 21, 82, 289, 300, 330, 331, 456, 539, 540]. Additionally, some studies have also questioned the best site to take a single slice measurement [355, 494], with the correlation to VAT volume found to be significantly larger at the L2/L3 slice compared to the traditionally assessed L4/L5 slice [355]. Furthermore, a single slice MRI 5–10 cm above L4/L5 was found to be more powerful in detecting VAT changes [142, 501]. Given the above issues identified with single slice measures, it is unclear whether this would be an appropriate measure to use in an ethnically diverse population of elite athletes.

MRI is used frequently in athletic settings for the assessment and diagnosis of injuries. No studies on elite contact sport or RU athletes assessing VAT were found using either MRI or CT technologies. Given the ethnically heterogeneous population in RU, as well as the issues identified with body composition

assessment and lifestyle related disease risk identification in athletic populations, investigations using the reference MRI method would provide significant insight into the health status of these individuals.

Given the time commitment, cost, and availability of MRI and CT in practice, there has been recent interest in the use of other body composition techniques to provide estimates of VAT. BIA has been used in some studies; however, it has failed to provide a useful proxy measure of VAT in comparison to MRI measures [83, 84]. Indeed, BIA has been used in a population of RU athletes, although in this study the VAT outcomes were not compared to a reference measure [614]. The other body composition assessment technique of interest in the estimation of VAT is DXA.

Estimating VAT using DXA

As DXA technology has become more refined, software advancements have allowed for automated calculations of specific regions related to the identification of disease risk. Android and gynoid regions of interest are created based on reproducible boney anatomical landmarks and stature [236, 330, 411, 529]. These measurements, particularly the android region, have been significantly associated with cardiometabolic disease risk [25, 189, 269, 280, 522, 575, 601]. More recently estimates of VAT area and volume have been made possible, using geometric modeling parameters, with VAT being calculated by subtracting SAT in the android region from the total fat, after SAT overlaying the visceral cavity is estimated from SAT lateral to the abdominal wall musculature [284, 492]. This method has been validated against CT criterion measures [284, 378], and DXA measures of VAT are highly correlated with both CT [100, 284, 341, 378] and MRI [100, 399].

DXA derived VAT is being reported more frequently in the literature, with recent studies using this measure in populations of chronic obstructive pulmonary disease patients [139], obese women [63], and bariatric patients [8]. Specifically in elite athletic populations, DXA has been used to assess the abdominal body

composition of NFL athletes [73], and female judokas [434]. Although android and gynoid measures via DXA have been reported in elite RU populations [242], specific VAT estimates via DXA are absent from the literature. Gaining an appreciation of the ability for DXA to estimate VAT in a RU population, compared to the reference MRI method, would be extremely valuable for practitioners to assess the potential risk in athletes during an assessment they are likely to undertake regardless.

Summary

With the number of available methodologies to assess different aspects of body composition increasing, it is important to understand the inter-relationship between these techniques to accurately interpret results. Given that the concurrent use of SA and DXA is becoming common practice in elite RU circles, being able to interpret these results correctly is of interest. Furthermore, given the ability of DXA to now estimate VAT, and the well-established link between VAT and cardiometabolic complications, being able to appreciate the appropriateness of DXA to estimate VAT in a population of athletes, many of which may be “supersized”, will be of value to sport science and sport medicine practitioners. Given the inconsistencies with obesity related assessments based on ethnicity, gaining an appreciation of how body composition assessment is influenced by ethnicity in this elite population would also be of interest to sport science practitioners.

CONCLUSION

The current review has identified a number of important and complex relationships between ethnicity, physique characteristics, and disease risk. Polynesians possess greater whole body LM for any given body size in comparison to Caucasians, including greater proportional LM in the peripheral regions. Further, Polynesians possess higher VAT levels than Caucasians. Given the high correlation between visceral adiposity and cardiometabolic disease risk, and the fact that Polynesians have some of the highest rates of obesity internationally, it is not surprising Polynesians have some of the highest incidence of cardiometabolic disease in the world. At this stage, there is no published literature examining what impact these relationships have on elite RU athletes, who undergo routine body composition assessment, and display specific physique traits which may make them susceptible to certain disease outcomes. As such, the association between ethnicity and body composition in RU athletes at the elite level warrants significant investigation. The aims of this thesis related to the gaps in the literature identified in the above review are described in detail in Chapter One and will be systematically investigated in the subsequent chapters.

CHAPTER THREE – BODY COMPOSITION

CHARACTERISTICS OF ELITE AUSTRALIAN RUGBY

UNION ATHLETES ACCORDING TO PLAYING POSITION

AND ETHNICITY

Zemski AJ¹, Slater GJ^{1,2} and Broad EM³. Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity. *Journal of Sports Sciences*. 2015; 33: 970-978.

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (80%), GJS/EMB (10%).
- Conceived and designed the experiment: AJZ, GJS, EMB.
- Collected and collated the data: AJZ, GJS.
- Analysed the data: AJZ, GJS, EMB.
- Wrote/reviewed the paper: AJZ, GJS, EMB.

ABSTRACT

This study describes the body composition traits of modern-day elite RU athletes according to playing position and ethnicity. Thirty-seven international Australian RU athletes of Caucasian and Polynesian descent undertook body composition assessment using DXA and SA. Forwards were significantly taller, heavier and had a greater total FM and LM than backs. Backs displayed a higher percentage LM, and lower sum of seven skinfolds (S7SF) and BF%. While no whole body composition differences were seen between ethnicities, significant regional differences were observed. In the periphery (arm and leg) regions, Polynesians had a greater proportion of FM (53.1% vs 51.3%, $P = 0.052$, $d = 0.5$) and LM (49.7% vs 48.6%, $P = 0.040$, $d = 0.9$), while in the trunk region a lower proportion of FM (37.2% vs 39.5%, $P = 0.019$, $d = 0.7$) and LM (45.6% vs 46.8%, $P = 0.020$, $d = 1.1$). Significant differences were also seen between Caucasian and Polynesian forwards in leg LM (31.4 kg vs 35.9 kg, $P = 0.014$, $d = 2.4$) and periphery LM (43.8 kg vs 49.6 kg, $P = 0.022$, $d = 2.4$). Elite Polynesian RU athletes have different distribution patterns of FM and LM compared to Caucasians, which may influence their suitability for particular positions.

INTRODUCTION

RU is an intermittent, full contact team sport characterised by bursts of high-intensity running, heavy tackling and frequent body contact, interspersed with periods of recovery. It requires a unique combination of strength, skill, speed and endurance [163]. Since becoming a professional sport in 1995, RU has become faster and more physically demanding [26, 169, 451]. This has resulted in a greater emphasis being placed on understanding the physiological demands of the sport. These demands are position specific [163], and an athlete's morphology together with their physiology will influence their likely on-field position [403].

Forwards are in continual close contact with opposition players, and need to be strong and powerful to gain and retain possession of the ball. Being tall and having a heavier BM is advantageous in the forward positions [163, 403, 451], and has been shown to positively correlate with scrummaging force [454] and competitive success [416, 496]. Excess body fat may negatively impact performance by reducing speed and acceleration [163], an outcome likely across all positions. Backs control possession of the ball once obtained by the forwards, and are required to accelerate away from opposition players to create scoring opportunities, and provide cover in defence. Speed and endurance are among the most important physical attributes for backs [163, 403, 450]. However, as the game evolves, backs are taking on more of the roles typically performed by forwards, with a greater stature and BM becoming increasingly important. Body composition differences between forwards and backs are well reported in the literature [163, 242, 416]. Being able to assess, manipulate and monitor the body composition of RU athletes has the potential to improve performance and has been identified as being beneficial [163, 465].

The assessment of body composition is routinely carried out on elite RU populations, with DXA [242, 448] and SA [49, 137, 166, 252, 367, 550] being the primary measurement methods reported in the literature. DXA is able to quantify total, as well as regional distribution of BMC, FM, and LM [370]. SA includes the

measurement of skinfolds at specific landmarks, and in conjunction with the LMI [511] is able to estimate longitudinal within-subject proportional changes in FM and LM. Both of these methods are recognised as being reliable with good precision [2]. Recently DXA has been utilised to look at specific regional body composition in athletes, which is of particular interest in RU populations due to the documented links between regional body composition and speed [320, 334]. Specific distribution of FM and LM may play a more important role than whole body composition in RU performance, something not previously investigated.

RU is an international sport participated in by people from a range of ethnic backgrounds. An increasing proportion of participants at the elite level anecdotally appear to be of non-Caucasian ethnicity, particularly of Polynesian descent. Furthermore, Olds [416] identifies there were enough New Zealand-born players (a nation with a high proportion of Polynesian athletes) playing for other countries in the 1999 RWC to make up two additional teams. Available evidence within sedentary populations suggest significant differences exist in body size, composition, and fat distribution between Caucasian and Polynesian individuals [122, 479, 480, 537, 538]. This evidence suggests that Polynesian athletes may have different regional distribution of FM and LM when compared to Caucasian athletes, which may influence their suitability to particular positions. The morphology and regional distribution of FM and LM in Polynesian RU athletes has not been reported in the literature to date.

This study aims to describe the body composition traits of modern-day elite RU athletes. In particular we will focus on comparing the morphology between forwards and backs, and also between Caucasian and Polynesian athletes, concentrating on differences in regional distribution of FM and LM, both in absolute and relative terms.

METHODS

Participants

Forty elite RU athletes were recruited via their involvement in the Australian Wallabies national squad in 2012. Athletes' characteristics were as follows (mean [95% confidence interval]): age 25.4 (24.4 to 26.4) years, stature 187.2 (184.6 to 189.7) cm, BM 102.5 (98.5 to 106.4) kg, BMI 29.2 (28.4 to 30.0) kg/m², S7SF 62.0 (56.9 to 67.1) mm and LMI 57.6 (55.8 to 67.1) mm/kg^{0.14}. All participants provided informed consent to participate in this study, and the research was approved by the relevant Human Research Ethics Committee.

Experimental design

Participants undertook routine body composition assessment during 2012 at the start and end of the international season (3 months between assessments) as per their Australian Rugby Union (ARU) contractual obligations. The participants were in a well-trained state at both time points given the start of the international season coincided with the end of the professional southern hemisphere season in which they competed. DXA and SA measures were taken between 0 and 7 days apart (average 3.6 days). Participants were assessed either one or two times over the season. For consistency, if a participant had two measures taken, the measure corresponding to their highest LMI value was used for analysis (average difference in LMI values in participants with two measures was 0.6 mm/kg^{0.14}). The highest LMI value was used as theoretically this is when the participants were in their peak physical condition.

Body composition

Dual-energy X-ray absorptiometry

Measures were taken using a fan-beam DXA scanner (Hologic Discovery A, Hologic, Bedford, MA), with analysis performed using Apex 12.7.3 software (Hologic, Bedford, MA). The scanner was tested for consistent calibration daily, with phantoms used as per manufacturer guidelines each day for quality control purposes. All the scans were undertaken using the array mode.

Scanning protocols were implemented as per techniques previously described to maximise technical reliability and minimise error [393-395]. Specifically, participants were scanned first thing in the morning prior to food, fluid, or exercise. Participants were requested to remove all metal items from their person, and lay supine on the scanning bed as still as possible for the duration of the scan. Participants were scanned wearing tight-fitting sports shorts or underwear, and those too big for the scanning bed undertook multiple scans. For positioning consistency the same experienced and qualified technician performed all measurements, and the participants leg positioning was standardised using a set width foot strap that was placed over both feet anterior to the lateral malleolus.

The whole body scan was segmented into regions manually during the analysis process by the same technician that performed the scan. The arms were separated from the trunk by positioning a cut through the axilla and then to the medial head of the humerus. The legs were separated from the trunk by placing an angled cut through the bottom of the ischium, forming a triangle with a horizontal line over the top of the iliac crest. The head was separated from the trunk by cutting just below the mandible.

Surface anthropometry

A single Level 3 ISAK accredited anthropometrist with a technical error of measurement (TEM) of 1.7% for S7SF took all measurements. BM was assessed using electronic scales (A&D Mercury, Adelaide, Australia) to 0.1 kg accuracy upon waking with bladder voided. Skinfolds were assessed using Harpenden calipers (British Indicators, Hertfordshire, UK) to 0.1 mm accuracy at a time later that day. All anthropometric equipment was calibrated as recommended by the manufacturers.

Skinfold measurements were made on the right side of the body using ISAK techniques previously described [410], with a S7SF calculated from the measures of the triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, and medial calf skinfold sites. All measurements were undertaken in duplicate to establish within-day retest reliability. If the difference between the duplicate measures exceeded 4% for an individual skinfold, a third measurement was taken after all other measurements were completed. The mean of duplicate or median of triplicate anthropometric measurements were used for all subsequent analysis. LMI was calculated using methods previously described [511].

Ethnicity

At the time of consent the participants were requested to provide researchers with the ethnicity of their grandparents, and their own opinion of their ethnicity via open-ended questions. It was made clear this was optional and would not impact their involvement in the research.

A universally accepted method of distinguishing an individual's ethnicity was unable to be identified due to the inherent difficulty in defining "ethnicity" [75]. As this research is investigating the phenotype expression and differences of ethnicity on body composition based on differences previously described in sedentary populations [122, 480, 537, 538], grandparental heritage was chosen as in previous research [116, 155, 480].

Statistical methods

The statistical procedures were performed with SPSS 22 (SPSS Inc., Chicago, Illinois, USA). Descriptive statistics including means, frequencies and 95% confidence intervals (CI) were calculated on a range of body composition variables discussed later. An analysis of covariance (ANCOVA) with a generalised linear model, involving the factors playing position and ethnicity, was undertaken on the body composition data. The covariate age was significant for a number of the variables investigated, and for consistency was retained as a covariate in all analyses. The means reported are arithmetic means, while significance testing was completed on the adjusted means. Cohen's *d* was used to calculate effect size correlation. Participants were considered outliers if they were greater than two standard deviations (SD) away from the mean in over eight of the body composition variables analysed. A Bonferroni correction was not used as all the comparisons were preplanned, and as there was a likelihood of high correlations among variables, this procedure would have acted as an overcorrection.

RESULTS

The initial study population consisted of 41 athletes, with one athlete declining to participate. The remaining athletes were arranged into groups based on their on-field playing position, ethnicity, and combination of position and ethnicity.

Ten participants in this study identified the majority of their grandparents as being of Tongan, Samoan or Maori descent, while one participant was identified as being of New Guinean descent. Although New Guinea is regarded as being part of Melanesia, for the purpose of this research all 11 participants were classified as being of Polynesian ethnicity.

After preliminary statistical analysis was undertaken, 3 athletes were removed from the final analysis as they were identified as extreme outliers, leaving 37 athletes (Figure 3.1). The outliers comprised one Polynesian back and two Caucasian forwards.

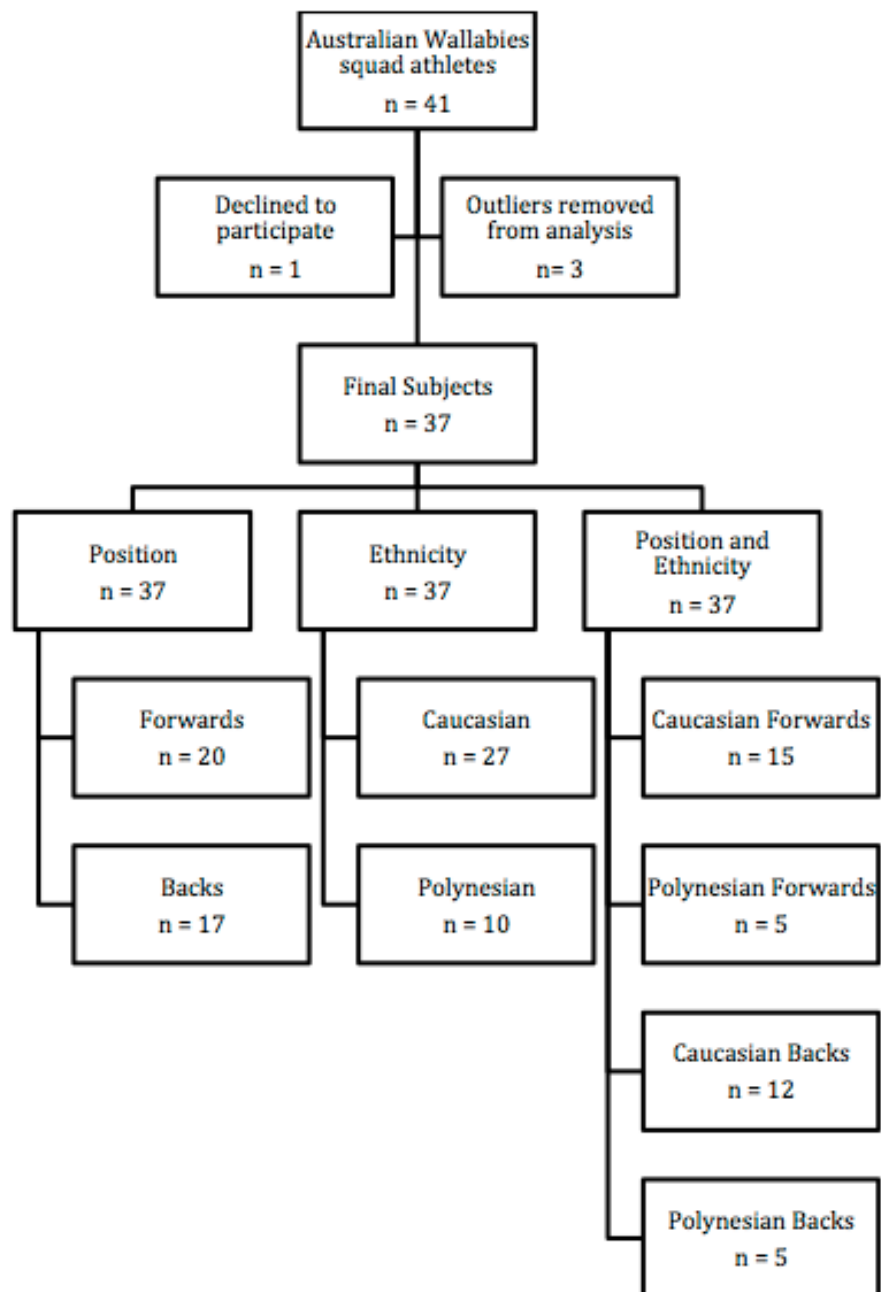


Figure 3.1. Flow diagram of the study population.

Whole body composition differences according to playing position and ethnicity

No interactions ($P > 0.05$) between playing position and ethnicity were found (Table 3.1). Significant differences were found between forwards and backs using a number of body composition measures, including BM, stature, S7SF, LMI, plus absolute and proportion of FM and LM (all $P < 0.001$). No significant differences ($P > 0.05$) in whole body composition were seen between Caucasians and Polynesians.

Regional body composition differences according to playing position and ethnicity

Table 3.2 describes the regional body composition differences according to playing position and ethnicity measured by DXA. There was a significant interaction effect between position and ethnicity in the absolute mass and proportional regional mass distribution of LM in the legs, and absolute mass in the total peripheries (arms and legs). Significant differences were seen between Caucasian and Polynesian forwards in absolute leg LM (31.4 kg vs. 35.9 kg, $P = 0.014$, $d = 2.4$), proportional regional leg LM distribution (34.9% vs. 36.5%, $P = 0.033$, $d = 1.8$), and absolute periphery LM (43.8 kg vs. 49.6 kg, $P = 0.022$, $d = 2.4$). No differences ($P > 0.05$) were seen between Caucasian and Polynesian backs in these measures.

Significant differences ($P < 0.05$) were seen between forwards and backs in all body regions in absolute mass distribution both in FM and LM using DXA (Table 3.2), and in FM using SA (Table 3.3), with forwards having higher amounts of FM and LM in all regions. There were also proportional regional mass distribution differences noted in FM using DXA between playing positions, with forwards carrying significantly less FM in their arms than backs, and significantly more in their legs and total peripheries (Table 3.2).

Table 3.1. Whole body composition differences using DXA and surface anthropometry measures according to playing position and ethnicity (mean (95% confidence intervals)).

	Position n = 37		Ethnicity n = 37	
	Forwards n = 20	Backs n = 17	Caucasian n = 27	Polynesian n = 10
Stature (cm)	191.0 (187.7, 194.3)	182.6 ^{a,*} (180.0, 185.3)	187.8 (185.0, 190.5)	185.5 (179.6, 191.4)
Mass (kg)[^]	111.7 (108.1, 115.2)	91.7 ^{a,*} (89.1, 94.3)	101.4 (97.4, 105.5)	105.3 (95.5, 115.2)
BMI	30.6 (29.7, 31.6)	27.5 ^{a,*} (26.8, 28.2)	28.7 (28.0, 29.4)	30.5 (28.5, 32.5)
Sum 7 skinfolds (mm)	73.1 (67.7, 78.4)	49.0 ^{a,*} (45.4, 52.5)	62.0 (56.0, 68.0)	62.1 (51.8, 72.4)
LMI	61.3 (59.5, 63.2)	53.3 ^{a,*} (51.6, 55.0)	57.1 (55.2, 59.0)	59.1 (54.7, 63.6)
Bone mass (kg)	4.5 (4.3, 4.7)	3.9 ^{a,*} (3.7, 4.0)	4.1 (4.0, 4.3)	4.4 (4.0, 4.8)
Bone mass %	4.0 (3.9, 4.1)	4.2 (4.0, 4.3)	4.0 (3.9, 4.1)	4.1 (4.0, 4.3)
Lean mass (kg)[^]	92.2 (89.5, 94.9)	79.1 ^{a,*} (76.7, 81.6)	85.3 (82.4, 88.2)	88.6 (81.7, 95.5)
Lean mass %	81.8 (81.0, 82.6)	85.2 ^{a,*} (84.5, 85.8)	83.4 (82.5, 84.2)	83.2 (81.6, 84.9)
Fat mass (kg)[^]	16.1 (14.9, 17.3)	9.9 ^{a,*} (9.2, 10.7)	13.1 (11.7, 14.4)	13.8 (10.9, 17.0)
Fat mass %	14.2 (13.4, 15.0)	10.7 ^{a,*} (10.0, 11.4)	12.6 (11.7, 13.5)	12.6 (10.9, 14.4)

BMI = body mass index (kg/m²); LMI = lean mass index (kg/sum 7 skinfolds mm^{0.14})^a Main effect for position (P < 0.05)* Large effect size (Cohen's *d* > 0.8)[^] Age was a significant covariate (P < 0.05)

Table 3.2. Body composition proportional distribution differences using DXA measures according to playing position and ethnicity (mean (95% confidence intervals)).

		Position n = 37		Ethnicity n = 37	
		Forwards n = 20	Backs n = 17	Caucasian n = 27	Polynesian n = 10
Arms	Lean (kg)	12.7 (12.3, 13.2)	10.5 ^{b,*} (10.0, 10.9)	11.5 (11.0, 12.0)	12.2 (11.1, 13.3)
	Lean %	13.8 (13.5, 14.1)	13.3 (12.9, 13.6)	13.5 (13.2, 13.8)	13.8 (13.5, 14.2)
	Fat (kg)	1.9 (1.7, 2.0)	1.2 ^{b,*} (1.1, 1.3)	1.5 (1.4, 1.7)	1.7 (1.4, 2.0)
	Fat %	11.6 (11.0, 12.1)	12.5 ^b (12.1, 13.0)	11.9 (11.4, 12.3)	12.4 (11.6, 13.3)
Legs	Lean (kg) ^a	32.5 (31.3, 33.8)	28.0 [*] (27.1, 29.0)	30.0 (28.9, 31.0)	31.8 (29.0, 34.7)
	Lean % ^{^ a}	35.3 (34.8, 35.8)	35.4 (34.9, 35.9)	35.1 (34.7, 35.5)	35.9 [*] (35.5, 36.5)
	Fat (kg)	6.7 (6.1, 7.2)	3.8 ^{b,*} (3.5, 4.1)	5.2 (4.6, 5.8)	5.7 (4.3, 7.2)
	Fat %	41.2 (39.6, 42.9)	38.1 ^{b,*} (37.2, 39.1)	39.5 (38.3, 40.7)	40.6 (38.2, 43.1)
Arms + legs ^{\$}	Lean (kg) ^a	45.3 (43.7, 46.9)	38.5 [*] (37.3, 39.7)	41.4 (40.0, 42.9)	44.0 (40.2, 48.0)
	Lean % [^]	49.1 (48.4, 49.7)	48.7 (48.2, 49.2)	48.6 (48.1, 49.0)	49.7 ^{c,*} (49.0, 50.4)
	Fat (kg)	8.5 (7.8, 9.2)	5.0 ^{b,*} (4.6, 5.4)	6.7 (6.0, 7.5)	7.4 (5.7, 9.2)
	Fat %	52.8 (51.1, 54.5)	50.7 ^b (49.6, 51.7)	51.3 (50.2, 52.5)	53.1 ^{#c} (50.8, 55.4)
Trunk	Lean (kg)	42.7 (41.5, 44.0)	36.8 ^{b,*} (35.6, 38.1)	39.9 (38.4, 41.3)	40.3 (37.4, 43.2)
	Lean %	46.4 (45.8, 47.0)	46.5 (46.1, 47.0)	46.8 (46.3, 47.2)	45.6 ^{c,*} (45.0, 46.1)
	Fat (kg) [^]	6.4 (5.8, 7.0)	3.8 ^{b,*} (3.4, 4.1)	5.2 (4.6, 5.8)	5.2 (4.0, 6.3)
	Fat %	39.5 (37.8, 41.2)	38.1 (36.8, 39.4)	39.5 (38.2, 40.8)	37.2 ^c (35.3, 39.1)

^a Interaction effect for position*ethnicity (P < 0.05);^b Main effect for position (P < 0.05);^c Main effect for ethnicity (P < 0.05);^{#c} Narrowly missed significance (P = 0.052)^{*} Large effect size (Cohen's *d* > 0.8);[^] Age was a significant covariate (P < 0.05)^{\$}Arms + legs = periphery

NOTE: Head data excluded from table, % distribution values will not add up to 100%

While no differences were seen in absolute FM or LM using DXA between Caucasians and Polynesians, significant differences were seen in the proportional regional distribution of both FM and LM using DXA in the periphery and trunk regions (Table 3.2). No differences were found in absolute FM distribution between Caucasians and Polynesians using SA; however, a large effect size was present when looking at proportional regional FM (Table 3.3).

Table 3.3. Regional body composition differences using surface anthropometry measures according to playing position and ethnicity (mean (95% confidence intervals)).

		Position n = 37		Ethnicity n = 37	
		Forwards n = 20	Backs n = 17	Caucasian n = 27	Polynesian n = 10
Arms	Skinfolds (mm)	14.0 (12.5, 15.4)	10.6 ^{a,*} (9.5, 11.7)	12.5 (11.3, 13.7)	12.3 (9.8, 14.8)
	Skinfolds %	19.1 (17.8, 20.4)	21.6 ^a (20.5, 22.7)	20.3 (19.3, 21.2)	20.1 (17.6, 22.6)
Legs	Skinfolds (mm)	20.3 (18.3, 22.4)	13.1 ^{a,*} (12.2, 14.0)	17.9 (15.9, 19.8)	14.6 (11.8, 17.5)
	Skinfolds %[^]	28.1 (25.6, 30.6)	27.0 (25.2, 28.8)	29.0 (27.4, 30.7)	23.7 [*] (21.0, 26.2)
Arms + legs^{\$}	Skinfolds (mm)	34.3 (31.2, 37.3)	23.7 ^{a,*} (22.0, 25.4)	30.3 (27.4, 33.2)	26.9 (22.2, 31.7)
	Skinfolds %[^]	47.1 (44.1, 50.2)	48.6 (46.8, 50.4)	49.3 (47.4, 51.1)	43.8 [*] (40.0, 47.5)
Trunk	Skinfolds (mm)	38.8 (34.9, 42.7)	25.3 ^{a,*} (23.1, 27.5)	31.6 (28.0, 35.3)	35.1 (28.5, 41.8)
	Skinfolds %[^]	52.9 (49.8, 55.9)	51.4 (49.6, 53.3)	50.7 (48.9, 52.6)	56.2 [*] (52.5, 60.0)

Arms – biceps, triceps; Legs – mid thigh, medial calf; Periphery (arms + legs) – biceps, triceps, mid thigh, medial calf; Trunk – subscapular, supraspinale, abdominal

^a Main effect for position ($P < 0.05$)

^{*} Large effect size (Cohen's $d > 0.8$)

[^] Age was a significant covariate ($P < 0.05$)

^{\$} Arms + legs = periphery

DISCUSSION

The primary findings of this investigation were that Caucasian and Polynesian RU athletes have different regional distributions of FM and LM in their periphery and trunk regions, despite no differences in whole body composition being evident. Regional body composition differences have been previously reported in non-athletic Polynesian populations [479, 480], and in elite athletic populations comparing ethnicities other than Polynesian [385, 534]. However, to our knowledge this is the first investigation which has looked at regional body composition differences using an elite athletic Polynesian population. As has been previously reported, significant differences were found in whole body and regional body composition between forwards and backs [163, 242, 448].

Regional LM differences were noted between ethnicities (Table 3.2), similar to the findings by Rush et al. [480] in a non-athletic population. These differences were related to playing position, with Polynesian forwards having a greater differential between LM and FM in the leg and periphery regions compared with Caucasian forwards. This differential could provide an advantageous shift in power to mass ratio, and thus improve an athlete's ability to create greater force in explosive movements including tackles, mauls, scrums, rucks, hits and sprints. In support of this, research into specific physique characteristics have found an association with sprinting performance, including greater gastrocnemius lateralis muscle thickness [320], and regional skinfold distribution between the trunk and extremities [334]. Future research is warranted to investigate specific regional body composition traits and their association with RU specific performance. The findings of such research could potentially facilitate the development of specific training and dietary programs to drive training adaptations.

Polynesian RU athletes were shown to have a higher proportion of FM in their peripheries, and a lower proportion in their trunk when compared to Caucasian RU athletes using DXA (Table 3.2). In a non-athletic population, Rush et al. [480] also found Pacific Islanders and Maoris had less FM than Europeans in the

abdominal region; however, they also found less FM in the thigh region. Interestingly, other studies have identified that non-athletic Polynesians have less FM for the equivalent BMI when compared to Caucasians [122, 537, 538], which was not evident in this elite athletic population (Table 3.1).

The population used in this study is very unique in nature, all highly trained athletes trying to optimise physique to meet specific physiological demands. As differences in body composition distribution between Caucasians and Polynesians were identified in this population undertaking the same training, it could be stipulated the differences are due to genetic dissimilarities between ethnicities. It is, however, recognised that other factors which influence phenotype expression (e.g. nutrition) have not been accounted for or standardised. Interestingly, a study looking at anthropometric differences between Polynesian and non-Polynesian junior representative rugby league athletes found Polynesian players exhibited advantageous anthropometric attributes [99]. This could be used as further evidence that Polynesians are predisposed to possess physical characteristics potentially beneficial to RU performance [416, 496], which may be position specific.

Although not statistically significant, a large effect size was observed when looking at proportional regional FM distribution between ethnicities (Table 3.3). In contrast to DXA, SA indicated that Caucasians had a larger proportion of FM in their peripheries (49.3% vs. 43.8%, $P > 0.05$, $d = 1.0$), and a smaller proportion in their trunk (50.7% vs. 56.2%, $P > 0.05$, $d = 1.0$) when compared to Polynesians. Differences could be as a consequence of assumptions associated with inferring whole body composition from a small number of defined anatomical sites. Alternatively, it could be due to the fact that SA only infers SAT, whilst DXA is able to assess both SAT and VAT. It could be postulated that the VAT deposition tendencies of Polynesians are different to that of Caucasians. It has been identified that racial differences exist in VAT deposition between African Americans and Caucasians [116]; however, this has not been investigated in a Polynesian population.

From a practical perspective, DXA is used less often in the field than SA for reasons including cost and practicality. As SA does not provide a direct indication of FM, regression equations are often utilised to estimate this. Given we found inconsistent inferred regional FM distribution using the two assessment techniques, this would provide further evidence to support not using regression equations as previously advocated by Johnston [276]. However, the ability of such equations to track changes over time in elite athletic populations has not been as widely assessed in the literature [506], and to our knowledge no such studies have taken into account ethnicity.

Whole body composition differences between playing positions are well documented [163]. As expected forwards were taller, heavier, and had a greater S7SF and LMI. They also displayed a greater amount of absolute FM and LM in all body regions compared to backs, supporting previous research [242, 448]. As regional distribution of LM has been identified to influence sprinting performance [320], future research into the relationship between regional body composition and rugby-specific performance outcomes would be of interest to sports scientists and coaches.

International representation by foreign-born athletes in RU is increasing, with 12% of players in the 1999 RWC born in countries outside their national squad [416], a trend that seems to be on the rise based on the sample population. This is increasing due to a combination of international recruitment, increasing ethnic diversity in developed nations, and the large financial incentives available for playing RU in certain countries. It may also be because the evolving physical demands of the sport may now be better complemented by the intrinsic body composition traits of Polynesian athletes. For this reason, whilst the trend of increasing size in elite RU athletes continues [416], and success appears to be closely linked to size in elite RU athlete [416, 496], it could be speculated that the proportion of Polynesians participating in RU at the elite level will also continue to rise.

The authors recognise this study utilises a relatively small sample population. However, due to the Darwinian nature of sport in that only the “fittest” reach the highest level of participation [409], small sample sizes are a reality in research involving elite athletes. The fact that the results align closely with both recent research in the sport [242, 448], and with longitudinal trends [416], suggest the sample is valid. Despite the Darwinian nature of sport, there are always going to be exceptions to the rule and some athletes may not fit the morphological mould, yet display alternate athletic qualities such as extreme skill, outstanding physiology and match instincts which allow them to compete at the elite level. In this study, three such athletes were identified as being extreme outliers from the group in terms of body composition. As these participants were not typical within the population of interest in relation to their morphology, they were removed from the statistical analyses. The outliers comprised one Polynesian back and two Caucasian forwards, who in general exhibited higher levels of FM and less relative LM than the remainder of the population.

CONCLUSION

This up-to-date description of current body composition characteristics and trends amongst elite RU athletes provides coaches and sport science staff an indication of what physique traits may be required for success in international RU. This study has identified regional body composition traits found in Polynesian athletes which may have the potential to direct RU athletes to particular positions from a body composition perspective.

CHAPTER FOUR – ABDOMINAL ADIPOSITY DISTRIBUTION IN ELITE RUGBY UNION ATHLETES USING MAGNETIC RESONANCE IMAGING

Zemski AJ¹, Keating SE², Broad EM³, Marsh, DJ⁴, and Slater GJ¹. Abdominal adiposity distribution in elite rugby union athletes using magnetic resonance imaging. *Sport Sciences for Health*. 2018; Online First Article (accepted 7 August 2018).

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (75%), GJS (10%), SEK/EMB/DJM (5%).
- Conceived and designed the experiment: AJZ, DJM, GJS.
- Collected and collated the data: AJZ, DJM, GJS.
- Analysed the data: AJZ, SEK.
- Wrote/reviewed the paper: AJZ, SEK, EMB, DJM, GJS.

ABSTRACT

Purpose – This study aimed to assess VAT, an established marker for cardiometabolic complications, in elite RU athletes, with specific consideration given to ethnicity. The ability of DXA to estimate VAT in athletic populations compared to the criterion MRI was also explored.

Methods – Thirty elite male RU athletes (age 23.9 ± 4.0 years; stature 186.7 ± 7.0 cm; mass 101.9 ± 11.2 kg) underwent assessment via DXA for body composition, and MRI for abdominal adiposity, at the start of the pre-season training period. Participants were ascribed a specific ethnicity when three or more of their grandparents were of either Caucasian or Polynesian descent.

Results – MRI VAT did not differ between ethnicities (Caucasian 92.7 ± 26.7 cm²; Polynesian 86 ± 27.3 cm²; $p = 0.52$); however, there was a trend for forwards (96.7 ± 25.0 cm²) to have higher VAT than backs (81.7 ± 27.3 cm²; $p = 0.13$) which provides an area of interest for researchers. Thirty-seven percent of athletes (8 forwards, 3 backs) were found to have VAT >100 cm², a threshold for increased cardiometabolic risk within the general population. Bland Altman analysis indicated that DXA VAT underestimated MRI VAT by ~ 25 cm², with relatively wide limits of agreement (-24.0 to 75.6 cm²).

Conclusions – Given the size of RU athletes, and the association between elevated VAT and cardiometabolic complications in “supersized” athletes from other sports, further investigation into VAT and other markers of cardiometabolic disease in RU populations is warranted. Further, DXA was found to underestimate VAT compared to the criterion MRI in this athletic population.

INTRODUCTION

RU is a high contact, dynamic, field-based team sport in which athletes have a diverse range of physical attributes. This makes RU an atypical sport due to the heterogeneity of physique traits and physical performance characteristics [449]. Backs are required to control possession of the ball and create scoring opportunities, whilst providing cover in defense, with speed, acceleration and agility being among their most important physical attributes [163]. In contrast, forwards are in continual close contact with opposition players, and need to be strong, powerful and robust to gain and retain possession of the ball. Indeed, a higher body mass is associated with greater force production in the RU scrum [454], and has been shown to have a strong correlation with overall team competitive success [416, 496].

Forwards have consistently been shown to be heavier, taller, and possess greater absolute and relative LM and FM compared to backs, whilst backs display proportionally lower body fat [620]. Furthermore, front row forwards have higher body mass relative to height (BMI) and body fat compared to second row and back row forwards [40]. Only three in 1000 Australians have been found to achieve and/or exceed the physique traits exhibited by the average national team forward, and with mass and BMI in RU athletes increasing at rates well above secular trends [416], the propensity to “supersize” forwards appears set to continue. However, it is important to consider that the relative FM of forwards, particularly those in the front row, may also exceed proposed general population thresholds for lifestyle related disease risk [199]. Indeed, elite “supersized” American football (NFL) athletes with similar physique traits have higher stores of VAT [73], and greater incidence of post-career health and cardiometabolic complications [43, 380].

VAT, which encompasses fat stores in the intra-abdominopelvic region bounded by the abdominal wall and pelvic floor [502], has been shown to be associated with incident cardiovascular disease [77], and is an established marker for cardiometabolic disease risk independent of BM, FM and SAT in non-athletic

populations [145]. Additionally, VAT is an independent risk factor for atherosclerosis in men [329], and there is a robust association between VAT and cardiovascular endpoints in non-athletic populations [258]. VAT diagnostic thresholds for increased risk ($>100\text{ cm}^2$) and high risk ($>160\text{ cm}^2$) have been established for use in general populations [431]. Further, VAT:SAT has been proposed as a useful measure to screen for cardiovascular issues, with a cut-off of 0.4 used as a threshold above which individuals in the general population are likely to show glucose intolerance and hyperlipidemia [190]. However, the application of these risk thresholds in athletic populations has not been explored.

MRI is the reference imaging method used to assess VAT [502]. It does, however, have limitations in practice given that MRI is expensive, and requires time consuming post-assessment analysis by highly skilled technicians. Given these restrictions, there has been recent interest in the use of other body composition techniques to provide estimates of VAT, including DXA, which is increasingly being used to assess body composition in athletic populations [377]. Indeed, DXA estimates of VAT have been shown to be highly correlated with MRI in general populations [399]. VAT has not previously been investigated in a RU population using criterion assessment techniques [614].

Anecdotally, there is an increasing proportion of RU athletes at the elite level of Polynesian descent. This may be due to the morphology of Polynesians predisposing them to a body composition compatible with success in RU [416]. Polynesians exhibit lower total body fat levels at any given BMI compared to Caucasians [537]. However, they exhibit greater absolute and relative abdominal fat [480], potentially predisposing this population to an increased risk of cardiometabolic disease. Indeed, the proportion of obese Polynesian males far exceeds rates elsewhere in the world [402], with the prevalence of cardiometabolic disease through the Pacific region amongst the highest internationally [98, 533].

Given the sheer size of some RU athletes, the diversity of ethnic profiles within the sport, and the association between high levels of VAT and the development of cardiovascular disease, gaining a better understanding of the abdominal adiposity profile of elite RU athletes, some of which are “supersized”, is warranted. The primary aim of this study is to investigate levels of VAT in elite RU athletes, incorporating comparisons based on player position and ethnicity. The study will also assess the ability of DXA to estimate VAT compared to the criterion MRI in a population of large athletes.

METHODS

Participants

A convenience sample of thirty elite RU athletes were recruited via their involvement in a single Super Rugby squad, which is the premier professional RU competition in the southern hemisphere. All participants provided informed consent to partake in the study, and the protocols for testing on human subjects were submitted to, and approved by, the Human Ethics Committee of the University of the Sunshine Coast (EC00297, S/12/424).

Participants undertook body composition assessment at the start of the Super Rugby pre-season training period (which was subsequent to a 4 week transition phase involving three weeks of annual leave and one week of active rest) via DXA and MRI, with all assessments undertaken within a 72 hour period. Ethnicity (Caucasian and Polynesian), and position (forwards and backs) were documented, with front row forwards separated from the second/back row forwards for subsequent analysis.

Dual-energy X-ray absorptiometry

Prior to DXA assessment, body mass was measured using electronic scales (A&D Mercury, Adelaide, Australia) to 0.1 kg accuracy after an overnight fast with bladder voided. Stature was self-reported to the nearest 1.0 cm. BMI was subsequently calculated (mass [kg]/stature [m]²).

DXA measures were taken using a fan-beam scanner (Hologic Discovery A, Hologic, Bedford, MA), with analysis performed using Apex 12.7.3 software (Hologic, Bedford, MA). The scanner was calibrated daily using a phantom as per manufacturer guidelines for quality control purposes. All scans were undertaken using the array mode.

Scanning presentation protocols were implemented as per techniques previously described to maximise technical reliability and minimise error [396]. Specifically, participants were scanned after voiding their bladder first thing in the morning prior to food, fluid, or exercise. Participants were tested wearing sports shorts, and those exceeding the size of the scanning bed undertook multiple scans [178]. For positioning consistency, the same experienced and qualified technician performed all measurements using the NHANES positioning protocol, with participants' leg position standardised using a set width foot strap that was placed over both feet anterior to the lateral malleolus [223]. VAT was analysed retrospectively by an experienced DXA operator with updated software Apex 13.4.2.7 (Hologic, Bedford, MA). Auto positioning of the VAT area was used, with manual adjustments made to the edge of subcutaneous fat placement and visceral cavity area if required.

Magnetic resonance imaging

Participants were placed supine on a 1.5 Tesla Siemens Avanto scanner with their arms positioned beside them. Localisers were used to identify the L4/5 intervertebral disc space, which was used to centre the axial slice blocks for all sequences. The abdomen was interrogated with a T2-weighted true FISP sequence (balanced gradient echo, TR: 3.6, TE: 1.46, flip angle: 75°, slice thickness 8 mm) and a volume interpolated breath-hold examination (VIBE, TR: 7.48, TE: 4.76/2.38, flip angle: 10°, slice thickness 2.5 mm), both performed on inspiration. Examinations took 15 minutes to perform.

Two trained operators performed image analysis with OsiriX Imaging Software v5.8 using the T1W VIBE sequence, and the results were averaged. The level of the L4/5 intervertebral disc was determined from sagittal reconstructions and analysis was performed on the axial image at this level. A closed polygon ROI tool was used to generate a total abdominal area measurement. For SAT, threshold segmentation was used to manually select fat pixels. SAT was then “discarded” by setting the pixels within the measured SAT to a negative value and removing. VAT was measured using the same threshold segmentation technique. Diagnostic

thresholds for VAT were set at $>100 \text{ cm}^2$ for increased risk, and $>160 \text{ cm}^2$ for high risk [431]. VAT:SAT was calculated by dividing the VAT area by the SAT area, with a cut-off of 0.4 used as a threshold for increased cardiovascular risk [190].

Ethnicity

At the time of consent the participants were requested to disclose the ethnicity of their grandparents, and their perception of their own ethnicity via open-ended questions. It was made clear that this was optional and would not impact participants involvement in the research, or within the Super Rugby program.

A universally accepted method of distinguishing an individual's ethnicity was unable to be identified due to the inherent difficulty in defining "ethnicity" [75]. As this research investigated the phenotype expression and differences of ethnicity on body composition based on variances previously described in sedentary populations [479, 537], grandparental heritage was chosen as in previous research [616, 620]. Participants were ascribed a specific ethnicity when three or more of their grandparents were of the same ethnicity.

Statistical analysis

Statistical analyses procedures were completed using Microsoft Excel (Microsoft, Redmond, WA, USA). Descriptive statistics on body composition measures were calculated and presented as mean $\pm$ SD. Data was explored using box plots and Q-Q plots to identify any potential outliers. Assumptions of homogeneity of variance using Levene's test of equality of error variance were conducted. All measurements undertaken in the study were normally distributed. A two-way between-subjects ANOVA was conducted to compare the effect of position and ethnicity on criterion MRI measures. Subsequently, independent t-tests were run as post-hoc analysis to investigate the differences in body composition measures based on position (forwards vs backs, and front row forwards vs second/back row forwards) and ethnicity. Bonferroni corrections were made to counteract

multiple comparisons. Statistical significance was accepted at a p -value of <0.05 throughout. Pearson's correlations (r) were used to assess the strength of relationship between measures of VAT and SAT and ranked according to Hopkins [254]. A Bland Altman plot was created to compare DXA to the criterion MRI measure for estimating VAT. Interclass correlation coefficients (ICC) and CV were used to determine the inter-tester reliability between the two technicians who analysed the MRI scans.

RESULTS

All athletes were able to be ascribed an ethnicity, and descriptive characteristics of the population are presented in Table 4.1. All physique traits measured by DXA were significantly different between forwards and backs. Differences in body composition were also noted between front row forwards and second/back row forwards, with front row forwards having greater absolute and relative FM, and more relative fat distributed in the android region. Based on MRI VAT, 11 of 30 athletes had VAT >100 cm², including 8 forwards (6 Caucasian, 2 Polynesian), and 3 backs (2 Caucasian, 1 Polynesian). No athlete had VAT >160 cm². Twenty-three of the 30 athletes had a VAT:SAT >0.4. The two-way between subjects ANOVA indicated there were no interactions between ethnicity and position for MRI VAT ($F = 0.15$, $p = 0.70$). The ICC (95% confidence interval) for abdominal total area was 1.00 (1.00 to 1.00), 0.99 for SAT (CI 0.99 to 1.00) and 0.96 for VAT (CI 0.93 to 0.98), with a CV of 0.4%, 2.4% and 4.3% respectively.

Correlations between MRI VAT and SAT, with BMI and DXA measures of whole body and abdominal adiposity, are described in Table 4.2. A moderate correlation was found between MRI VAT and DXA VAT ($r = 0.46$, $p = 0.01$), with BMI seen to be a poor estimate of MRI VAT ($r = 0.21$, $p = 0.27$). Slight differences were noted in the ability of DXA VAT to estimate MRI VAT based on ethnicity, with a slightly higher correlation amongst Polynesians (Figure 4.1a). Bland Altman analysis indicated that DXA VAT underestimates MRI VAT by ~25 cm² with relatively wide limits of agreement (-24.0 to 75.6 cm²) (Figure 4.1b).

Table 4.1. Body composition characteristics of elite rugby union athletes categorised by position and ethnicity.

	Ethnicity			Position			Forwards		
	Caucasian (n = 19)	Polynesian (n = 11)	p-value	Forwards (n = 17)	Backs (n = 13)	p-value	Front Row (n = 7)	Second & Back Row (n = 10)	p-value
Characteristics									
Age (years)	23.6 ± 4.0	24.5 ± 3.9	0.56	24.7 ± 4.8	22.8 ± 2.3	0.16	24.1 ± 3.0	25.2 ± 5.8	0.63
Stature (cm)	188.1 ± 7.2	184.5 ± 6.3	0.17	189.9 ± 6.9	182.5 ± 4.5	<0.01*	184.7 ± 2.4	193.6 ± 6.7	<0.01*
Mass (kg)	102.9 ± 10.9	100.1 ± 12.1	0.54	110.2 ± 6.6	90.0 ± 4.4	<0.01*	110.3 ± 5.7	110.1 ± 7.5	0.94
BMI (kg/m ²)	29.1 ± 2.4	29.3 ± 2.3	0.75	30.6 ± 2.0	27.3 ± 1.1	<0.01*	32.3 ± 1.3	29.4 ± 1.4	<0.01*
DXA									
Bone mass (kg)	4.1 ± 0.4	4.1 ± 0.5	0.69	4.3 ± 0.3	3.8 ± 0.4	<0.01*	4.3 ± 0.2	4.3 ± 0.4	0.94
Fat mass (kg)	14.5 ± 4.1	13.4 ± 5.4	0.56	17.1 ± 3.6	10.1 ± 1.7	<0.01*	19.2 ± 2.7	15.7 ± 3.5	0.04*
Lean mass (kg)	82.3 ± 6.9	81.0 ± 7.7	0.66	86.5 ± 4.8	75.7 ± 4.4	<0.01*	84.7 ± 3.9	87.8 ± 5.2	0.18
Total mass (kg)	100.8 ± 10.2	98.6 ± 11.8	0.60	107.9 ± 6.1	89.6 ± 4.3	<0.01*	108.2 ± 5.3	107.8 ± 6.9	0.90
Body fat (%)	14.2 ± 3.0	13.3 ± 4.0	0.51	15.8 ± 2.9	11.3 ± 1.9	<0.01*	17.7 ± 1.9	14.5 ± 2.8	0.01*
Android fat mass (g)	1007 ± 433	1039 ± 676	0.89	1302 ± 530	649 ± 159	<0.01*	1562 ± 394	1119 ± 554	0.07
Android fat (%)	15.1 ± 4.5	15.1 ± 6.5	0.98	17.6 ± 5.3	11.8 ± 2.8	<0.01*	20.4 ± 4.1	15.6 ± 5.3	0.05*
Est. VAT mass (g)	316.6 ± 98.7	301.1 ± 116.1	0.71	370.2 ± 97.9	233.3 ± 41.2	<0.01*	392.9 ± 111.6	354.4 ± 89.9	0.47
Est. VAT area (cm ²)	65.6 ± 20.4	62.4 ± 24.0	0.71	76.7 ± 20.2	48.4 ± 8.6	<0.01*	81.4 ± 23.0	73.4 ± 18.5	0.46

MRI									
Abdominal total (cm ²)	605.9 ± 89.0	602.1 ± 105.7	0.92	664.9 ± 79.8	525.6 ± 28.1	<0.01*	713.6 ± 68.8	630.8 ± 71.0	0.03*
Abdominal SAT (cm ²)	146.9 ± 59.1	144.9 ± 76.7	0.94	182.0 ± 61.9	99.4 ± 28.9	<0.01*	229.3 ± 42.8	148.9 ± 51.4	<0.01*
Abdominal VAT (cm ²)	92.7 ± 26.7	86.0 ± 27.3	0.52	96.7 ± 25.0	81.7 ± 27.3	0.13	93.5 ± 30.3	99.0 ± 22.0	0.69

BMI = body mass index; DXA = dual-energy X-ray absorptiometry; MRI = magnetic resonance imaging; VAT = visceral adipose tissue, SAT = subcutaneous adipose tissue.

* Significant ($p \leq 0.05$) differences between Caucasians and Polynesians, forwards and backs, or front row and second/back row forwards.

Table 4.2. Correlation between MRI measures of SAT and VAT and abdominal fat measures via DXA and surface anthropometry.

	Abdominal MRI SAT (cm ²)			Abdominal MRI VAT (cm ²)		
	r	p-value	Qualitative Ranking	r	p-value	Qualitative Ranking
BMI (kg/m²)	0.88	<0.01*	Very Large	0.21	0.27	Small
DXA Android Fat (kg)	0.91	<0.01*	Almost Perfect	0.42	0.02*	Moderate
DXA Android Fat (%)	0.88	<0.01*	Very Large	0.34	0.07	Moderate
DXA Body Fat (kg)	0.94	<0.01*	Almost Perfect	0.35	0.06	Moderate
DXA Body Fat (%)	0.94	<0.01*	Almost Perfect	0.26	0.17	Small
DXA Estimated VAT (cm²)	0.75	<0.01*	Very Large	0.46	0.01*	Moderate

BMI = body mass index; DXA = dual-energy X-ray absorptiometry; MRI = magnetic resonance imaging; SAT = subcutaneous adipose tissue; VAT = visceral adipose tissue

r = correlation coefficient; p-value = significance

Qualitative ranking of correlation defined as trivial, $r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; perfect, $r = 1.0$ [254].

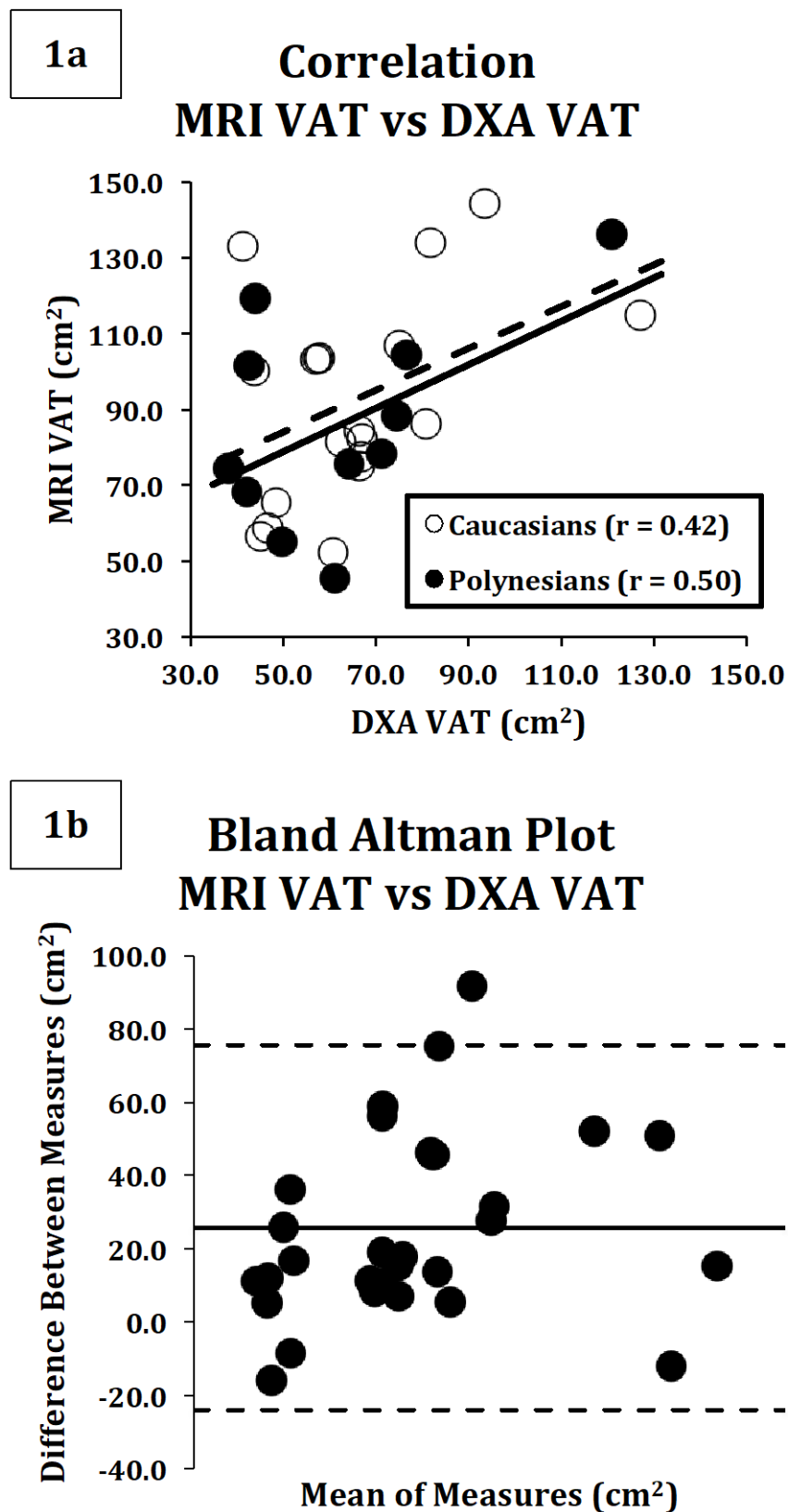


Figure 4.1. a) Correlation between criterion MRI VAT and DXA VAT, and b) Bland Altman plot of criterion MRI VAT and estimated DXA VAT. Difference is MRI VAT less DXA VAT. Mean difference (solid line), upper and lower limits of agreement (dotted lines).

DISCUSSION

The primary finding of this investigation is that, on average, the levels of VAT in elite RU athletes do not exceed the diagnostic threshold for cardiometabolic complications ($>100 \text{ cm}^2$). However, one-third of the athletes had a VAT $>100 \text{ cm}^2$, with over two-thirds having a VAT:SAT >0.4 . All athletes with a VAT $>100 \text{ cm}^2$ also had a VAT:SAT >0.4 , whilst no athletes had VAT $>160 \text{ cm}^2$. VAT levels did not differ between Caucasian and Polynesian athletes; however, there was a trend for forwards to have higher VAT than backs, which provides an indication this may be an area of interest to researchers moving forward [613]. Only a moderate correlation was found between the criterion MRI VAT and estimated DXA VAT, with DXA notably underestimating VAT.

Forwards in the present study exhibited higher total mass, plus absolute and relative (percentage) FM, compared to backs. Furthermore, forwards possessed greater abdominal SAT and tended to have higher VAT. The body composition characteristics of elite RU forwards in the present study are similar to those previously reported in RU [333, 448, 620]. Further, they are similar to body composition traits exhibited in NFL athletes, with linebackers, tight ends, and running backs exhibiting similar BMI (NFL $31.5 \pm 1.9 \text{ kg/m}^2$ vs RU $30.6 \pm 2.0 \text{ kg/m}^2$), LM (NFL $87.3 \pm 4.7 \text{ kg}$ vs RU $86.5 \pm 4.8 \text{ kg}$), and BF% (NFL $17.0 \pm 4.0\%$ vs RU $15.8 \pm 2.9\%$) [73]. Additionally, DXA measured VAT was similar between these NFL athletes ($0.3 \pm 0.2 \text{ kg}$) and the RU forwards in this study ($0.4 \pm 0.1 \text{ kg}$). However, NFL linemen, who were heavier with higher overall body fat, were found to have significantly more VAT ($1.2 \pm 0.6 \text{ kg}$) compared to both the forwards in the present study, and other NFL players [73]. Furthermore, it has been reported that after NFL athletes reach a mass of 250 lbs ($\sim 114 \text{ kg}$) the rate of LM accumulation decreases, and that above 20% body fat the rate of VAT accumulation increased relative to SAT [73]. This detail is particularly pertinent given that in the present study, 41% of forwards were over 114 kg, and there is a gradual trend for RU forwards to become even heavier over time, given forward packs possessing greater total mass are more successful [416, 496]. Although the literature suggests that the increasing mass in RU athletes is a result of

increasing mesomorphy and decreasing endomorphy [163], it could be postulated that the need for “supersized” athletes in RU may evolve similarly to the NFL, with absolute mass becoming an important physical attribute. In concordance with the present study, a 2015 paper reported that larger RU players had higher VAT levels, and that over a fifth of the athletes met the criteria for visceral obesity of VAT >100 cm² [614]. However, the athletes in that study were not elite, and VAT was estimated via bio-electrical impedance which shows poor correlation with accepted measures of VAT [84].

It is important to note the higher VAT levels in these “supersized” athletes may simply reflect their overall body size. Indeed, the reference ranges previously proposed for VAT area have been derived from older, shorter, and inactive populations [431]. Presently there are no VAT reference ranges established relative to size, or appropriate to athletic individuals able to be applied to this population. It has previously been reported in obese populations that a VAT:SAT >0.4 is associated with disorders of glucose and lipid metabolism [190]. More recently in a population of Korean men (age 52.1 ± 9.9 years; BMI 24.0 ± 2.2 kg/m²), VAT:SAT effectively predicted the presence of multiple metabolic risk factors [413]. In the present study, over two-thirds of the athletes had a VAT:SAT >0.4. However, given the VAT:SAT threshold of 0.4 was derived from an obese population, and this elite athletic population possessed relatively low SAT levels, the ratio may not provide an accurate indication of health status in RU athletes. Furthermore, the athletes in this study were all partaking in extremely high levels of activity which has been shown to be protective of cardiometabolic complications [426]. Indeed, cardiorespiratory fitness has been shown to be a far more important indicator of cardiovascular disease and all-cause mortality than obesity, with fit-obese persons exhibiting similar mortality risk compared to normal weight and fit individuals [42]. Moreover, higher levels of cardiorespiratory fitness have been shown to substantially reduce the adverse effects of obesity on morbidity and mortality [183], suggesting that during their athletic career “supersized” elite athletes may be protected from obesity-related cardiometabolic complications.

Although no currently available reference ranges are applicable to elite RU players, “supersized” athletes with higher relative VAT levels have previously been linked with post-career cardiometabolic complications. In a study of retired NFL linemen, who have been shown to possess higher levels of VAT than other athletes in their sport [73], a significantly higher prevalence of type 2 diabetes (10.4% vs 4.0%) and metabolic syndrome (59.8% vs 30.1%) was noted in comparison to non-linemen [380]. Coronary artery calcium (CAC), a marker of the presence and severity of subclinical atherosclerosis [149], can also be used as a surrogate of cardiovascular disease risk. Indeed, retired linemen have less likelihood of CAC absence (33.8% vs 47.7%, $p = 0.02$), and a higher likelihood of moderate to severe subclinical atherosclerosis (32.9% vs 26.4%, $p = 0.04$) compared to non-linemen [43]. Presently, there is nothing in the literature discussing post-career health status in elite RU athletes. Given the established long-term health complications identified in “supersized” NFL athletes, and their physique similarities with RU forwards, cardiometabolic disease markers in elite RU athletes, both during and post-career, deserves further exploration. This is particularly relevant given that a number of athletes in the present study displayed elevated VAT, despite their high levels of physical activity. Therefore, it could be postulated that these athletes may be more susceptible to complications following retirement when activity levels are likely to decrease.

In this study, no significant differences were noted between Caucasians and Polynesians in any of the abdominal body composition measures assessed. Previously, among non-athletic populations, Polynesians exhibited greater abdominal FM than Caucasians both in absolute terms (2.3 ± 1.0 kg vs 1.5 ± 1.0 kg, $p < 0.001$), and as a percentage of total mass ($9.0 \pm 1.7\%$ vs $8.0 \pm 1.5\%$, $p < 0.001$) [480]. It has been proposed that major changes in traditional lifestyle factors such as nutrition and a decrease in physical activity amongst Polynesians are the main cause of their poor cardiometabolic profiles [98], therefore participation in elite sport may be protective in this RU population. However, in this study dietary intake was not quantified, nor were hematological markers of cardiometabolic disease risk assessed. Given there is evidence describing increased blood related cardiometabolic disease risk factors present in

Polynesians [533], investigations exploring changes in abdominal body composition and hematological status under controlled training conditions would be of value. Interestingly, VAT accumulation has been shown to be influenced by ethnicity in studies involving African Americans and Caucasians in both non-athletic [93], and athletic populations [43]. This has not been researched in Polynesians, and may be a contributing factor to the immensity of cardiometabolic complications in this population. Furthermore, whether participation in an elite athletic environment remains protective for Polynesian athletes post-career is yet to be determined.

When comparing the criterion MRI VAT with DXA estimated VAT, only a moderate correlation was observed ($r = 0.46$, $p = 0.01$). However, given MRI access to screen for elevated VAT is limited outside of a research setting, the use of DXA estimated VAT may be of value since it provided the highest correlation of all the abdominal measures taken using DXA or BMI, and is increasingly being used to monitor body composition of athletes [377]. Specifically, elite athlete may have up to 3-4 DXA scans per year for body composition purposes, and the VAT value generated from these reports may be used as a screening tool for further investigations [377]. In this study, 6 of the highest 7 recorded DXA VAT measures belonged to those with an MRI VAT $>100 \text{ cm}^2$. Given previous studies have reported very high correlations ($r > 0.90$) between MRI and DXA estimates of VAT [399], it was surprising to see the predictive power of DXA was not as strong in our population. This is likely because prior studies were undertaken on non-athletic groups where a larger proportion of individuals had considerably higher VAT. This suggests, as evidenced by the Bland Altman results in this study, that DXA may underestimate VAT at lower body fat levels [399].

This study was limited by the fact only a single MRI slice was analysed from within the abdominal cavity. This is often the case in research and clinical practice given the increased cost and time commitment in the analysis process to measure multiple slices and/or a volume [501]. Further, studies sampling a single slice have been observed to be affected by ethnicity, with maximum VAT being recorded at different vertebral levels [142]. Moreover, the best slice to take

has been questioned, with the L2/L3 slice sometimes utilised as opposed to the L4/L5 slice as was taken in this study [494], identifying a potential limitation of this research. Ideally, volumetric measures of VAT would be taken to account for the different distribution of adiposity within the abdominal cavity [501], but this was not an option in this investigation as only a single slice was acquired at assessment due to time and cost constraints. Further, the present study was limited by the relatively small sample size, as is inherent in all elite-level studies due to the rarity and availability of elite athletes. Finally, the measures were taken at the beginning of the pre-season period, which for this particular group of athletes was preceded by a 4 week transition phase between seasons comprising of a reduced training load, and in some cases limited training due to off-season surgery. Thus, theoretically the athletes' physical condition was at its poorest. Future studies would benefit from analysing VAT at multiple time-points during the season to ascertain if the training stimulus influences abdominal adiposity. Additionally, further investigation is warranted into whether or not higher VAT levels than those of the general population in an elite group of athletes is indeed a risk factor. Such investigations would benefit from measures of lipid profiles and other cardiovascular disease risk factors. Finally, investigations looking into whether changes in lifestyle and body composition after the conclusion of the athletes' playing careers has the potential to put them at further risk once the protective effects of exercise are removed should be considered.

CONCLUSION

This study was undertaken with a view to develop a better understanding of whether those RU athletes who are more “supersized” are prone to possess elevated VAT levels. While larger athletes with higher total body fat possessed higher VAT, no differences were evident according to ethnicity. The results of this research provides sport scientists and medical professionals insight into the VAT levels of this group of athletes, which may direct further screening and/or interventions to establish and manage disease risk. Given the elevated VAT levels in some “supersized” RU athletes from this study, and the association between high VAT levels with post-career obesity related complications in other “supersized” athletes, the exploration of VAT and other cardiometabolic risk factors in this population warrants further investigation.

CHAPTER FIVE – SKINFOLD PREDICTION EQUATIONS FAIL TO PROVIDE AN ACCURATE ESTIMATE OF BODY COMPOSITION IN ELITE RUGBY UNION ATHLETES OF CAUCASIAN AND POLYNESIAN ETHNICITY

Zemski AJ¹, Broad EM², and Slater GJ^{1,3}. Skinfold prediction equations fail to provide an accurate estimate of body composition in elite rugby union athletes of Caucasian and Polynesian ethnicity. *International Journal of Sports Nutrition and Exercise Metabolism*. 2018; 28: 90-99.

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (80%), EMB/GJS (10%).
- Conceived and designed the experiment: AJZ, EMB, GJS.
- Collected and collated the data: AJZ, GJS.
- Analysed the data: AJZ, EMB, GJS.
- Wrote/reviewed the paper: AJZ, EMB, GJS.

ABSTRACT

Body composition in elite RU athletes is routinely assessed using SA, which can be utilised to provide estimates of absolute body composition using regression equations. This study aims to assess the ability of available skinfold equations to estimate body composition in elite RU athletes, who have unique physique traits and divergent ethnicity. The development of sport-specific and ethnicity-sensitive equations was also pursued. Forty-three male international Australian RU athletes of Caucasian and Polynesian descent underwent SA and DXA assessment. BF% was estimated using five previously developed equations, and compared to DXA measures. Novel sport and ethnicity-sensitive prediction equations were developed using forward selection multiple regression analysis. Existing skinfold equations provided unsatisfactory estimates of BF% in elite RU athletes, with all equations demonstrating a 95% prediction interval in excess of 5%. The equations tended to underestimate BF% at low levels of adiposity, whilst overestimating BF% at higher levels of adiposity, regardless of ethnicity. The novel equations created explained a similar amount of variance to those previously developed (Caucasians 75%, Polynesians 90%). The use of skinfold equations, including the created equations, cannot be supported to estimate absolute body composition. Until a population-specific equation is established that can be validated to precisely estimate body composition, it is advocated to use a proven method such as DXA when absolute measures of LM and FM are desired, and raw SA data routinely to derive an estimate of body composition change.

INTRODUCTION

RU is an intermittent, full contact team sport characterised by bursts of high intensity running, heavy tackling, and frequent body contact, interspersed with periods of recovery. It requires a unique combination of strength, skill, speed and endurance [163]. Since becoming a professional sport in 1995, RU has become faster and more physically demanding [169], with modern day elite RU athletes becoming more mesomorphic [416]. This has resulted in a greater emphasis being placed on understanding the physiological demands of the sport, including athletes evolving body composition traits. Routine physique assessment is advocated in RU due to the role gravitational force plays and its relationship with on-field success [416, 496].

The most common methods used in practice to assess body composition are SA DXA [2, 620]. SA, which includes the indirect assessment of SAT, is an easily accessible, inexpensive, mobile and robust method of assessment. The application of absolute skinfold measurement is recommended to assess changes in body composition [2, 459], whilst the use of equations to estimate BF% is advocated only if being applied to the population from which it was derived [459]. Currently, there is not a specific equation available for estimating body composition in RU athletes, nor one that differentiates between Caucasian and Polynesian athletes who have unique physique traits [620].

In practice, there is regularly a need to estimate absolute measures of LM and FM, for example, in the development and assessment of training and/or dietary interventions. Given DXA is validated to quantify BMC, FM and LM, both at regional and whole body levels, its use is increasing amongst athletic populations [2]. However, the frequency of DXA scanning may be limited by practical issues like cost or facility availability, or regulatory constraints aimed at limiting radiation exposure. Given this, validated SA based equations to estimate absolute body composition with adequate prediction power would be advantageous.

The aims of this study were to: 1) assess the ability of currently available skinfold regression equations to estimate body composition relative to DXA in an elite RU population of different ethnic backgrounds; and 2) derive RU, and ethnicity-sensitive equations for predicting body composition.

METHODS

Participants

Forty-three male elite RU athletes (age 25.5 ± 3.1 years) were recruited via their involvement in the Australian national squad. All participants provided informed consent to participate in the study, and the research was approved by the Human Research Ethics Committee at the University of the Sunshine Coast (EC00297, S/12/424).

Experimental design

Participants undertook routine body composition assessment via DXA and SA over two consecutive international seasons. Participants were assessed between one and three times over this period, with DXA and SA measurements occurring within 48 hours of each other. For consistency, if a participant had multiple measures taken in the time period, the measure corresponding to their highest LMI value – a measure that tracks within-subject proportional change in BM adjusted for skinfold changes [511] – was used for analysis, as theoretically this is when the participant was in their peak physical condition.

Surface anthropometry

An ISAK Level 3 accredited anthropometrist with a historical TEM of 1.7% for S7SF took all measurements. BM was assessed using electronic scales (A&D Mercury, Adelaide, Australia) to 0.1 kg accuracy upon waking after an overnight fast with bladder voided. Skinfolds were assessed using Harpenden calipers (British Indicators, Hertfordshire, UK) to 0.1 mm accuracy. All anthropometric equipment was calibrated as recommended by the manufacturers. Stature was self reported to the nearest 1.0 cm.

Skinfold measurements were made using ISAK techniques previously described [410], across seven skinfold sites, including triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, and medial calf. All measurements were undertaken in duplicate to establish within-day retest reliability. If the difference between the duplicate measures exceeded 4% for an individual skinfold, a third measurement was taken. The mean of duplicate or median of triplicate anthropometric measurements were used for all analysis. LMI [511] was calculated using the equation:

$$\text{LMI} = \text{BM} / \text{S7SF}^{0.14}$$

Derived surface anthropometry measures

Regression equations were selected for comparison in this study if they were male specific, created using Harpenden skinfold calipers, and followed ISAK techniques [410]. Using this criteria the following equations were identified for comparison: Evans [179], Reilly [459], Lohman [347], and Withers [608]. Durnin and Womersley (D&W) [162], was also assessed, which used ISAK identified sites and a combination of Harpenden and other calipers. Where body density (BD) was calculated the formula of Siri [509] was used to estimate body composition (Table 5.1).

Table 5.1. Details of previously published regression equations used for comparison in this study.

Author (year)	Sample Size	Demographics (mean $\pm$ SD)	Skinfold Sites Used	Reference Assessment Used	Equation As Applied To This Study
Evans (2005)	78 male collegiate athletes	Age 20.9 ± 1.7 years Stature 184.0 ± 7.9 cm Mass 93.1 ± 21.6 kg	Tricep, abdominal, mid-thigh	4-compartment model	$BF\% = 8.997 + (0.24658 \times (\text{triceps} + \text{abdominal} + \text{mid-thigh})) - 6.343$
Reilly (2009)	45 male professional soccer players	Age 24.2 ± 5.0 years Stature 182.0 ± 7.0 cm Mass 82.0 ± 8.5 kg	Tricep, abdominal, mid-thigh, medial calf	DXA	$BF\% = 5.174 + (0.196 \times \text{triceps}) + (0.147 \times \text{abdominal}) + (0.124 \times \text{mid-thigh}) + (0.130 \times \text{medial calf})$
Lohman (1981)	149 male subjects from a combination of studies	Group demographics unknown	Tricep, subscapular, abdominal	Hydrodensitometry	$BD = 1.0982 - 0.000815X + 0.0000084X^2$ X = sum of triceps, subscapular, abdominal $BF\% = (4.95/BD - 4.50) \times 100$

Withers (1987)	207 state and international athletes from a range of sports	Age 24.2 ± 4.7 years Stature 180.0 ± 8.3 cm Mass 74.5 ± 10.5 kg	Triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, medial calf	Hydrodensitometry	$BF\% = (495 / (1.0988 - (0.0004 \times S7SF))) - 450$
Durnin and Womersley (1974)	92 males with a variety of body types aged between 20-29	Age 20 – 29 years Stature 177 ± 6.9 cm Mass 70.1 ± 12.2 kg	Tricep, subscapular, bicep, supraspinale	Hydrodensitometry	$BD = 1.1631 - (0.0632 \times L)$ $L = \log(\text{triceps} + \text{subscapular} + \text{bicep} + \text{supraspinale})$ $BF\% = (4.95 / BD - 4.50) \times 100$

Dual-energy X-ray absorptiometry

Measures were taken using a fan-beam DXA scanner (Hologic Discovery A, Hologic, Bedford, MA), with analysis performed using Apex 12.7.3 software (Hologic, Bedford, MA) using the NHANES 2008 reference group. The scanner was calibrated daily using a phantom as per manufacturer guidelines for quality control purposes. All scans were undertaken using the array mode.

Scanning protocols were implemented as per techniques previously described to maximise technical reliability and minimise error [396]. Specifically, participants were scanned first thing in the morning prior to food and fluid ingestion, or exercise. Participants were scanned wearing tight fitting sports shorts, and those too big for the scanning bed undertook multiple scans. Specifically, those too tall to fit within the defined scanning area undertook two scans, the first of which captured the body from the menton (the inferior point of the mandible) down whilst the head was positioned in the Frankfort plane. After body repositioning on the scanner and realignment of the head into the Frankfort plane, the second scan captured from the menton up to the vertex of the head. The results were then combined post-analysis to produce whole body composition [395]. None of the participants in this study were too broad for the scanning area. For positioning consistency the same experienced and qualified technician performed all measurements using the International Society for Clinical Densitometry (ISCD) positioning protocol [223], and the participants leg positioning was standardized using a set width foot strap that was placed over both feet anterior to the lateral malleolus. Fat-free mass index (FFMI) and fat mass index (FMI) [493] were calculated using the equations:

$$\text{FFMI} = \text{FFM (kg)} / \text{stature (m)}^2$$

$$\text{FMI} = \text{FM (kg)} / \text{stature (m)}^2$$

Ethnicity

At the time of consent the participants were requested to provide researchers with the ethnicity of their grandparents via open ended questions. It was made clear that this was optional and would not impact participants involvement in the research or national squad.

A universally accepted method of distinguishing an individual's ethnicity was unable to be identified due to the inherent difficulty in defining "ethnicity" [75]. As this research investigated the phenotype expression and differences of ethnicity on body composition based on differences previously described in sedentary populations [480, 537], grandparental heritage was chosen as in previous research [155, 620]. If a participant had three or four grandparents of Caucasian or Polynesian ethnicity, this was used to describe the participant's ethnicity. If they were unable to be identified as Caucasian or Polynesian they were excluded from the study.

Statistical methods

Statistical analyses were carried out using SPSS 22 (SPSS Inc., Chicago, Illinois, USA). Descriptive statistics on relevant body composition measures were calculated and presented as mean $\pm$ SD. Data was explored using box plots and Q-Q plots to identify any potential outliers, with participants considered outliers if they were greater than two SD away from the mean in over a quarter of the body composition variables analysed. Differences in body composition measures based on ethnicity were investigated using independent t-tests. A least squares regression analysis was used to assess the validity of the BF% equations, where DXA derived BF% (DXA-BF%) were regressed against each equation independently. The potential for any fixed bias was assessed by determining whether the intercept for the regression was different from zero. To identify if proportional bias was present the slope of the regression line was assessed to determine if it was different from one. The random error was quantified using the standard error of the estimate (SEE) from the regression. Visual inspection of

the residual plots was completed to determine if the random error was constant along the range of measures taken. To evaluate the predictive accuracy of each equation for individuals, the 95% prediction interval (95% PI) for each equation was calculated. Forward selection multiple regression analysis was performed using the data from which novel RU and ethnicity-sensitive prediction (“Zemski”) equations were derived, ensuring both upper and lower body skinfold sites were incorporated as previously advocated [177, 459]. Data for the regression analysis conformed to the assumptions of homoscedasticity, independent and normally distributed errors, with no multicollinearity.

RESULTS

The initial study population consisted of forty-four athletes. These athletes were arranged based on their ethnicity, with seventeen being identified as of Polynesian descent. The remaining athletes were identified as Caucasian. After preliminary statistical analysis was undertaken, one athlete, a Caucasian, was removed from the final analysis as they were identified as an extreme outlier, leaving forty-three participants.

Descriptive characteristics

Descriptive characteristics of the combined athlete population and the respective ethnicities are presented in Table 5.2. No significant differences in any measures were found between ethnicities.

Correlation analysis

All skinfold equations estimating BF% (skinfold-BF%) correlated with DXA-BF% values (Table 5.3). No equation significantly outperformed the others, however the Reilly equation had the highest correlation values, and also the least systematic bias when assessing the range of physiques in this population.

Table 5.2. Body composition characteristics of the elite rugby union athletes combined and by ethnicity.

Variable	All participants (n = 43)		Caucasians (n =26)		Polynesians (n = 17)	
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
Stature (cm)	188.0 $\pm$ 7.8	173.0 – 203.0	189.1 $\pm$ 7.9	173.0 – 201.0	186.4 $\pm$ 7.5	174.0 – 203.0
Scale mass (kg)	104.2 $\pm$ 11.9	80.4 – 122.6	104.0 $\pm$ 11.3	82.3 – 119.0	104.6 $\pm$ 13.1	80.4 – 122.6
Sum 7 skinfolds (mm)	68.8 $\pm$ 22.5	40.2 – 130.2	68.4 $\pm$ 19.5	43.4 – 119.8	69.4 $\pm$ 27.0	40.2 – 130.2
Lean mass index	57.9 $\pm$ 5.4	46.5 – 66.7	57.7 $\pm$ 5.2	46.5 – 66.5	58.2 $\pm$ 5.9	47.3 – 66.7
Fat-free mass index (kg/m²)	25.9 $\pm$ 1.7	23.4 – 30.9	25.6 $\pm$ 1.3	23.5 – 28.3	26.5 $\pm$ 2.2	23.4 – 30.9
Fat mass index (kg/m²)	4.0 $\pm$ 1.2	2.1 – 6.7	3.9 $\pm$ 1.0	2.3 – 6.7	4.1 $\pm$ 1.4	2.1 – 6.6
DXA – BMC (kg)	4.3 $\pm$ 0.5	3.1 – 5.7	4.2 $\pm$ 0.4	3.2 – 5.0	4.4 $\pm$ 0.7	3.1 – 5.7
DXA – lean mass (kg)	87.5 $\pm$ 8.8	69.3 – 101.9	87.3 $\pm$ 8.1	69.3 – 101.1	87.8 $\pm$ 10.0	69.3 – 101.9
DXA – fat mass (kg)	14.2 $\pm$ 4.2	7.2 – 23.2	14.1 $\pm$ 3.9	7.3 – 22.8	14.3 $\pm$ 4.8	7.2 – 23.2
DXA – BF%	13.2 $\pm$ 2.9	8.2 – 21.1	13.2 $\pm$ 2.6	8.6 – 19.5	13.2 $\pm$ 3.4	8.2 – 21.1

Data are mean $\pm$ SD. DXA = dual-energy X-ray absorptiometry; BMC = bone mineral content; BF% = body fat percent; lean mass index = kg/sum 7 skinfolds (mm)^{0.14}; fat-free mass index = fat-free mass (kg)/stature (m²); fat mass index = fat mass (kg)/stature (m²).

Table 5.3. Least squares regression analysis of previously developed skinfold regression equations in an elite rugby union population.

Group	Equation	Mean $\pm$ SD	Intercept	Slope	SEE	r	Mean 95% PI*
All participants (n = 43)	DXA – BF%	13.2 $\pm$ 2.9	-	-	-	-	-
	D&W	13.7 $\pm$ 3.6	3.92 (1.95-5.88)	0.67 (0.53-0.81)	1.59	0.84 (0.72-0.91)	3.28 (6.56)
	Lohman	13.5 $\pm$ 4.3	5.46 (3.92-6.99)	0.57 (0.46-0.68)	1.50	0.86 (0.75-0.92)	3.10 (6.19)
	Withers	12.1 $\pm$ 3.9	5.31 (3.95-6.68)	0.65 (0.54-0.76)	1.35	0.89 (0.80-0.94)	2.80 (5.60)
	Evans	11.7 $\pm$ 3.1	3.56 (1.95-5.18)	0.82 (0.69-0.95)	1.33	0.89 (0.80-0.94)	2.75 (5.50)
	Reilly	11.6 $\pm$ 2.2	-0.84 (-2.96-1.27)	1.20 (1.03-1.38)	1.24	0.90 (0.83-0.95)	2.58 (5.16)
Caucasians (n = 26)	DXA – BF%	13.2 $\pm$ 2.6	-	-	-	-	-
	D&W	13.3 $\pm$ 3.3	4.72 (2.09-7.35)	0.63 (0.44-0.83)	1.52	0.81 (0.62-0.91)	3.26 (6.53)
	Lohman	13.2 $\pm$ 3.7	5.96 (3.53-8.38)	0.55 (0.37-0.72)	1.59	0.79 (0.59-0.90)	3.41 (6.82)
	Withers	12.0 $\pm$ 3.4	5.56 (3.41-7.70)	0.63 (0.46-0.81)	1.42	0.84 (0.67-0.93)	3.04 (6.09)
	Evans	11.8 $\pm$ 2.7	3.89 (1.13-6.66)	0.78 (0.56-1.01)	1.49	0.82 (0.64-0.92)	3.18 (6.36)
	Reilly	11.7 $\pm$ 1.8	-0.84 (-4.42-2.73)	1.20 (0.89-1.50)	1.34	0.86 (0.70-0.93)	2.89 (5.78)
Polynesians (n = 17)	DXA – BF%	13.2 $\pm$ 3.4	-	-	-	-	-
	D&W	14.3 $\pm$ 4.0	2.50 (-0.76-5.76)	0.74 (0.52-0.96)	1.65	0.88 (0.70-0.96)	3.72 (7.43)
	Lohman	13.9 $\pm$ 5.2	4.85 (2.73-6.97)	0.60 (0.45-0.74)	1.39	0.92 (0.78-0.97)	3.14 (6.27)
	Withers	12.2 $\pm$ 4.7	5.05 (3.09-7.01)	0.66 (0.51-0.81)	1.33	0.92 (0.80-0.97)	2.99 (5.98)
	Evans	11.5 $\pm$ 3.8	3.34 (1.43-5.24)	0.85 (0.70-1.01)	1.11	0.95 (0.86-0.98)	2.50 (5.01)
	Reilly	11.5 $\pm$ 2.6	-0.84 (-3.51-1.82)	1.22 (0.99-1.44)	1.12	0.95 (0.86-0.98)	2.56 (5.12)

95% PI = 95% prediction interval; r = correlation coefficient; SEE = Standard Error of Estimates; Mean 95% PI = mean 95% prediction interval of DXA–BF% vs. skinfold equations BF%; D&W = Durnin and Womersley. *PI ranges calculated by multiplying the 95% PI interval by 2 (ranges are in parentheses).

Regression analysis

The slopes, intercepts and SEE together with 95% PI for each equation are presented in Table 5.3. The random error associated with each of the individual equations was relatively comparable between the different groups, as was the magnitude of the 95% PI. The Reilly and Evans equations performed the best in these measures across both ethnicities, with the Reilly equation providing slightly lower error measurements.

The potential for any bias was assessed by visual inspection of the regression lines (Figure 5.1). The slopes and positions of the regression lines for all of the Reilly and Evans equations graphs provide evidence of a fixed bias that results in underestimation of skinfold-BF% compared to DXA-BF% across the range of adiposity, although less so at higher ranges of adiposity for the Evans equation. D&W, Lohman and Withers all display a significant proportional bias, shown by the regression line intersecting the line of best fit in all graphs. These equations are prone to underestimation of BF% at the lower levels of adiposity, and overestimation of BF% at the higher levels of adiposity.

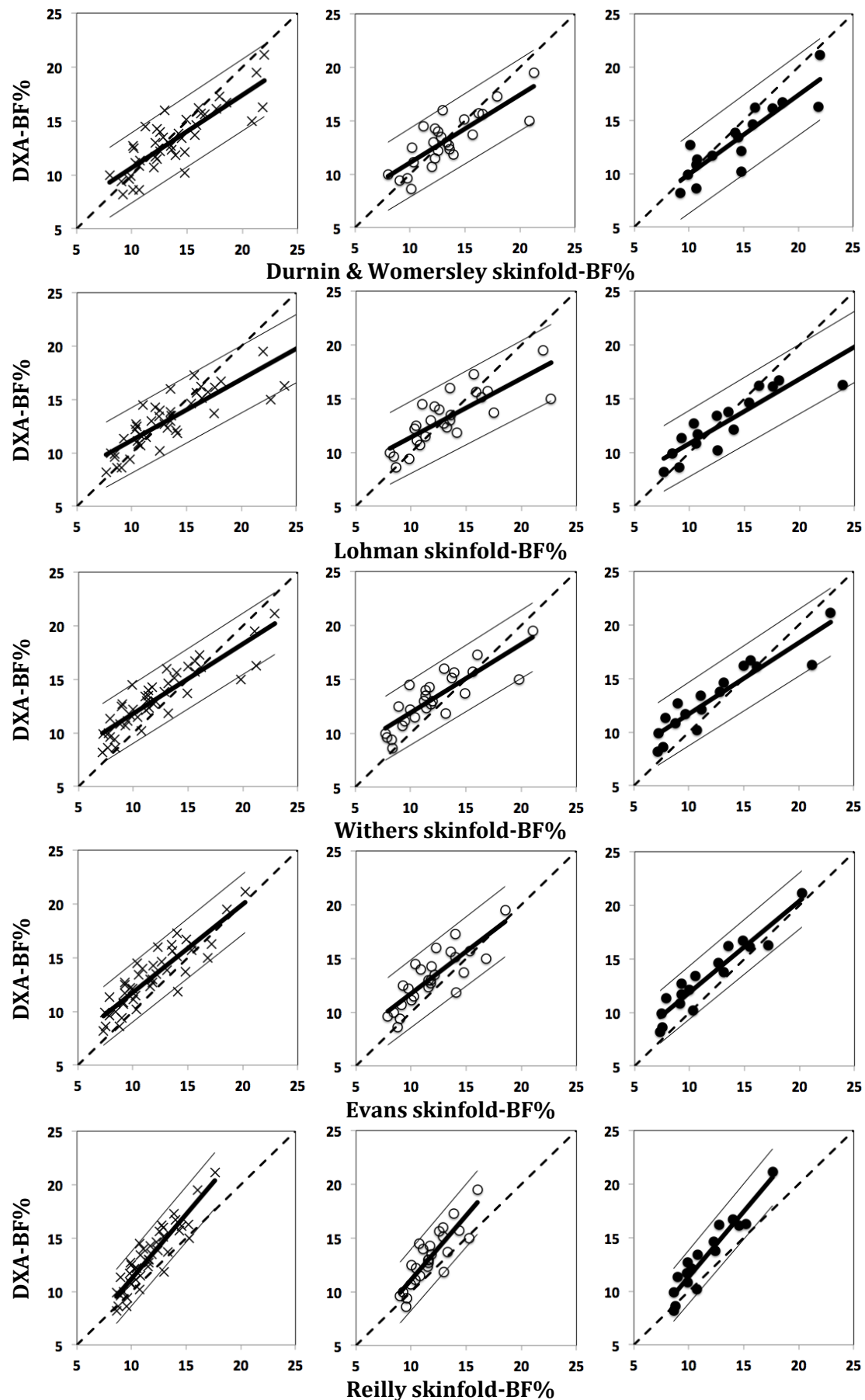


Figure 5.1. Least squares regression plots of DXA-BF% versus skinfold equations BF% (skinfold-BF%) for elite rugby union athletes. Line of equilibrium (dotted line), line of regression (bold line), and 95% prediction intervals (solid lines). Crosses denote all participants, open circles Caucasians, and closed circles Polynesians.

Forward selection multiple regression analysis

Of the equations tested, Reilly appears to be the best fit for an elite RU population, both as a whole, and when split into Caucasians and Polynesians (Table 5.3, Figure 5.1). It had the lowest measures of error, and provided a consistent variance in comparison to DXA, as opposed to the Evans equation which varied in consistency across the different physiques found in the population. When the skinfold sites identified in Reilly were used in multiple regression analysis of this population, they were able to explain 83% of the variation in DXA-BF% in the whole population, 77% in Caucasians and 91% in Polynesians.

Using forward selection multiple regression analysis on the Caucasian population, the combination of triceps, supraspinale and calf skinfolds explained 75% variance in DXA-BF% using the “Zemski Caucasian” formula:

$$\text{BF\%} = 5.896 + (0.265 \text{ tricep}) + (0.251 \text{ supraspinale}) + (0.394 \text{ calf})$$

In the Polynesian population the combination of abdominal and calf skinfolds explained 90% variance in DXA-BF% using the “Zemski Polynesian” formula:

$$\text{BF\%} = 5.577 + (0.170 \text{ abdominal}) + (0.749 \text{ calf})$$

DISCUSSION

The primary finding of this investigation is that the skinfold prediction equations evaluated had a reasonably poor ability to estimate BF% relative to the reference DXA measure. The equations of D&W, plus Lohman and Withers show a similar pattern, underestimating BF% at lower levels of adiposity and overestimating BF% at higher levels of adiposity. The equation of Evans displayed a similar pattern at lower levels of adiposity; however, the higher the skinfold measures were, the better the equation's ability to provide an accurate estimate of BF%. The Reilly equation showed a reasonably consistent underestimation of BF%, and given its consistency of estimation across the population investigated it appears to be the most appropriate equation to use out of those tested for elite RU athletes (Figure 5.1). However, the prediction intervals of all equations in which 95% of the estimates would be expected to lie between the assessment methods ranged from 5.0–7.5%, indicating a lack of precision compared to DXA (Table 5.3). Given the prediction error of the equations is greater than the changes in body composition typically reported across a RU season [333], the application of these equations in this population could not be advocated.

The inability of this series of equations to accurately quantify absolute BF% relative to DXA in this population may in part be attributed to the phenotypical differences of the populations from which the equations were derived (Table 5.1). The Evans equation provided good estimates of BF% at higher levels of adiposity, perhaps reflecting the morphological similarities between the sample populations, with the Evans equation created using a number of larger athletes. Interestingly, whilst many of the equations used somewhat heterogeneous populations, Reilly used a group of professional athletes from a single sport (soccer). Although this equation was found to be the best fit of the equations analysed, it still lacked precision and underestimated BF% in elite RU athletes. This in part could be due to the unique muscularity of elite RU athletes, indicated by the average FFMI for the Caucasian participants placing them well above the 95th percentile for healthy Caucasians [493]. Furthermore, generalised equations

or those not derived from similar samples, genetically as well as environmentally, may not be appropriate for individual application [276].

A number of the equations examined were created utilising BD measures obtained from hydrodensitometry. This two-compartment method of body composition assessment is based on assumptions which may be violated in athletic populations [177]. Only one of the equations examined used the criterion 4C method, which may also explain some of the variability due to the use of different reference assessment methods. Note that using a 4C method as the criterion measure was not an option within this athletic population due to the time constraints associated with the deuterium dilution technique to measure total body water [111].

An important consideration when assessing the accuracy of skinfold related data is the way in which it is collected. The anthropometrist's training, skill and TEM are important considerations, with data collected without strict standardisation of landmarking and technique introducing the potential for additional error [260]. When assessed by a qualified and experienced anthropometrist, the use of a S7SF measure recorded in absolute terms (mm), has been shown to provide an accurate indication of changing adiposity [293, 294, 459], as LMI, which uses the S7SF measure, has for LM [511]. In this study, the use of a single highly proficient and experienced ISAK-accredited anthropometrist with a low historical TEM of 1.7% ensured accurate anthropometric data was collected. Importantly, presently there are very few, if any, regression equations that have been validated to track changes in body composition longitudinally [103, 506]. Given this, the application of regression equations to track changes in body composition without sufficient validation is inconsistent with best practice.

It has been shown in elite RU populations there are differences in the distribution of LM and FM based on the ethnicity of the athlete [620]. Compared to Caucasians, Polynesians have a greater proportion of FM and LM in their peripheries, whilst in the trunk region a lower proportion of FM and LM was observed. The ethnicity-sensitive regression equations investigated in this study

utilised different combinations of skinfold sites to estimate BF% (Table 5.1). Based on the differences in tissue distribution previously shown between ethnicities in both athletic [620] and non-athletic [480, 537] populations, the application of non-ethnicity specific skinfold equations in an elite RU population notorious for high proportions of athletes with differing ethnicity would appear flawed.

The skinfold and DXA data collected in this study were also used to create novel RU and ethnicity-sensitive skinfold equations. Using forward selection multiple regression analysis, the “Zemski” equations were created for Caucasians and Polynesians, using only three and two skinfold sites respectively. Previously, it has been recognized that a three skinfold site model showed similar accuracy to a seven site model, thus these equations were seen as appropriate [506].

Interestingly both equations selected a skinfold site from the lower body, which aligns with previous research showing highest correlations between total body fat and lower body skinfolds [177]. These equations explain a moderate proportion of the variability in DXA derived BF% for Caucasians and Polynesians, 75% and 90% respectively (Table 5.4), which is similar to the Reilly equation (77% and 91% respectively). The Reilly equation was also developed using DXA as a reference model, and had a similar sample size (Table 5.1). Based on the findings of this study, the use of currently available equations, including the Zemski equations, cannot be advocated.

Given the unique physiques of elite RU athletes, the search for a specialised tool for estimating absolute body composition and/or longitudinal changes in body composition from anthropometric measures remains of interest. It is recommended future equations are created with a larger sample size, be validated against a multi-compartment model, and possibly be established based on change scores so it is able to be implemented longitudinally.

CONCLUSION

The skinfold equations evaluated in this study, including the population-specific equations developed as part of this investigation, provide unsatisfactory estimates of absolute body composition in elite RU athletes, thus their application in this specific population cannot be advocated. It is recommended when using anthropometric measures to utilise the absolute value of skinfold thickness measures as an indicator of adiposity changes over time, using an ISAK-accredited technician. Furthermore, where absolute estimates of body composition are required, practitioners are encouraged to utilise validated body composition assessment methods including DXA, ensuring best practice protocols of assessment are undertaken to enhance precision of measurement.

Table 5.4. Multiple regression using Riley specified measurement sites and multiple regression with forward selection to develop new equations.

Equation	Intercept	Triceps	Supraspinale	Abdominal	Thigh	Calf	R²
Reilly	5.174	0.196	-	0.147	0.124	0.130	0.73
Reilly – All Participants	5.169 (0.630)	0.153 (0.096)	-	0.162 (0.036)	0.135 (0.078)	0.358 (0.119)	0.83
Reilly – Caucasian	4.867 (1.040)	0.134 (0.208)	-	0.146 (0.058)	0.174 (0.115)	0.371 (0.144)	0.77
Reilly – Polynesian	5.481 (0.850)	0.121 (0.125)	-	0.187 (0.073)	0.113 (0.174)	0.365 (0.436)	0.91
Zemski – Caucasian	5.896 (1.000)	0.265 (0.186)	0.251 (0.108)	-	-	0.394 (0.146)	0.75
Zemski – Polynesian	5.577 (0.826)	-	-	0.170 (0.700)	-	0.749 (0.242)	0.90

All participants, Caucasian and Polynesian equations are with Riley identified skinfold sites with participants from this study; Zemski equations are newly developed sport and ethnicity-sensitive equations; Standard error in parentheses; Subscapular and bicep skinfold sites not included in the table as they were not used by equations described within.

CHAPTER SIX – LONGITUDINAL CHANGES IN BODY COMPOSITION ASSESSED USING DXA AND SURFACE ANTHROPOMETRY SHOW GOOD AGREEMENT IN ELITE RUGBY UNION ATHLETES

Zemski AJ¹, Keating SE², Broad EM³, and Slater GJ¹. Longitudinal changes in body composition assessed using DXA and surface anthropometry show good agreement in elite rugby union athletes. *International Journal of Sports Nutrition and Exercise Metabolism*. 2018; 14: 1-25 [Epub ahead of print].

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (85%), SEK/EMB/GJS (5%).
- Conceived and designed the experiment: AJZ, EMB, GJS.
- Collected and collated the data: AJZ, GJS.
- Analysed the data: AJZ, SEK.
- Wrote/reviewed the paper: AJZ, SEK, EMB, GJS.

ABSTRACT

RU athletes have divergent body composition based on the demands of their on-field playing position and ethnicity. With an established association between physique traits and positional requirements, body composition assessment is routinely undertaken. SA and DXA are the most common assessment techniques utilised, often undertaken synchronously. This study aims to investigate the association between DXA and SA when assessing longitudinal changes in FFM and FM in RU athletes. Thirty-nine elite male RU athletes (age 25.7 ± 3.1 years; stature 187.6 ± 7.7 cm; BM 104.1 ± 12.2 kg) underwent assessment via DXA and SA multiple times over three consecutive international seasons. Changes in the LMI, an empirical measure to assess proportional variation in FFM, showed large agreement with changes in DXA FFM ($r = 0.54$, SEE = 1.5%, $P < 0.001$); the strength of association stronger amongst forwards ($r = 0.63$) compared with backs ($r = 0.38$). Changes in the S7SF showed very large agreement with changes in DXA FM ($r = 0.73$, SEE = 5.8%, $P < 0.001$), with meaningful differences observed regardless of ethnicity (Caucasians $r = 0.75$; Polynesians $r = 0.62$). The LMI and S7SF were able to predict the direction of change in FFM and FM, respectively, 86% and 91% of the time when DXA change was >1 kg. SA measures provide a robust indication of the direction of change in FFM and FM, although caution may need to be applied when interpreting magnitude of change, particularly with FM.

INTRODUCTION

RU is an internationally-competitive field-based team sport, in which athletes from a wide variety of ethnic backgrounds participate. Given the unique and divergent physiological demands of the positional packs [26, 163, 454], distinct differences in body composition exist. Forwards have consistently been shown to be heavier, taller, and possess more FFM and FM, whilst backs display proportionally lower body fat [333, 620]. Optimal body composition assists athletes in executing the distinctive on-field requirements associated with their specific positions [94, 184]. Given this, the monitoring of physique traits in RU has become routine.

Anecdotally, there is an increasing proportion of RU participants at the elite level of Polynesian descent. Polynesians have been shown to possess greater relative FFM and less FM compared to Caucasians [123, 479, 537], physique traits that predispose them to morphological optimisation in RU. Polynesians also display differences in regional adiposity, a trait common to non-athletic individuals [480] as well as elite RU athletes [620]. The impact these differences in regional physique distribution have on the selection and interpretation of different body composition assessment techniques has not previously been explored.

SA is the scientific procedure of acquiring surface anatomical dimensional measurements, including skinfolds, and is an easily accessible, inexpensive, mobile and robust method of body composition assessment utilised in RU [2, 163]. It is minimally impacted by client presentation when ISAK protocols are followed [293]. Recommended practice is to assess changes in FM via variations in skinfolds, including sites from both the upper and lower body [460]. Changes in FFM can be indicated via fluctuations in the LMI, which assesses within-athlete proportional changes in BM adjusted for changes in the S7SF [511]. However, SA measures are unable to accurately quantify absolute [153, 459, 616], or changes in, FFM and FM [506]. Given this limitation, anthropometric data is increasingly being complemented by other measures.

DXA is able to quantify whole body and regional BMC, FFM, and FM, and is becoming more accessible and popular as a technique to monitor body composition in athletic populations [377, 396]. However, DXA does have some limitations for application in an elite sport environment, including the logistical issues associated with following best practice protocols, equipment availability, cost, and the limits on assessment frequency to minimise radiation exposure [396, 419]. As such, it is common practice for DXA to be utilised in conjunction with SA to monitor body composition. A recent study found LMI was good at estimating DXA derived FFM changes in a relatively homogenous population of rugby league athletes [141]. However, the ability of anthropometric measures to infer absolute body composition changes in elite populations of athletes with widely varying physique traits remains relatively untested. Specifically, it is unclear whether changes in skinfolds are equally reflective of whole body changes in FFM and FM in both Caucasian and Polynesian athletes given the different regional FM patterning observed [620]. Moreover, as DXA has been shown to underestimate FM in some leaner populations [444, 552, 570, 604], it is uncertain whether anthropometric changes are equally as reflective of DXA changes across the different positional groups, given the relative leanness of backs in comparison to forwards.

As DXA and SA are often both used over the course of a season and/or an athlete's career, an understanding of the interrelationship between the two assessment techniques is imperative when attempting to interpret body composition change longitudinally. The aim of this study is to investigate the association between DXA and SA when measuring changes in FFM and FM in elite RU athletes, and to explore whether differences exist due to the physique traits of the athlete based on ethnicity and position.

METHODS

Participants

Thirty-nine elite RU athletes were recruited via their involvement in the Australian national squad, the Wallabies. All participants provided informed consent to participate in the study, and the research was approved by the Human Research Ethics Committee at the University of the Sunshine Coast (EC00297, S/12/424).

At the time of consent, participants were requested to provide researchers with the ethnicity of their grandparents via open ended questions. It was made clear that this was optional and would not impact their involvement in the research or the national squad. As this study investigated the role of phenotype expression, grandparental heritage was chosen as in previous research [616, 620]. Participants were ascribed a specific ethnicity if three or more of their grandparents were of the same ethnicity.

Experimental design

Participants undertook routine body composition assessment via DXA and SA over three consecutive international seasons. Participants were assessed between two and five times over this period with the variability due to selection, injury, and availability for international representation. SA and DXA measurements were generally undertaken within 48 hours of each other at each time point. Where this was not logistically possible, the time frame between SA and DXA measurement never exceeded seven days. A repeated-measures approach was used to establish the parallel validity of DXA and SA measures.

Surface anthropometry

An ISAK Level 3 accredited anthropometrist with a TEM of 1.7% for S7SF took all measurements. BM was assessed using electronic scales (A&D Mercury, Adelaide, Australia) to 0.1 kg accuracy upon waking after an overnight fast with bladder voided. Stature was self reported to the nearest 1.0 cm. Skinfolts were assessed using Harpenden calipers (British Indicators, Hertfordshire, UK) to 0.1 mm accuracy on the same day waking BM was assessed. All anthropometric equipment was calibrated as recommended by the manufacturers.

Skinfold measurements were made on the right side of the body using ISAK techniques previously described [410], with a S7SF calculated from measures of the triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, and medial calf skinfold sites. All measurements were undertaken in duplicate to establish within-day retest reliability. If the difference between the duplicate measures exceeded 4% for an individual skinfold, a third measurement was taken after all other measurements were completed. The mean of duplicate or median of triplicate measurements were used for all subsequent analysis. LMI was calculated using methods previously described [166] using the equation below, with the exponent x set at 0.14 for forwards, and 0.13 for backs:

$$\text{LMI} = \text{BM (kg)} / \text{S7SF}^x \text{ (mm)}$$

Dual-energy X-ray absorptiometry

Measures were taken using a fan-beam DXA scanner (Hologic Discovery A, Hologic, Bedford, MA), with analysis performed using Apex 12.7.3 software (Hologic, Bedford, MA). The scanner was calibrated daily using a phantom as per manufacturer guidelines for quality control purposes. All the scans were undertaken using the array mode.

Scanning protocols were implemented as per techniques previously described to maximise technical reliability and minimise error [396]. Specifically, participants were scanned early in the morning prior to food, fluid, or exercise. Participants were requested to remove all metal items from their person, and lay supine on the scanning bed as still as possible for the duration of the scan. Participants were scanned wearing sports shorts, and those taller than the 196 cm area of the scanning bed (7 participants) undertook multiple scans [178]. For positioning consistency, the same experienced and qualified technician performed all measurements using the NHANES positioning protocol previously described [223], with the participants leg positioning standardised using a set width foot strap that was placed over both feet anterior to the lateral malleolus.

Statistical methods

All statistical procedures were performed with SPSS 22 (SPSS Inc., Chicago, Illinois, USA). Descriptive statistics were calculated and reported as mean $\pm$ SD with a 95% CI. All measures used in the study were checked for normality, and as they were not normally distributed, subsequently log-transformed before analysis. For change scores, Spearman's correlations (r) for nonparametric data were calculated, and the line of best fit was forced through the origin. As a result, the slope of this line represents the scaling factor for predicting percentage change in DXA FFM using SA estimates, and the SEE was the prediction error. For correlations, coefficients were qualitatively ranked by magnitude [254], with the strength of correlation coefficients defined as trivial, $r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; and perfect, $r = 1.0$. Since not all players were present at all testing occasions, change scores were calculated for each available pairing of two unique time points for each participant.

RESULTS

All 39 participants (age 25.7 ± 3.1 years; stature 187.6 ± 7.7 cm; BM 104.1 ± 12.2 kg) were able to be ascribed an ethnicity, with 26 identifying as Caucasian (17 forwards, 9 backs), and 13 (6 forwards, 7 backs) as Polynesian. A flow diagram describing the configuration of participants investigated is shown in Figure 6.1, with descriptive characteristics corresponding to the time point at which each individual presented with their highest LMI value presented in Table 6.1. The highest LMI value was used for consistency, as theoretically this was when the athletes were in their peak physical condition. Significant differences were seen in all body composition characteristics between forwards and backs ($P < 0.001$), whilst no differences were observed based on ethnicity. No differences were noted in any analyses undertaken based on whether the athletes undertook single versus multiple scans due to their stature exceeding the boundaries of the scanning bed.

Changes in DXA FFM and LMI showed a moderate to large agreement (Table 6.2, Figure 6.2), with minimal influence from ethnicity (Caucasians $r = 0.55$; Polynesians $r = 0.51$). However, the strength of association was stronger amongst forwards ($r = 0.63$) compared to backs ($r = 0.38$). The SEE for the prediction of change in DXA FFM ranged between 1.3–1.6% (Table 6.2). The LMI was able to predict the direction of change (increase or decrease) 74% of the time in all cases, and 86% of the time when the DXA FFM identified change was >1 kg.

Changes in DXA FM and S7SF showed large to very large agreement (Table 6.3 and Figure 6.3). The difference in correlation based on position was minor (forwards $r = 0.72$; backs $r = 0.76$), whilst the difference based on ethnicity was more noteworthy (Caucasians $r = 0.75$; Polynesians $r = 0.62$). The SEE for the prediction of change in DXA FM in all sub-categories ranged between 4.6–7.0%. The S7SF was able to predict the direction of change (increase or decrease) 83% of the time in all cases, and 91% of the time when the DXA FM identified change was >1 kg.

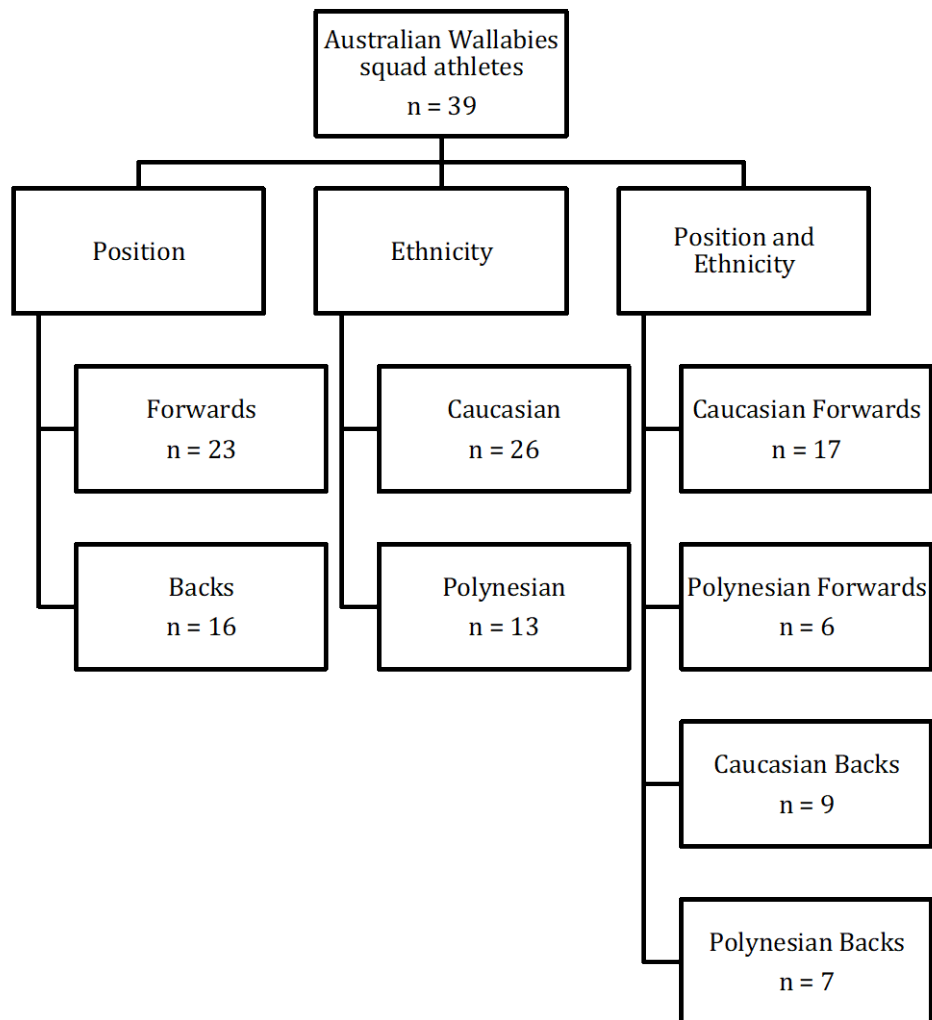


Figure 6.1. Flow diagram of the study population.

Table 6.1. Body composition characteristics of the elite rugby union athletes by position and ethnicity.

	All n = 39	Position		Ethnicity	
		Forwards n = 23	Backs n = 16	Caucasians n = 26	Polynesians n = 13
Age (years)	25.7 ± 3.1 (24.8 – 26.7)	26.5 ± 3.4 (25.1 – 27.9)	24.7 ± 2.3 (23.6 – 25.8)	25.5 ± 2.7 (24.5 – 26.5)	26.2 ± 3.8 (24.2 – 28.3)
Stature (cm)	187.6 ± 7.7 (185.2 – 190.0)	191.2 ± 7.1 (188.3 – 194.1)	182.4 ± 5.4* (179.8 – 185.1)	188.0 ± 7.7 (185.0 – 191.0)	186.8 ± 8.1 (182.4 – 191.1)
Scale mass (kg)	104.1 ± 12.2 (100.2 – 107.9)	112.4 ± 7.3 (109.4 – 115.3)	92.2 ± 6.6* (88.9 – 95.4)	103.2 ± 11.6 (98.7 – 107.6)	105.8 ± 13.7 (98.4 – 113.3)
Sum of 7 skinfolds (mm)	69.4 ± 23.2 (62.1 – 76.7)	80.6 ± 22.1 (71.6 – 89.7)	53.2 ± 13.4* (46.7 – 59.8)	69.1 ± 22.7 (60.4 – 77.8)	70.0 ± 25.2 (56.3 – 83.7)
LMI	58.6 ± 4.9 (56.0 – 59.5)	61.1 ± 4.1 (59.4 – 62.7)	54.8 ± 4.0* (51.1 – 54.9)	58.0 ± 4.5 (55.3 – 59.3)	59.8 ± 5.8 (55.2 – 62.3)
BMI (kg/m²)	29.5 ± 2.6 (28.7 – 30.3)	30.8 ± 2.5 (29.8 – 31.8)	27.7 ± 1.3* (27.0 – 28.3)	29.1 ± 2.3 (28.3 – 30.0)	30.3 ± 3.0 (28.7 – 31.9)
DXA fat-free mass (kg)	90.9 ± 9.2 (88.0 – 93.8)	96.5 ± 6.3 (93.9 – 99.1)	82.8 ± 5.9* (79.9 – 85.7)	90.1 ± 8.5 (86.8 – 93.4)	92.4 ± 10.6 (86.7 – 98.2)
DXA fat mass (kg)	14.7 ± 4.7 (13.2 – 16.1)	17.4 ± 4.0 (15.8 – 19.0)	10.8 ± 2.2* (9.7 – 11.8)	14.5 ± 4.8 (12.6 – 16.3)	15.1 ± 4.6 (12.6 – 17.6)

Mean ± SD, 95% confidence intervals in parentheses.

LMI = lean mass index (body mass/sum 7 skinfolds^x (mm); x = 0.13 backs; x = 0.14 forwards); BMI = body mass index

*Significant difference found between forwards and backs (P < 0.001)

Table 6.2. Correlation between changes in dual-energy X-ray absorptiometry fat free mass and surface anthropometric lean mass index measures.

		r	SEE (%)	P	Ranking
	All (n = 106)	0.54	1.5	<0.001	Large
Position	Forwards (n = 72)	0.63	1.4	<0.001	Large
	Backs (n = 34)	0.38	1.6	0.029	Moderate
Ethnicity	Caucasian (n = 85)	0.55	1.5	<0.001	Large
	Polynesians (n = 21)	0.51	1.3	0.019	Large

Qualitative ranking of correlation defined as trivial, $r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; perfect, $r = 1.0$.
 r = Spearman's correlation coefficient; SEE = standard error of the estimate;
 P = significance

Table 6.3. Correlation between changes in dual-energy X-ray absorptiometry fat mass and surface anthropometric sum of 7 skinfold measures.

		r	SEE (%)	P	Ranking
	All (n = 106)	0.73	5.8	<0.001	Very large
Position	Forwards (n = 72)	0.72	4.8	<0.001	Very large
	Backs (n = 34)	0.76	7.0	<0.001	Very large
Ethnicity	Caucasian (n = 85)	0.75	5.9	<0.001	Very large
	Polynesians (n = 21)	0.62	4.6	0.003	Large

Qualitative ranking of correlation defined as trivial, $r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; perfect, $r = 1.0$.
 r = Spearman's correlation coefficient; SEE = standard error of the estimate;
 P = significance

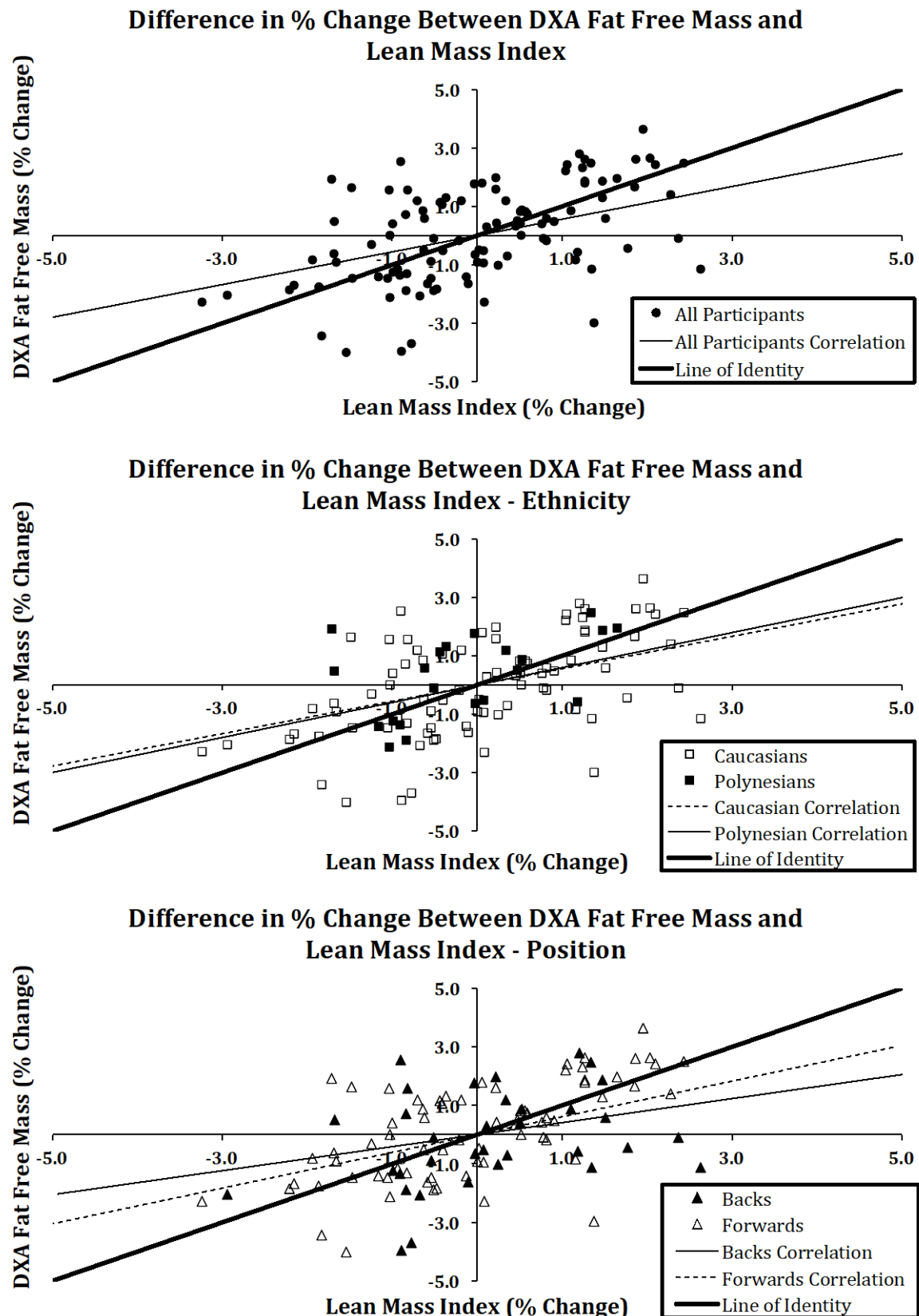


Figure 6.2. Relationship between relative changes in dual-energy X-ray absorptiometry (DXA) measures of fat free mass and changes in lean mass index.

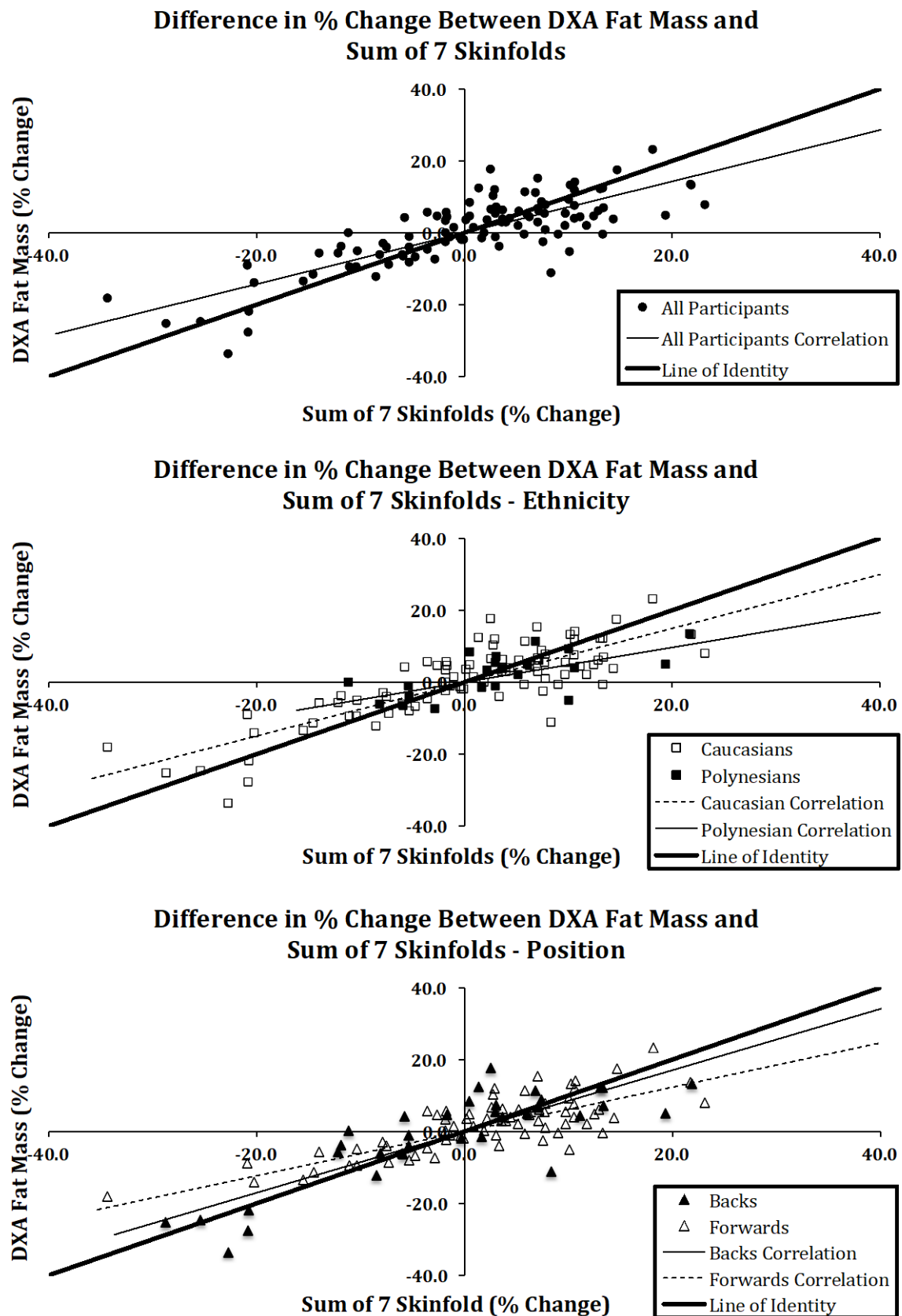


Figure 6.3. Relationship between relative changes in dual-energy X-ray absorptiometry (DXA) measure of fat mass and changes in sum of seven skinfolts.

DISCUSSION

The primary finding of this study was that in elite RU athletes, SA derived measures appear suitable to track changes in DXA measures of FFM and FM. Specifically, LMI was suitable for both identifying the direction of change and tracking proportional changes in FFM, whilst S7SF was able to correctly identify the direction of change, but less accurately able to quantify the magnitude of change in FM. Additionally, the LMI was better able to predict proportional changes in FFM amongst forwards compared to backs independent of ethnicity, whilst S7SF was better able to predict proportional change in FM amongst Caucasians in comparison to Polynesians.

The ability of the LMI to track proportional FFM change has varied in the literature, perhaps being impacted by the population under investigation. In an elite rugby league group, a higher correlation ($r = 0.69$) was found than that in the present study ($r = 0.54$) despite similar assessment techniques being used [141]. The unique heterogeneity of RU athletes based on size and ethnicity compared to their rugby league counterparts may explain the slightly lower agreement observed in the current study. Differences were identified between forwards ($r = 0.63$, $P < 0.001$) and backs ($r = 0.38$, $P = 0.029$) in regards to the ability of LMI to track longitudinal changes in DXA FFM. Although the association found in backs was low compared to forwards, it was similar to that previously reported in a group of elite RU athletes not differentiated by position ($r = 0.37$) [511]. Given the relative leanness of backs in comparison to forwards, the propensity of DXA overestimate FFM in leaner populations [444, 552, 570, 604] may explain this variation in agreement. In a study investigating the validity of a skinfold-based estimate of FFM changes in a steroid-enhanced population, the relationship reported was significantly higher than in this or the above mentioned studies ($r = 0.88$) [571]. However, it is most likely a result of the comparatively large increase in FFM resulting from the intervention. In the present study, longitudinal variation of FFM according to LMI and DXA was found to be similar between ethnicities. The findings suggest that the LMI may not be able to detect small changes in FFM ($<1.6\%$ or ~ 1.5 kg in this population),

and may be slightly less reliable for backs. However, in the majority of cases (83%) the LMI was able to indicate the change in direction of DXA FFM when changes were >1 kg, which is approximately the threshold for least significant change for DXA previously proposed in rugby league athletes [37].

It is well established that skinfold based regression equations are not an effective way of estimating absolute body composition in RU [616] or other sports [153, 459], nor changes in body composition amongst athletes [506]. For this reason, SA regression equations were not used to assess change, instead utilising the S7SF as a comparison measure. This study found strong linear associations between the methodologies when assessing change in FM, with the S7SF able to predict the direction of change 83% of the time, or 91% when DXA FM change >1kg, which is approximately the threshold for least significant change (LSC) previously reported in a similar population [37]. Despite this, the relative changes estimated by S7SF will be 4.6–7.0% different in magnitude from those measured by DXA, potentially due to questions raised about the reliability of DXA for assessing FM, particularly in lean individuals [444, 552, 570, 604]. A recent study found a typical error of 3.2% in DXA-estimated FM in resistance trained individuals with BMI (mass (kg) divided by stature (m) squared) >25 kg/m² [293]. Furthermore, poor validity ($r = 0.67$, 90% CI = 0.39–0.84) and reliability (CV% = 17.2%, 90% CI = 13.4–24.6) of DXA for quantifying FM in comparison to a whole-body phantom has been reported [65]. However, it is important to note the phantom used in this study had significantly lower proportions of FM in comparison to the athletes tested in that particular investigation. Interestingly, the agreement between skinfolds and DXA when assessing changes in body fat were lower for Polynesians ($r = 0.62$) in comparison to Caucasians ($r = 0.75$). This may be a result of the different regional body fat distribution Polynesian athletes display. In analysis previously undertaken by this group comparing specific DXA regions with skinfolds, it has been shown that Polynesians have higher relative measures from the trunk skinfold sites, yet lower relative DXA derived FM in the trunk region compared to Caucasians [620]. As such, it appears differences in ethnicity dictates the way region specific subcutaneous adiposity is distributed, and thus changes in specific skinfold sites may not equally reflect

DXA regional change for Caucasians and Polynesians. Furthermore, ethnic differences in fat patterning may be impacted by the fact that SA only quantifies SAT, while DXA quantifies both SAT and VAT. Indeed, ethnicity has been shown to influence SAT to VAT ratios [93, 95, 282]; however, this has not been explored in Polynesian populations. In either case, changes in skinfold measurement may not as accurately reflect changes in whole body or regional FM for Polynesians, given the correlation value was found to be lower in this group compared to the Caucasians. This is an important consideration for sport science practitioners when interpreting changes in SA. The findings suggest that although skinfolds are an excellent proxy for detecting the direction of changes in FM in comparison to DXA, they may not be able to accurately estimate the magnitude of changes.

As DXA is able to quantify regional and whole body tissue it has a number of benefits in sport science practice, including estimating nutritional requirements and tracking injury rehabilitation [2]. However, given the best practice recommendations for DXA, frequent scans are often logistically not feasible in elite athlete scheduling. Furthermore, the small amount of radiation exposure needs to be considered within the context of other imaging assessments undertaken by the athletes in this sport given the high incidence of injury [191]. As such, it is recommended that the frequency of DXA assessment is determined according to the likelihood that any change exceeds the measurement error [396], and if the results are likely to influence athlete management [419]. Therefore, being able to gain more timely information regarding longitudinal changes in body composition via SA is of value, especially when this information is used to further refine interventions.

A limitation of this study was that although best practice guidelines for both DXA and SA were followed at each assessment, due to the availability of the athletes and facilities it was not always possible to assess both DXA and SA on the same day. On the majority of occasions (84 out of 106) anthropometric and DXA measures were taken within 48 hours; however, due to logistical complexities a small number of assessments were taken up to 7 days apart (22 out of 106). As all testing was undertaken between the months of July and November, which in

Australia is the international season, no meaningful changes in body composition would be expected over a week, given relatively minor in-season adaptations have been observed over significantly longer periods [333]. To confirm this, data collected >48 hours apart was compared with data collected <48 hours apart. Statistical analysis revealed relatively small differences in the Spearman's correlation coefficient values when the data from >48 hours was compared to the data collected <48 hours for both FFM ($r = 0.50$, $P = 0.008$ vs $r = 0.56$, $P < 0.001$) and FM ($r = 0.79$, $p < 0.001$ vs $r = 0.70$, $P < 0.001$). As only minor differences were noted between the two subsets of data, and in both cases the analysis fell within the same qualitative ranking band, it was deemed appropriate to use the extended data set to add more statistical power to the ethnicity and position group analysis.

CONCLUSION

The results from this study provide sport scientists and coaches with valuable information to assist with the planning and interpretation of longitudinal body composition assessment. Whilst SA measures provide a robust indication of the direction of change in FFM and FM, caution may need to be applied when interpreting magnitude of change, particularly with FM. Given the usefulness of DXA in regards to whole body and regional quantification of absolute tissue mass, and the practicality of SA in regards to frequent and robust assessment, where resources allow it may be of value to use both techniques concurrently. This would facilitate an opportunity to assess changes acutely, whilst also being able to more accurately quantify absolute changes over longer periods of time. Furthermore, this would ensure the use of DXA is appropriate to both minimise radiation exposure, and allow time to ensure meaningful change that exceeds the measurement error.

CHAPTER SEVEN – PRE-SEASON BODY COMPOSITION ADAPTATIONS IN ELITE CAUCASIAN AND POLYNESIAN RUGBY UNION ATHLETES

Zemski AJ¹, Keating SE², Broad EM³, Marsh, DJ⁴, Hind K⁵, and Slater GJ¹. Pre-season body composition adaptations in elite Caucasian and Polynesian rugby union athletes. *International Journal of Sports Nutrition and Exercise Metabolism*. 2018; 14: 1-24 [Epub ahead of print].

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (75%), SEK/EMB/DJM/KH/GJS (5%).
- Conceived and designed the experiment: AJZ, SEK, DJM, GJS.
- Collected and collated the data: AJZ, SEK, DJM, GJS.
- Analysed the data: AJZ, SEK.
- Wrote/reviewed the paper: AJZ, SEK, EMB, DJM, KH, GJS.

ABSTRACT

During pre-season training, RU athletes endeavour to enhance physical performance characteristics that are aligned with on-field success. Specific physique traits are associated with performance, therefore body composition assessment is routinely undertaken in elite environments. This study aimed to quantify pre-season physique changes in elite RU athletes with unique morphology and divergent ethnicity. Twenty-two Caucasian and Polynesian professional RU athletes received DXA assessments at the beginning and conclusion of an 11-week pre-season. Interactions between on-field playing position and ethnicity in body composition adaptations were explored, and the LSC model was used to evaluate variations at the individual level. There were no combined interaction effects with the variables position and ethnicity, and any body composition measure. After accounting for baseline body composition, Caucasians gained more LM during the pre-season than Polynesians (2425 ± 1303 g vs 1115 ± 1169 g; $F = 5.4$, $P = 0.03$). Significant main effects of time were found for whole body and all regional measures with FM decreasing ($F = 31.1$ – 52.0 , $P < 0.01$), and LM increasing ($F = 12.0$ – 40.4 , $P < 0.01$). Seventeen athletes (9 Caucasian, 8 Polynesian) had a reduction in FM, and 8 athletes (6 Caucasian, 2 Polynesian) increased LM. This study describes significant and meaningful physique changes in elite RU athletes during a pre-season period. Given the individualised approach applied to athletes in regards to nutrition and conditioning interventions, a similar approach to that used in this study is recommended to assess physique changes in this population.

INTRODUCTION

Professional RU athletes may compete in several different competitions and tournaments throughout a calendar year. Following a period of rest (off-season), athletes typically embark on a high volume pre-season training program of increasing intensity that incorporates multifaceted aspects of physical conditioning [20, 76]. The physical goals of pre-season are to increase aerobic and anaerobic fitness, speed, strength and power [17], in conjunction with undertaking RU specific technical and tactical training. Adjustments in body composition, such as increases in LM, are associated with favourable changes in a number of performance traits [64, 127]. Therefore, being able to accurately quantify pre-season physique changes is of value to sport science practitioners and coaches to facilitate further personalisation of training and/or dietary interventions.

The desire to increase BM, in particular LM, to gain a competitive advantage in RU has become more pronounced since the introduction of professionalism in 1995 [416, 451]. Increases in LM can influence the power-to-weight ratio of players, thus increasing the potential to proliferate momentum, strength, power and speed [55]. Excess FM has negative implications for thermoregulation [499], and concurrently increases energy expenditure during exercise, both of which may limit an athlete's ability to perform at a high intensity for the duration of a match [165]. Additionally, an increase in FM has the potential to attenuate force production according to Newton's second law of motion ($a = F/M$), whereby increases in FM (M) without a corresponding increase in muscle force (F) will reduce acceleration (a) [165, 333].

Pre-season increases in LM and decreases in FM have previously been reported in elite RU athletes using SA [17, 76]. However, there are limits to relying on anthropometric measures for estimating body composition in athletes, given the regression equations haven't been validated for use in RU, or to track changes in body composition [506, 616]. Over recent years, the use of DXA for body composition assessment in elite RU has increased [333, 620]. This technology

provides an in-depth analysis of whole body and regional BMC, FM and LM, and is recognised as a valid and precise body composition assessment tool [229, 570] when client presentation is standardised in accordance with best practice guidelines [396].

In recent years there has been a surge in the number of Polynesian athletes securing professional RU contracts. One study has investigated 3-compartment body composition in Polynesian RU players and reported different distributions of regional FM and LM [620]. In non-athletes, large differences in physique have been reported between Caucasian and Polynesian individuals, with Polynesians having more LM and greater LM to FM ratios [479, 537, 538]. To date, no study has explored differences in physique adaptations to training by ethnicity in RU. Therefore, the aim of this study was to investigate pre-season team and individual athlete DXA body composition adaptations in elite RU athletes, with sub-group analysis to compare changes between Polynesian and Caucasian individuals.

METHODS

Participants

Twenty-two professional male RU athletes were recruited via their involvement in a single Australian Super Rugby franchise, which is the premier professional RU competition in the southern hemisphere. All athletes provided informed consent to participate in the study, and the research was approved by the Human Research Ethics Committee at the University of the Sunshine Coast (EC00297, S/16/959).

At the time of consent, all athletes provided researchers with the ethnicity of their grandparents via open ended questions. Given this research investigated potential differences based on phenotype expression, Ethnicity was ascribed when ≥ 3 grandparents were of the same ethnicity, as in previous studies in both athletic and sedentary populations [480, 537, 616, 620].

Study design

As part of routine training in preparation for the 2017 Super Rugby season, the athletes undertook a high-volume, high-intensity, 11-week pre-season training program. During the first three days of the pre-season period all athletes undertook body composition assessment via DXA, with the athletes re-assessed in the same order within the final three days of pre-season. The athletes undertook a similar training program the day before each assessment.

Body composition assessment

Body composition was assessed using a fan-beam DXA scanner (Hologic Discovery A, Hologic, Bedford, MA), with analysis performed using Apex 13.4.2:3 software (Hologic, Bedford, MA). A spine phantom was used to calibrate the scanner daily as per manufacturer guidelines for quality control purposes.

A standardised scanning protocol was implemented to maximise technical reliability and minimise error. This protocol has been described in detail elsewhere [396]. Specifically, athletes were scanned first thing in the morning (between 5:00 am and 8:30 am) prior to food and fluid ingestion, or exercise. The athletes were requested to remain well hydrated the day before, and to consume their normal prescribed training diet the day before the assessment. They were scanned wearing sports shorts, and those taller than the 196 cm scanning boundary undertook two scans, the first of which captured the body from the menton (the inferior point of the mandible) down whilst the head was positioned in the Frankfort plane. The athletes were then repositioned on the scanner, with the subsequent scan capturing from the menton up to the vertex of the head. The results of the two scans were combined during the analysis process to yield whole body composition [178]. None of the athletes in this study were too broad for the scanning area. To ensure consistency, the same experienced and qualified technician performed all measurements and post-scan analysis, including the manual adjustment of all regions of interest. FFMI was calculated using the equation FFM (kg) divided by stature (m) squared [574].

Pre-season training program

Following a 4-week period of unsupervised annual leave which included an active rest program (strength x2/week, conditioning x2/week) after the previous competitive RU season, the athletes undertook an 11-week pre-season training period. This comprised a 4-week supervised training block prior to a 2-week unsupervised maintenance block, followed by another 5-week supervised training block. Throughout each training week technical (x2/week) and tactical

(x4/week) rugby sessions along with sessions to improve underpinning physical qualities and body composition were performed (speed/agility x1/week, strength x4/week, conditioning x3-4/week, boxing x1/week). Training was typically executed Monday through Friday with an approximate weekly training load of 15 hours. Additional time was spent on individual recovery and regeneration modalities (flexibility, mobility, massage, hydrotherapy and physiotherapy). All athletes were under the management of an experienced sports dietitian, who was accredited with the national governing body, and received individualised dietary plans aimed at supporting training adaptations throughout the pre-season period.

Statistical analysis

Statistical analyses were completed using SPSS (Version 22.0, IBM Corp., Armonk, NY) and Microsoft Excel 2011 (Microsoft, Redmond, WA, USA). Before analysis, assumptions of normality in the data were made using visualisations of normality plots and the Shapiro-Wilk test. Changes in body composition over the pre-season period were analysed using mixed-model ANOVA, with the pre-season period acting as the within-subject factor, and playing position and ethnicity as the between subject factors. Additionally, a two-way ANCOVA was conducted using both position and ethnicity as independent variables, and the start of pre-season as covariate, to test for interactions between position and ethnicity controlled for baseline values. Significant effects were subsequently explored using Bonferroni post hoc tests to counteract multiple comparisons. Sphericity of the data was assessed using the Mauchly test, assumptions of homogeneity of variance using Levene's test of equality of error variances, and Box's test of equality of covariance matrices were conducted. Between subject-effects were evaluated using the partial eta squared (η_p^2) rankings of small (>0.01), medium (>0.09) and large (>0.25). Data are presented as mean $\pm$ SD with statistical significance for all analyses defined $P \leq 0.05$.

The short term precision root-mean-square-standard deviation (RMS-SD), percent coefficient of variation (%CV), and corresponding LSC was calculated using standardised protocols as recommended by the ISCD [223]. This was done in a population of resistance trained athletes using the same Hologic Discovery A scanner used in this study [617]. Precision errors from same day scans (technical error) for whole body BMC, LM and FM, were 21.1 g, 238.4 g, and 222.7 g respectively. Precision error from consecutive day scans (technical error and biological variation) was calculated as the RMS-SD, with LSC subsequently derived as $\text{RMS-SD} \times 2.77$ (95% CI), and is presented in Table 7.1. Meaningful changes in individual athletes were identified if they exceeded the LSC as described elsewhere [333].

Table 7.1. Short-term precision and corresponding LSC in resistance trained athletes using the same Hologic Discovery A scanner [617].

	Same day Technical error				Consecutive days Technical error & biological variation			
	Precision		LSC-95% CI		Precision		LSC-95% CI	
	RMS-SD	%CV	RMS-SD	%CV	RMS-SD	%CV	RMS-SD	%CV
Whole body								
BMC (g)	21.1	0.6	59.0	1.7	25.2	0.7	69.8	1.9
Fat mass (g)	238.4	1.8	660.4	5.1	455.2	2.9	1261.0	8.0
Lean mass (g)	222.7	0.3	616.8	0.9	752.0	1.1	2083.0	3.2
Arms								
BMC (g)	5.6	1.1	15.5	3.0	6.8	1.3	18.9	3.7
Fat mass (g)	43.5	2.5	120.5	6.8	89.1	5.3	246.8	14.5
Lean mass (g)	101.1	1.2	279.9	3.3	154.1	1.9	426.7	5.2
Trunk								
BMC(g)	9.7	0.8	27.0	2.2	9.8	0.9	27.1	2.6
Fat mass (g)	123.7	2.2	342.5	6.0	221.3	3.6	612.9	9.9
Lean mass (g)	319.4	0.8	884.7	2.1	678.7	1.9	1880.0	4.1
Legs								
BMC(g)	20.2	1.5	56.1	4.2	18.6	1.5	51.6	4.1
Fat mass (g)	146.0	2.7	404.4	7.5	230.7	3.4	639.1	9.5
Lean mass (g)	335.6	1.1	929.6	3.0	406.5	1.5	1126.0	4.1
RMS-SD = root-mean-square standard deviation; CV = coefficient of variance; LSC = least significant change; BMC = bone mineral content.								

RESULTS

Descriptive characteristics

Eleven athletes were identified as Caucasian (6 forwards, 5 backs), and 11 as Polynesian (5 forwards, 6 backs). Body composition according to position and ethnicity are presented in Table 7.2. There were no differences in whole or regional body composition between Caucasians and Polynesians. All whole body and regional DXA measures for BMC, FM and LM were greater ($P < 0.01$) in forwards compared to backs at both time points.

Team changes in whole and regional body composition

Pre-season body composition changes are presented in Table 7.2. There were no combined interaction effects between the variables position and ethnicity, with any body composition measure. After accounting for baseline body composition, Caucasians gained more LM during the pre-season than Polynesians (2425 ± 1303 g vs 1115 ± 1169 g; $F = 5.4$, $P = 0.03$). Significant main effects of time were found for whole body and all regional measures with FM decreasing (whole body $F = 52.0$, $P < 0.01$; arms $F = 31.1$, $P < 0.01$; trunk $F = 44.8$, $P < 0.01$; legs $F = 39.5$, $P < 0.01$), LM increasing (whole body $F = 40.4$, $P < 0.01$; arms $F = 33.7$, $P < 0.01$; trunk $F = 14.8$, $P < 0.01$; legs $F = 12.0$, $P < 0.01$), and trunk BMC increasing ($F = 5.1$, $P = 0.04$). Between-subject effects were found based on position for all variables ($F = 3.8$ – 13.2 ; $P = 0.01$ – 0.03 ; $\eta_p^2 = 0.39$ – 0.69 [large effect]).

Table 7.2. Differences in surface anthropometry measures and indices, and dual-energy X-ray absorptiometry measured total and regional body composition characteristics of elite rugby union athletes over the course of a pre-season based on position and ethnicity.

	Position (n = 22)				Ethnicity (n = 22)			
	Forwards (n = 11)		Backs (n = 11)		Caucasians (n = 11)		Polynesians (n = 11)	
	Start pre-season	End pre-season	Start pre-season	End pre-season	Start pre-season	End pre-season	Start pre-season	End pre-season
Age (years)	22.9 ± 3.5	-	22.8 ± 3.0	-	22.1 ± 2.4	-	23.5 ± 3.8	-
Stature (cm)^c	191.3 ± 7.5	-	182.2 ± 6.9	-	189.4 ± 8.7	-	184.1 ± 7.6	-
Mass (kg)^{b c}	112.5 ± 7.6	112.1 ± 7.6	90.5 ± 8.6	90.4 ± 8.1	101.2 ± 14.3	101.7 ± 14.0	101.8 ± 13.9	100.8 ± 13.6
FFMI (kg/m²)^{b c}	26.1 ± 1.2	26.6 ± 1.1	23.8 ± 1.2	24.3 ± 1.1	24.4 ± 1.3	25.1 ± 1.2	25.5 ± 1.8	25.8 ± 1.9
WB BMC (g)^c	4352 ± 439	4377 ± 437	3618 ± 379	3637 ± 364	4003 ± 553	4027 ± 548	3966 ± 571	3987 ± 569
WB FM (g)^{b c}	19629 ± 3879	17166 ± 3837	13438 ± 2723	11449 ± 1872	15495 ± 4839	13338 ± 4353	17572 ± 4214	15278 ± 3897
WB LM (g)^{a b c}	91087 ± 5489	92912 ± 5711	75598 ± 6971	77312 ± 6436	84005 ± 10306	86430 ± 10447	82680 ± 10173	83795 ± 10431
Arms BMC (g)^{b c}	662 ± 76	661 ± 78	541 ± 68	535 ± 67	600 ± 106	602 ± 107	603 ± 85	594 ± 88
Arms FM (g)^{b c}	2287 ± 426	2038 ± 415	1470 ± 228	1304 ± 157	1759 ± 535	1601 ± 489	1999 ± 554	1741 ± 494
Arms LM (g)^c	11698 ± 1098	12162 ± 928	9742 ± 1314	10198 ± 1454	10706 ± 1672	11191 ± 1636	10734 ± 1452	11169 ± 1556
Trunk BMC (g)^{b c}	1361 ± 179	1381 ± 193	1116 ± 117	1131 ± 127	1270 ± 186	1282 ± 196	1207 ± 205	1231 ± 219
Trunk FM (g)^{b c}	8594 ± 2392	7179 ± 2224	5419 ± 1191	5370 ± 824	6326 ± 2183	5079 ± 1910	7687 ± 2627	6470 ± 2293
Trunk LM (g)^{b c}	43339 ± 3136	44282 ± 3509	36259 ± 2564	36964 ± 2832	40498 ± 4305	41729 ± 4492	39100 ± 4939	39518 ± 5187
Legs BMC (g)^c	1623 ± 183	1624 ± 175	1372 ± 162	1383 ± 148	1485 ± 212	1491 ± 198	1510 ± 222	1517 ± 212
Legs FM (g)^{b c}	7570 ± 1745	6765 ± 1755	5527 ± 1373	4757 ± 983	6348 ± 2191	5584 ± 2086	6749 ± 1529	5938 ± 1357
Legs LM (g)^{b c}	31977 ± 1872	32372 ± 1916	26056 ± 3616	26615 ± 3881	29126 ± 4553	29791 ± 4755	28908 ± 3888	29196 ± 3763

FFMI = fat-free mass index; WB = whole body; BMC = bone mineral content; FM = fat mass; LM = lean mass.

Data presented as Mean ± Standard Deviation, significance set at 0.05.

^a Significant interaction between time and ethnicity.

^b Significant main effect for time.

^c Significant difference between forwards and backs.

Individual player body composition changes

Meaningful individual player changes were identified if they exceeded LSC (Table 7.3) and are illustrated in Figures 7.1, 7.2 and 7.3. Over the 11-week pre-season period, 17 athletes (9 Caucasian, 8 Polynesian) reduced FM, and 8 athletes (6 Caucasian, 2 Polynesian) increased LM. Meaningful increases in whole body BMC were observed in 4 athletes (3 Caucasian, 1 Polynesian), and 1 Caucasian athlete had a loss of BMC. Seven athletes both increased LM and reduced FM (5 Caucasians, 2 Polynesians). Only minor differences in whole body and regional individual body composition changes in FM and LM were observed in athletes based on position.

Table 7.3. Individual athletes who made meaningful dual-energy X-ray absorptiometry measured whole body and regional body composition changes (>LSC-95% CI – technical error and biological variation) during the pre-season.

		All (n = 22)	Position (n = 22)		Ethnicity (n = 22)	
			Forwards (n = 11)	Backs (n = 11)	Caucasians (n = 11)	Polynesians (n = 11)
↑Bone Mineral Content	Arms	1 (5%)	1 (9%)	0 (0%)	1 (9%)	0 (0%)
	Trunk^a	9 (41%)	6 (55%)	3 (27%)	3 (27%)	6 (55%)
	Legs^b	5 (23%)	2 (18%)	3 (27%)	3 (27%)	2 (18%)
	WB^c	4 (18%)	2 (18%)	2 (18%)	3 (27%)	1 (9%)
↓Fat Mass	Arms	10 (45%)	6 (55%)	4 (36%)	3 (27%)	7 (64%)
	Trunk	17 (77%)	9 (82%)	8 (73%)	9 (82%)	8 (73%)
	Legs	14 (64%)	8 (73%)	6 (55%)	8 (73%)	6 (55%)
	WB	17 (77%)	9 (82%)	8 (73%)	9 (82%)	8 (73%)
↑Lean Mass	Arms	11 (50%)	6 (55%)	5 (45%)	6 (55%)	5 (45%)
	Trunk	3 (14%)	3 (27%)	0 (0%)	3 (27%)	0 (0%)
	Legs	2 (9%)	0 (0%)	2 (18%)	1 (9%)	1 (9%)
	WB	8 (36%)	4 (36%)	4 (36%)	6 (55%)	2 (18%)

Data shown as – number of athletes (% of athletes)

WB = whole body

^a 2 athletes lost BMC in their trunk (Caucasian forward, Polynesian back)

^b 2 athletes lost BMC in their legs (Caucasian forward, Polynesian back)

^c 1 athlete lost BMC in their whole body (Caucasian forward)

Pre-Season Changes – Bone Mineral Content

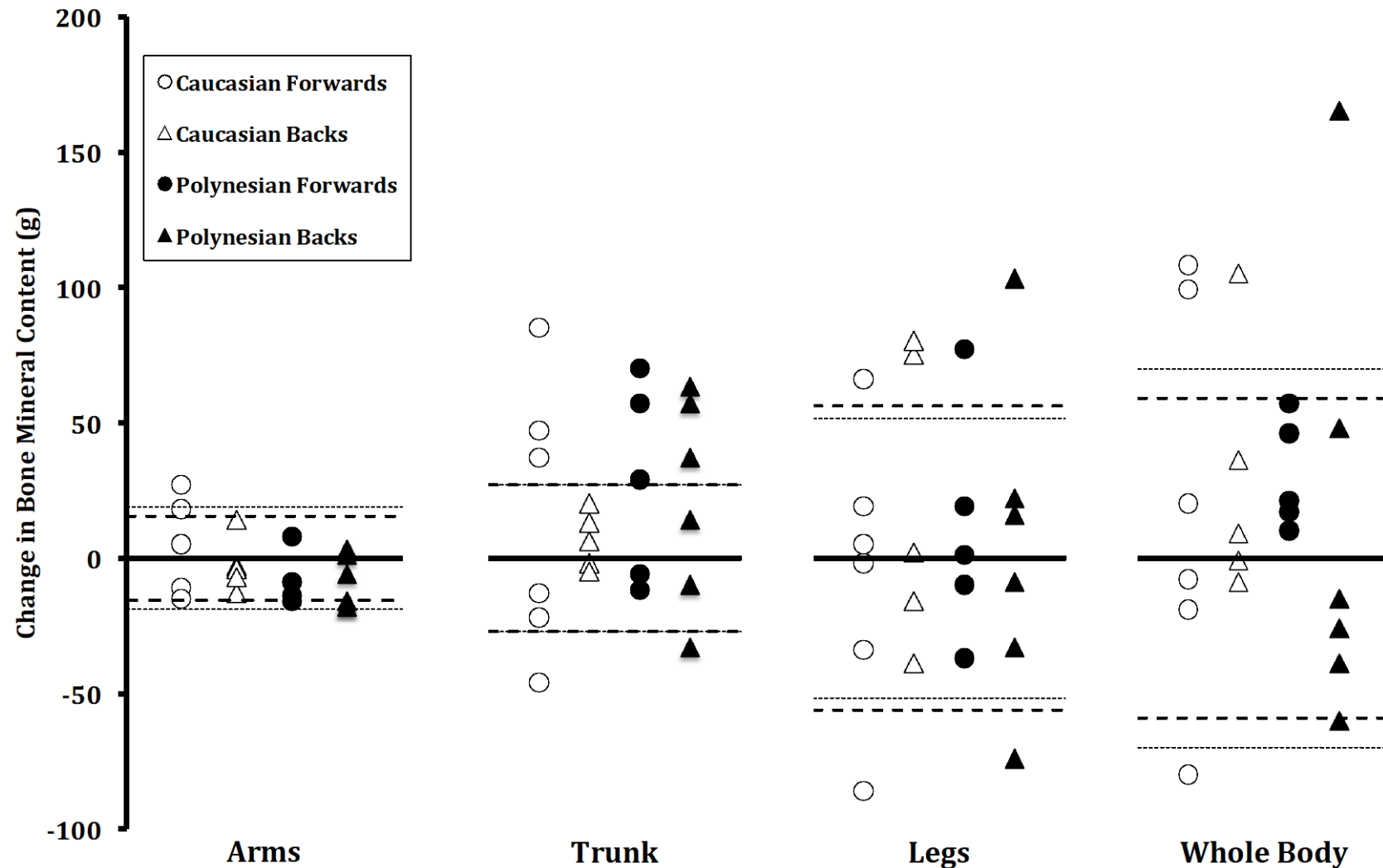


Figure 7.1. Individual whole body and regional changes in bone mineral content by the least significant change (LSC) previously determined [617] over a pre-season in elite rugby union athletes. Dashed lines indicate LSC-95% CI same day precision (technical error). Dotted lines indicate LSC-95% CI consecutive day precision (technical error and biological variation).

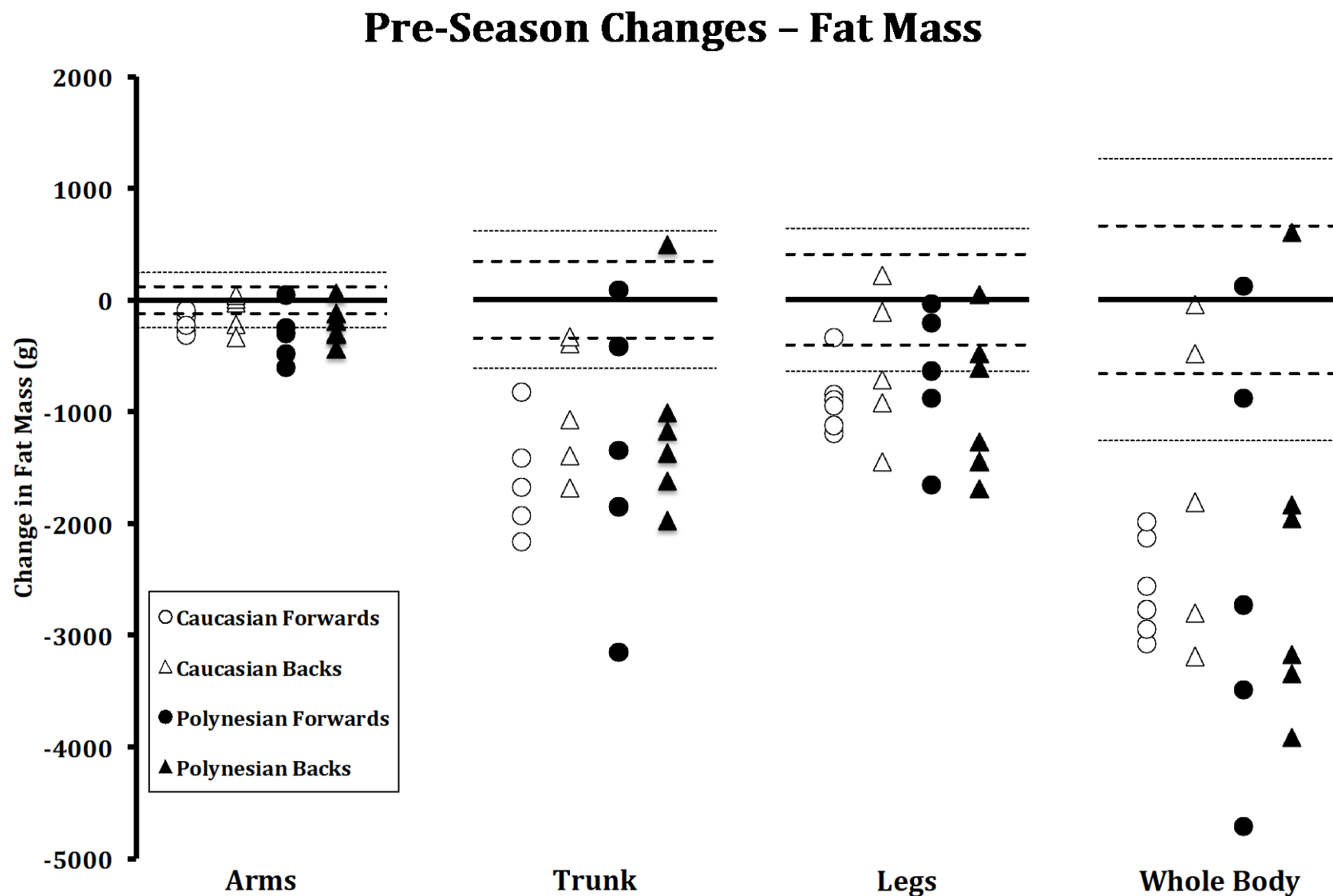


Figure 7.2. Individual whole body and regional changes in fat mass by the least significant change (LSC) previously determined [617] over a pre-season in elite rugby union athletes. Dashed lines indicate LSC-95% CI same day precision (technical error). Dotted lines indicate LSC-95% CI consecutive day precision (technical error and biological variation).

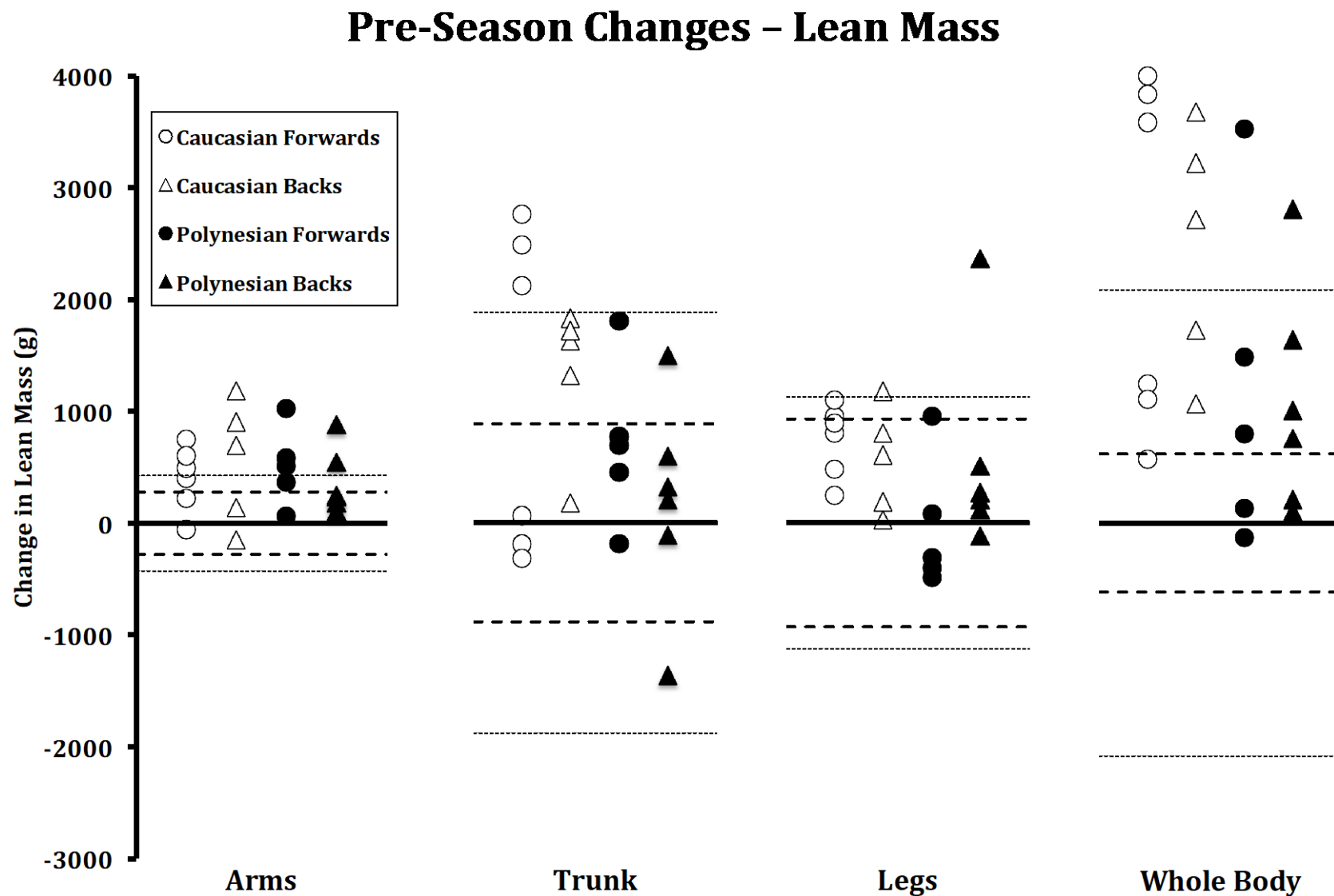


Figure 7.3. Individual whole body and regional changes in lean mass by the least significant change (LSC) previously determined [617] over a pre-season in elite rugby union athletes. Dashed lines indicate LSC-95% CI same day precision (technical error). Dotted lines indicate LSC-95% CI consecutive day precision (technical error and biological variation).

DISCUSSION

This is the first study using an individualised approach in the analysis of pre-season body composition changes in RU athletes, which extends previous work looking at individual in-season changes [333]. In doing so, we identified that over three-quarters of the athletes (17 out of 22) decreased FM, while over one-third (8 out of 22) increased LM. Further to this, 7 of the 8 athletes who increased LM also experienced meaningful reductions in FM. The changes in physique observed during the pre-season occurred independent of position or ethnicity; however, more Caucasian athletes increased LM in comparison to Polynesians.

Significant changes in body composition during pre-season training have been reported in as little as 4-weeks in a similar population of professional RU athletes [17]. However, given that body composition changes were inferred via a SA derived regression equation, the validity of such a marked increase in LM (2.0 ± 0.6 kg) in such a short time period is questionable [506]. Indeed, only 8 athletes in the present investigation observed similar gains in LM, despite an 11-week pre-season period. FM losses in this study were slightly larger than in the aforementioned study (1.4 ± 0.4 kg), although this would be expected given the duration of the pre-season was considerably longer. Pre-season increases in LM and decreases in FM of a similar magnitude to those observed in this study have also been reported in professional AFL athletes using DXA [66], corroborating that the pre-season period in professional sport is a time of noteworthy body composition change.

An individualised approach to evaluating adaptations provides a unique insight not possible from a more traditional assessment, where group mean changes are reported. For example, although statistically significant gains in LM were observed in the current investigation, only one-third of athletes had meaningful increases in LM based on LSC analysis (>2083 g). This may be a result of the challenges associated with increasing LM once high levels of muscularity are reached [1]. Indeed, the rate of LM accumulation has been reported to decline in NFL athletes when BM exceeds ~ 114 kg (forwards in this study 112.5 ± 7.6 kg)

[73], and an upper limit in FFMI of 25 kg/m² has been suggested in non-steroid using males [314]. However, the validity of this FFMI cut-off has been questioned in athletic populations [557]. Specifically, professional RU forwards routinely exceed this threshold [620], including all 11 of the forwards in the present study (26.1 ± 1.2 kg/m²; range 25.5–29.0 kg/m²). Characterising athletes and measuring adaptations at the group level may not tell the whole story, as was the case with LM adaptations in this study. Therefore, being able to evaluate changes in body composition at the individual level provides practitioners the opportunity to appreciate more deeply individual adaptations, which may provide benefits in program personalisation and performance optimisation.

Polynesians have consistently been shown to display higher LM and lower FM compared to Caucasians [479, 480, 537, 538]; however, longitudinal adaptations have not previously been investigated. More Caucasian athletes increased LM than Polynesians (6 athletes vs 2 athletes) particularly in the trunk region (3 athletes vs 0 athletes), and a statistically significant group main effect based on ethnicity was found. Future investigations incorporating ethnicity differentiated within and between season measures may provide further insight into the role ethnicity plays in training adaptations not only during the season, but also post-season in the absence of the training stimulus, where previously significant compromises in body composition have been noted in other elite contact team-sport populations [66].

Few differences were observed between forwards and backs in regards to meaningful individual adaptations achieved, with the only substantial difference being that more forwards had significant increases in trunk LM compared to backs (3 athletes vs 0 athletes). As forwards are required to engage in more static match activities such as scrums, mauls, and rucks, greater core and upper body strength is advantageous [465]. As such, forwards undertake more field-based training activities that replicate these specific match performance movements, which may have amplified the observed adaptations.

The use of the individualised LSC method of analysis in this study has provided great insight into the individual adaptations of elite RU athletes over a pre-season period, as did the same approach when looking at in-season changes previously reported [333]. Although research traditionally reports statistical significance in regard to group changes, the individualised approach is more closely aligned to the practical interpretation of results undertaken by sports scientists. As such, appreciating the precision error of the DXA equipment being used, and ensuring best practice protocols are followed [396], can facilitate the identification of true changes and thus influence interpretation of results. This would then enable practitioners to further personalise dietary and/or training interventions in the pursuit of improved performance outcomes.

There are a number of considerations to make when interpreting the findings of this study. Firstly, it was impractical for individual training loads and dietary intake to be quantified. While it would be invaluable to understand the association between energy intake, energy expenditure, and body composition changes, significant challenges exist in being able to quantify high intensity exercise energy expenditure [156], particularly in contact sports where the tools available are not suitable during physical collisions [76]. Additionally, due to the high number of routine measurements being taken on the athletes for monitoring purposes, training load could not be quantified. Further, given there is no gold standard assessment of energy intake, any method employed would be subject to considerable error, particularly over a long period in an athletic population [353]. Such information may have provided further insight into the underlying reasons for the observed individual physique changes, and warrants consideration when appropriate and reliable technologies are available. Also, researchers were not made aware of individual athlete body composition goals over the pre-season, which may have added to the interpretation of results. Secondly, off-season changes and events likely to influence body composition were not taken into consideration when interpreting the results. An appreciation of such changes would allow for a more meaningful interpretation of the pre-season adaptations in the context of each individual athlete. Finally, associations between body composition and physical performance changes were not explored

in this study. Future research investigating the association between physique adaptations and specific performance measures and fitness traits over a pre-season would be of great interest, in particular how these changes impact game performance in-season.

CONCLUSION

In conclusion, we identified significant whole body and regional body composition changes in elite RU athletes during a pre-season period, at both the team and individual level. Practitioners are encouraged to take an individualised approach to the interpretation of adaptations when tracking physique variables longitudinally, for which knowledge of LSC data is required. Future work exploring ethnicity differentiated body composition changes across the entire season, including the post-season period, would provide practitioners with valuable information allowing for a more personalised approach to athlete training and dietary interventions.

CHAPTER EIGHT – DIFFERENCES IN VISCERAL ADIPOSE TISSUE AND BIOCHEMICAL CARDIOMETABOLIC RISK MARKERS IN ELITE RUGBY UNION ATHLETES OF CAUCASIAN AND POLYNESIAN DESCENT

Zemski AJ¹, Keating SE², Broad EM³, Marsh, DJ⁴, Hind K⁵, Walters KJ⁶, and Slater GJ¹. Differences in visceral adipose tissue and biochemical cardiometabolic risk markers in elite rugby union athletes of Caucasian and Polynesian descent. *Sports Medicine*. (To be submitted, September 2018).

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (70%), SEK (15%), EMB/DJM/KH/KJW/GJS (3%).
- Conceived and designed the experiment: AJZ, SEK, DJM, GJS.
- Collected, collated and analysed the data: AJZ, SEK, DJM, KJW, GJS.
- Wrote/reviewed the paper: AJZ, SEK, EMB, DJM, KH, KJW, GJS.

ABSTRACT

Background – Polynesian individuals are leaner with greater musculature than Caucasians of an equivalent size, and this genetically different morphology provides a physique that is often compatible with success in a number of sports, including RU. Evidence indicates that Polynesians have greater stores of absolute and relative abdominal FM and this is known to confer cardiometabolic risk.

Objectives – To explore the relationship between ethnicity, VAT, and cardiometabolic disease risk markers in elite Caucasian and Polynesian RU athletes; and to assess the impact of a pre-season training program on these markers.

Methods – Twenty-two professional RU athletes of Caucasian (n=11) and Polynesian (n=11) descent underwent physique assessment via SA, DXA, and MRI before and after an 11-week pre-season. A fasted blood test was undertaken at both time points.

Results – Compared to Caucasians, at baseline Polynesians displayed significantly higher VAT ($771 \pm 609 \text{ cm}^3$ vs $424 \pm 235 \text{ cm}^3$; $P = 0.043$), TG ($1.0 \pm 0.9 \text{ mmol/L}$ vs $0.6 \pm 0.2 \text{ mmol/L}$; $P = 0.050$), and LDL-C ($3.1 \pm 0.9 \text{ mmol/L}$ vs $2.3 \pm 0.7 \text{ mmol/L}$; $P = 0.019$). Similar changes were observed in both groups over the pre-season period in VAT and blood biochemical markers.

Conclusion – Polynesian athletes were more likely than Caucasians to exhibit risk factors which are associated with cardiometabolic disease, such as elevated VAT and unfavorable lipid profiles. Further longitudinal research is required to identify and explain the short- and long-term risk of cardiometabolic disease in athletes of Polynesian descent.

KEY POINTS

- Polynesians have greater LM compared to Caucasians of comparable relative mass, whilst possessing greater absolute and relative abdominal adiposity which is associated with elevated cardiometabolic disease risk.
- Elite RU athletes of Polynesian descent had similar overall physique traits compared to their Caucasian counterparts, including similarities in relative and absolute FM, but had higher levels of VAT. Polynesian athletes also displayed higher LDL-C, TG, and TC than Caucasian athletes; however, in most cases these remained within normal clinical ranges.
- Polynesian athletes may be at an increased long-term risk of cardiometabolic disease. This requires longitudinal exploration in larger athlete cohorts.

INTRODUCTION

RU is a contact team sport which places significant physiological demands on the athlete [163]. The development of LM is desirable to enhance speed, strength and power [166], which are fundamental attributes for competitive success [416]. Additionally, BM has been identified as being strongly associated with overall team performance [40, 416, 496]. The emphasis on muscularity and overall size may explain the anecdotal rise in Polynesian athletes competing at the elite level in RU, and the relative success of national teams from Pacific nations in international competition. Polynesians have been shown to be significantly leaner with greater LM than Caucasians at an equivalent BMI [537, 538]. Further, they display proportionally higher levels of FFM and lower levels of FM after adjustments for stature and BM [480]. As such, the genetic morphology of Polynesians appears to predispose them to a physique compatible with success in RU.

A large proportion of elite RU athletes are defined as overweight or obese using the traditional Caucasian ethnicity BMI cut-offs of 25–30 kg/m² and >30 kg/m², respectively [199, 619], but BMI is not suitable for estimating FM in athletic populations [2]. WC [5, 327] and WHt [22] are commonly used to identify increased disease risk associated with higher abdominal adiposity, with a recent study identifying WHt to be a superior measure for obesity characterisation in adults [536]. However, the application of these measures to an athletic population with unique morphology, such as that found in RU, is questionable due to the different ratio of FM and LM in athletic individuals compared to the general population [409]. It is now recognised that the topography of body fat distribution is a better predictor of cardiometabolic complications than the overall amount of FM [544]. Indeed, high levels of VAT, which encompasses fat stores in the intra-abdominopelvic region bounded by the abdominal wall and pelvic floor [502], is an established marker for cardiometabolic risk and is independent of total BM, total FM and SAT [145, 187]. Additionally, VAT has been identified as an important risk factor for atherosclerosis in men [329] and there is evidence identifying a relationship between VAT and cardiovascular endpoints

[58, 258, 586]. This is of particular pertinence to Polynesians, who possess greater stores of abdominal FM than Caucasians in both absolute and relative terms [480]. Despite Polynesians having some of the highest rates of obesity and cardiometabolic disease worldwide [214, 402], VAT has not been reported in relation to this population.

Studies in overweight and obese populations have revealed that exercise is protective of cardiometabolic disease risk [42, 427], reduces VAT [266, 472], and lessens the adverse effects of obesity on morbidity and mortality [183, 222]. Nonetheless, “supersized” athletes have been shown to display signs of elevated cardiometabolic disease risk, including compromised lipid profiles [220, 264, 561] and higher VAT levels [73, 387] compared to non-heavyweight athletes or non-athletic controls. It is possible that elevated lipid markers in the presence of regular training may be an indicator of cardiovascular disease risk. Indeed, NFL linemen, the largest athletes in the sport, have almost double the prevalence of metabolic syndrome post-retirement compared to non-linemen (59.8% vs 30.1%; $P < 0.001$) [380]. Recently, elite RU athletes of Polynesian descent were shown not to have significantly different VAT compared to Caucasians [619]. However, this observation was based on single slice MRI and there is no general agreement as to the best location to take this measurement [494]. Further, studies sampling single slice VAT have been observed to be influenced by ethnicity [142]. No study has investigated levels of VAT using a volumetric measure in elite athletic populations, nor have ethnic differences in biochemical markers of cardiometabolic disease risk been examined in an elite RU population.

Given the increased number of Polynesians in professional RU, and the increasing size of elite athletes within the sport, an understanding of cardiometabolic disease risk in this population would be valuable to practitioners to assist with athlete management from a health care perspective. Therefore, the aims of this study were to: 1) explore the relationship between ethnicity, VAT, and cardiometabolic disease risk markers in elite RU athletes of Caucasian and Polynesian descent; and 2) assess the impact of a pre-season

training program on levels of VAT and biochemical markers of cardiometabolic disease risk.

METHODS

Participants

Twenty-two male professional RU athletes were recruited via their involvement in a Super Rugby franchise. Informed consent was obtained from all athletes included in the study and the research was approved by the Human Research Ethics Committees at the Royal Brisbane and Women's Hospital (EC00172, HREC/16/QRBW/545) and the University of the Sunshine Coast (EC00297, S/16/959).

At the time of consent the athletes provided the ethnicity of their grandparents via open ended questions. As this study investigated the role of phenotype expression, grandparental heritage was chosen as in previous research [616, 619, 620]. The athletes were ascribed a specific ethnicity if three or four of their grandparents were of the same ethnicity.

Study design

As part of the physical preparation for the Super Rugby season, the athletes undertook a high-volume, high-intensity, 11-week pre-season program (November – February) with the aims of increasing strength and power and improving aerobic and anaerobic fitness; some of which can be favourably impacted by strategic body composition manipulation [64, 127]. During the first three days of pre-season, the athletes undertook routine physique assessment via SA and DXA. In addition, they received a MRI scan of their abdominal cavity. Athletes were re-assessed using the same techniques within the final three days of the pre-season period. A fasted blood test was undertaken at the same time points.

Surface anthropometry

An ISAK Level 3 accredited anthropometrist with a historical TEM of 1.7% for S7SF performed all measurements. BM was assessed using electronic scales (A&D Mercury, Adelaide, Australia) to 0.1 kg accuracy, and stature measured using a mobile stadiometer (Seca 213, Birmingham, UK) to 0.1 cm accuracy. Both measurements were made on arrival at the testing facility after an overnight fast and with bladder voided. Skinfolds were assessed using Harpenden calipers (British Indicators, Hertfordshire, UK) to 0.1 mm precision. All anthropometric equipment was calibrated as recommended by the manufacturers.

Skinfold and WC measurements were made using ISAK techniques [410]. Skinfolds were assessed across seven sites: triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, and medial calf. For athletes for whom a reliable skinfold could not be taken at the abdominal site 5 cm from the umbilicus, the site was moved to 10 cm from the umbilicus at both time points. WC was measured at the level of the narrowest point between the lower costal border and the iliac crest and taken at the end of normal expiration. All measurements were undertaken in duplicate to establish within-day retest reliability. If the difference between the duplicate measures exceeded 4% for an individual skinfold or 1% for WC, a third measurement was taken. The mean of duplicate or the median of triplicate anthropometric measurements were used for all subsequent analysis. BMI was calculated using the formula mass (kg) divided by stature (m) squared. WHt ratio was calculated using the formula waist circumference (cm) divided by stature (cm).

Dual-energy X-ray absorptiometry

All athletes received whole body composition analysis via scans on a fan-beam DXA system (Hologic Discovery A, Hologic, Bedford, MA), with Apex 13.4.2:3 software (Hologic, Bedford, MA). The scanner was calibrated daily using a phantom as per manufacturer guidelines for quality control purposes.

Scanning protocols were implemented using proven techniques to maximise technical reliability and minimise error [396]. Specifically, the athletes were scanned prior to food and fluid ingestion, or exercise, early in the morning (5:00 – 8:30 am). The athletes were scanned wearing sports shorts and those taller than the defined 196 cm scanning boundary were subject to two scans. The first scan was used to capture the body from the menton (the inferior point of the mandible) down whilst the head was positioned in the Frankfort plane. After body repositioning on the scanner and realignment of the head into the Frankfort plane, a second scan was taken to capture from the menton up to the vertex of the head. The results were then combined post-analysis to produce whole body composition scans [178]. For positioning consistency the same experienced and qualified technician performed all measurements using the Nana et al. positioning protocol previously described [396]. The same qualified technician undertook all post-scan analysis, including the manual adjustment of all regions of interest. Auto positioning of the VAT area was used, with manual adjustments made to the edge of subcutaneous fat placement and visceral cavity area if required.

Magnetic resonance imaging

Abdominal SAT and VAT were measured on a PRISMA 3T MRI (Siemens Healthineers, Erlangen, Germany) at the Herston Imaging Research Facility (Brisbane, Queensland, Australia) by a qualified and experienced technician. A 32-channel spine array coupled with a 30-channel body array was utilised to perform the examination. Coverage extended from the diaphragm to the L5/S1 junction. The athletes were positioned either head first or feet first depending on their body habitus, and this position was repeated at the follow-up scan. Axial T1 weighted Dixon images were acquired in a single breath hold (TR 3.97 ms, TE 1.23/2.46 ms, flip angle 9°, matrix 320X240) with slice thickness of 4 mm and no inter-slice gaps. The field of view (FOV) was 450 mm in order to include the skin surface.

Cross-sectional areas and volumes of both abdominal SAT and VAT from L5/S1 to the diaphragm were measured by semi-automated specialized software (Slice-O-matic version 5.0; Tomovision, Montréal, Canada). SAT was quantified using the “mathematical morphology” function and VAT using the “region growing” function, with thresholds adjusted manually for each slice. All images were analysed by a single trained observer who was not informed of athlete ethnicity and playing position. Examples of the output provided by image analysis process is shown in Figure 8.1. Presently, there are no established cut-off values for VAT volume given it is a relatively new assessment. Intra-observer variability was assessed by re-analysing 11 randomly selected scans after a minimum 3-month interval.

Blood biochemistry

Venous blood was collected from the antecubital vein after an overnight fast (>10 hours). On the same day serum glucose, insulin, TC, TG, HDL-C and LDL-C concentrations were analysed by a commercially accredited laboratory using their standardised procedures.

Training

Athletes undertook an 11-week pre-season program. This followed a period of 4-weeks of leave, which included an active rest schedule of two strength and two conditioning sessions a week. The pre-season comprised a 4-week supervised training block prior to a 2-week unsupervised maintenance block, followed by another 5-week supervised training block. Throughout each training week, technical (x2/week) and tactical (x4/week) rugby sessions along with sessions to improve physical qualities and body composition were performed (speed/agility x1/week, strength x4/week, conditioning x3-4/week, boxing x1/week). Weekly training time was approximately 15 hours, with additional time spent on recovery and regeneration modalities (flexibility, mobility, massage, hydrotherapy and physiotherapy). All athletes were under the management of an experienced sports dietitian and received individualised

dietary plans and group education sessions aimed at supporting training adaptations throughout the pre-season period.

Statistical analysis

Statistical analysis procedures were completed using SPSS (Version 22.0, IBM Corp., Armonk, NY) and Microsoft Excel 2011 (Microsoft, Redmond, WA, USA). Before analysis, assumptions of normality in the data were made using the Shapiro-Wilk test and visualisations of normality histograms and Q-Q plots. If data were not normally distributed they were log transformed using the natural logarithm for all subsequent analyses. Independent t-tests were used to test for differences in body composition traits and cardiometabolic risk markers according to ethnicity at baseline. A one-way ANCOVA was conducted using ethnicity as the independent variable, and baseline measures entered as the covariate, to test for interactions between ethnicity and body composition changes over the pre-season period. Bonferroni post hoc corrections were applied. Correlations were calculated using Pearson's and Spearman's correlations for normally distributed and nonparametric data, respectively, to assess the relationship between body composition and cardiometabolic risk variables at baseline, and for changes over the pre-season period. For correlations, coefficients were qualitatively ranked by magnitude [254], with the strength of correlation coefficients defined as trivial, $r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; and perfect, $r = 1.0$. Data are presented as mean $\pm$ SD, or median (inter-quartile range; IQR) for non-parametric variables, with statistical significance for all analyses defined as $P \leq 0.05$. ICC determined the test-retest reliability of the MRI analyses.

Individual changes in DXA measures were evaluated through the application of LSC derived from precision data as previously described [333] using a group of resistance trained athletes on the same Hologic Discovery A scanner [617]. Precision error was calculated as RMS-SD, with LSC subsequently derived as RMS-SD x 2.77 (95% CI) [30]. LSC values were also created using the same methods for SA measures and MRI analysis using data collected within this population (Table 8.1).

Table 8.1. Short-term precision and corresponding LSC in resistance trained athletes using the same Hologic Discovery A scanner.

	Precision		LSC-95% CI	
	RMS-SD	%CV	RMS-SD	%CV
DXA ^a				
Whole body fat mass (g)	455.2	2.9	1261.0	8.0
Whole body fat mass (%)	0.7	3.1	1.8	8.6
Android fat mass (g)	29.0	3.5	80.5	9.7
Android fat mass (%)	0.7	3.9	1.8	10.8
Gynoid fat mass (g)	120.2	4.0	333.0	10.9
Gynoid fat mass (%)	0.8	2.3	3.4	9.4
Anthropometry ^b				
Sum of 7 skinfolds (mm)	0.7	1.9	0.7	1.9
Waist circumference (cm)	0.2	0.2	0.6	0.5
MRI ^c				
SAT volume (cm ³)	46.6	1.7	129.2	4.8
VAT volume (cm ³)	10.2	1.8	28.3	5.1

RMS-SD = root-mean-square standard deviation; CV = coefficient of variance; LSC = least significant change

^a DXA precision based on scans on consecutive days (accounting for technical error and biological variation) on resistance trained individuals on the same Hologic Discovery A scanner used in this study [617]

^b Anthropometry precision based on multiple measures taken on this study population using best practice protocols

^c MRI precision based on repeated analysis on scans using this study population

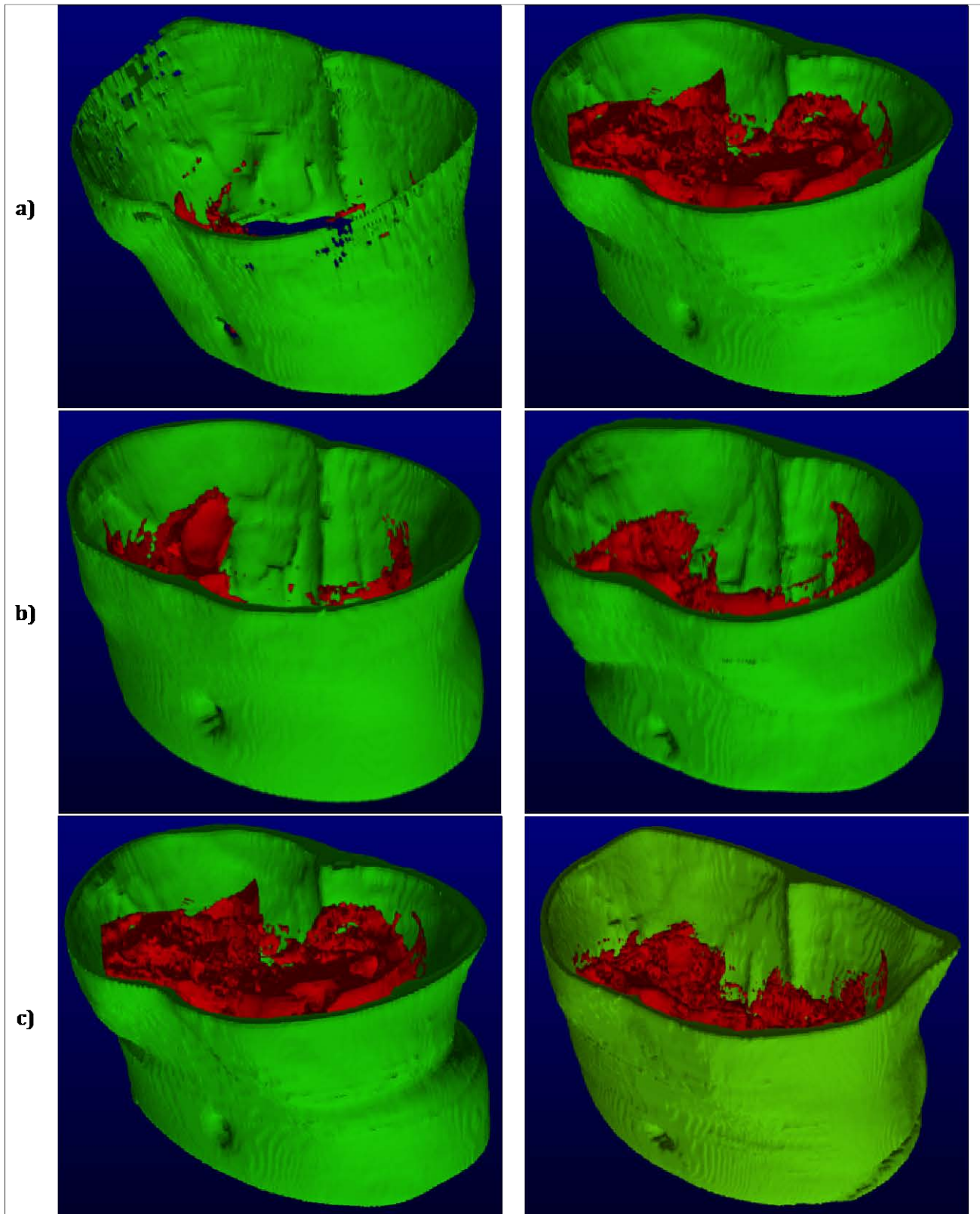


Figure 8.1. Three-dimensional images of subcutaneous adipose tissue (SAT; green) and visceral adipose tissue (VAT; red). a) Low VAT (left) vs high VAT (right). b) Caucasian (left; ~21% body fat, ~4700 cm³ SAT, ~ 600 cm³ VAT) vs Polynesian (right; 19% body fat, 5900 cm³ SAT, 800 cm³ VAT). c) Changes in SAT and VAT in the same athlete over the pre-season.

RESULTS

All twenty-two athletes (age 22.8 ± 3.2 years; stature 186.8 ± 8.4 cm; BM 101.5 ± 13.7 ; BMI 29.0 ± 2.5 kg/m²) were able to be ascribed an ethnicity, with 11 identifying as Caucasian, and 11 as Polynesian. Descriptive characteristics based on ethnicity are presented in Table 8.2. Differences were found between ethnicities at baseline, with Polynesians having significantly higher VAT (771 ± 609 cm³ vs 424 ± 235 cm³; $P = 0.043$), android FM percentage (19.4 ± 5.0 % vs 14.5 ± 3.8 %; $P = 0.020$), TG (1.0 ± 0.9 mmol/L vs 0.6 ± 0.2 mmol/L; $P = 0.050$), LDL-C (3.1 ± 0.9 mmol/L vs 2.3 ± 0.7 mmol/L; $P = 0.019$) and WHt (0.50 ± 0.03 vs 0.47 ± 0.02 ; $P = 0.019$), whilst trending towards higher SAT (3424 ± 1529 cm³ vs 2279 ± 1014 cm³; $P = 0.068$) and TC (5.1 ± 0.9 mmol/L vs 4.4 ± 0.8 mmol/L; $P = 0.057$). The ICC (95% CI) for VAT was 1.00 (CI 0.99–1.00) and for SAT was 1.00 (CI 0.98–1.00), with a CV of 2.0% and 2.7%, respectively.

Significant correlations were recorded at the start of pre-season with both SAT and VAT in relation to other measures of adiposity including skinfolds, WC, and absolute and relative android and gynoid fat (Table 8.3). Large correlations were noted between VAT ($r = 0.564$, $P < 0.01$) and SAT ($r = 0.435$, $P < 0.05$) with TC, and very large correlations between VAT ($r = 0.709$, $P < 0.01$) and SAT ($r = 0.705$, $P < 0.01$) with TG.

Ethnicity was found to be significantly related to changes over the pre-season period, with Polynesians having greater reductions in WC (-2.8 ± 1.6 cm vs -0.7 ± 1.2 cm; $F = 9.208$, $P = 0.007$) and WHt (-0.02 ± 0.009 vs -0.004 ± 0.006 ; $F = 7.206$, $P = 0.015$), whilst Caucasians had greater reductions in TC (-0.13 ± 0.32 mmol/L vs -0.08 ± 0.68 mmol/L; $F = 5.543$, $P = 0.029$) (Table 8.2).

Applying the LSC model, individual changes are shown in Table 8.4. Twenty-one (95%) athletes had reductions in VAT (exceeding LSC-95% CI; Table 8.1) and skinfolds over the pre-season period, whilst 19 (86%) decreased SAT and android FM percent (Figure 8.2). A similar proportion of Caucasians and Polynesians athletes made meaningful changes in all measures assessed, with the

exception of WC in which a larger proportion of Polynesians (91%) made a significant decrease in comparison to Caucasians (45%).

Large correlations in changes over the pre-season were found between VAT and skinfolds ($r = 0.575$, $P < 0.01$), WC ($r = 0.578$, $P < 0.01$), total FM ($r = 0.496$, $P < 0.05$), android FM ($r = 0.462$, $P < 0.05$), and gynoid FM ($r = 0.491$, $P < 0.05$). Similar or slightly larger and stronger correlations were seen between SAT and skinfolds ($r = 0.689$, $P < 0.01$), WC ($r = 0.558$, $P < 0.01$), total FM ($r = 0.557$, $p < 0.01$), android FM ($r = 0.625$, $P < 0.01$), and gynoid FM ($r = 0.488$, $P < 0.05$).

Table 8.2. Descriptive statistics of athletes grouped according to ethnicity.

	Caucasians (n = 11)		Polynesians (n = 11)		T-test p-value	ANCOVA p-value
	Start pre-season	End pre-season	Start pre-season	End pre-season		
Age (years)	22.1 ± 2.4	-	23.5 ± 3.8	-	0.322	-
Surface Anthropometry						
Stature (cm)	189.4 ± 8.7	-	184.1 ± 7.6	-	0.140	-
Body mass (kg)	101.2 ± 14.2	101.7 ± 14.0	101.8 ± 13.9	100.8 ± 13.6	0.926	0.053
Sum of 7 SF (mm) [#]	66.8 (56.4 to 90.2)	54.7 (47.4 to 71.8)	78.6 (67.1 to 103.7)	65.6 (55.5 to 86.7)	0.150	0.708
WC (cm)	88.7 ± 5.0	87.9 ± 4.5	91.3 ± 6.2	88.5 ± 5.9	0.292	0.007 [^]
BMI (kg/m ²)	28.1 ± 2.1	28.2 ± 2.0	29.9 ± 2.6	29.7 ± 2.7	0.081	0.098
WHt (cm/m ²)	0.47 ± 0.02	0.46 ± 0.02	0.50 ± 0.03	0.48 ± 0.03	0.019*	0.015 [^]
DXA						
Whole body LM (g)	84005 ± 10306	86430 ± 10447	82680 ± 10173	83795 ± 10431	0.767	0.658
Whole body FM (g)	15495 ± 4839	13338 ± 4353	17572 ± 4214	15278 ± 3897	0.296	0.809
Whole body FM (%)	14.7 ± 3.0	12.7 ± 2.7	16.7 ± 2.3	14.7 ± 2.4	0.099	0.515
Android FM (g)	1005 ± 416	818 ± 375	1396 ± 570	1083 ± 462	0.078	0.304
Android FM (%)	14.5 ± 3.8	12.0 ± 3.7	19.4 ± 5.0	15.5 ± 4.5	0.020*	0.351
Gynoid FM (g)	3249 ± 1260	2788 ± 1167	3615 ± 779	3145 ± 786	0.423	0.849
Gynoid FM (%)	17.6 ± 4.2	15.2 ± 4.0	20.2 ± 3.0	17.9 ± 3.2	0.116	0.694
FMI (kg/m ²)	4.3 ± 1.2	3.7 ± 1.1	5.1 ± 1.0	4.5 ± 1.0	0.077	0.915
MRI						
SAT volume (cm ³)	2279 ± 1014	1888 ± 979	3424 ± 1529	2886 ± 1370	0.068	0.786
VAT volume (cm ³) [#]	373 (239 to 649)	206 (181 to 420)	662 (434 to 799)	400 (213 to 547)	0.043*	0.534

Blood Biochemistry						
Fasting insulin (mU/L)	7.6 ± 4.5	11.0 ± 4.8	7.2 ± 5.3	9.4 ± 4.8	0.717	0.457
Fasting glucose (mmol/L)	4.2 ± 0.3	4.2 ± 0.7	4.1 ± 0.4	4.3 ± 0.2	0.848	0.452
Total cholesterol (mmol/L) [#]	4.3 (3.6 to 4.9)	4.2 (2.8 to 4.7)	4.9 (4.3 to 5.5)	5.0 (4.8 to 5.2)	0.057	0.029 [^]
Triglycerides (mmol/L) [#]	0.6 (0.3 to 0.7)	0.8 (0.6 to 0.9)	0.8 (0.6 to 1.0)	1.0 (0.8 to 1.2)	0.050*	0.151
HDL-C (mmol/L)	1.4 ± 0.2	1.4 ± 0.2	1.3 ± 0.2	1.3 ± 0.2	0.096	0.936
LDL-C (mmol/L) [#]	2.2 (1.8 to 2.4)	2.2 (1.8 to 2.5)	2.9 (2.5 to 3.7)	3.1 (2.9 to 3.4)	0.019*	0.122

DXA = dual-energy X-ray absorptiometry; MRI = magnetic resonance imaging; SF = skinfolds; WC = waist circumference; BMI = body mass index; WHt = waist to height ratio; FM = fat mass; LM = lean mass; FMI = fat mass index; SAT = subcutaneous adipose tissue; VAT = visceral adipose tissue; HDL-C = high-density lipoprotein cholesterol; LDL-C = low-density lipoprotein cholesterol

Data presented as mean ± SD

[#] Log transformed, data presented as median (IQR)

Independent T-test – * Significantly different at baseline ($P \leq 0.05$)

ANCOVA – [^] Significant interaction between ethnicity and change over pre-season ($P \leq 0.05$)

Table 8.3. Correlations between adiposity measures and blood biochemical markers of cardiometabolic disease risk with magnetic resonance imaging measured SAT and VAT.

	Baseline		Change over pre-season	
	MRI SAT $r^{\#}$	MRI VAT $r^{\#}$	MRI SAT r	MRI VAT $r^{\#}$
Mass (kg)	0.752**	0.365	0.484*	0.299
Sum 7 skinfolds (mm)	0.866**	0.639**	0.689**	0.575**
Waist circumference (cm)	0.842**	0.494*	0.558**	0.578**
BMI (kg/m ²)	0.820**	0.427*	0.496*	0.329
WHt (cm/cm)	0.525*	0.427*	0.548**	0.588**
Total fat mass (kg)	0.953**	0.709**	0.557**	0.496*
Total fat mass (%)	0.901**	0.723**	0.473*	0.453*
Android fat mass (kg)	0.964**	0.785**	0.625**	0.462*
Android fat mass (%)	0.897**	0.834**	0.587**	0.377
Gynoid fat mass (kg)	0.881**	0.581**	0.488*	0.491*
Gynoid fat mass (%)	0.737**	0.540**	0.420	0.506*
FMI (fat mass / Ht (m) ²)	0.939**	0.680**	0.545**	0.500*
Fasting insulin (mU/L)	0.386	0.263	0.309	0.070
Fasting glucose (mmol/L)	0.104	0.372	0.272	0.096
Total cholesterol (mmol/L)	0.435*	0.564**	-0.010	0.302
Triglycerides (mmol/L)	0.705**	0.709**	0.087	0.107
HDL-C (mmol/L)	0.098	-0.044	0.148	-0.067
LDL-C (mmol/L)	0.225	0.411	-0.104	0.078

BMI = body mass index; WHt = waist to height ratio; FMI = fat mass index; HDL-C = high-density lipoprotein cholesterol; LDL-C = low-density lipoprotein cholesterol; MRI = magnetic resonance imaging; SAT = subcutaneous adipose tissue; VAT = visceral adipose tissue;

** $P \leq 0.01$, * $P \leq 0.05$

r = Pearson's correlation coefficient; $r^{\#}$ = Spearman's correlation coefficient

$r < 0.1$; small, $0.1 \leq r < 0.3$; moderate, $0.3 \leq r < 0.5$; large, $0.5 \leq r < 0.7$; very large, $0.7 \leq r < 0.9$; almost perfect, $0.9 \leq r < 1.0$; and perfect, $r = 1.0$.

Table 8.4. Individual athletes who made meaningful reductions in whole body and regional body composition (> LSC-95% CI – technical error and biological variation) during the pre-season.

		All (n = 22)	Ethnicity (n = 22)	
			Caucasians (n = 11)	Polynesians (n = 11)
DXA	Total fat mass (g)	17 (77%)	9 (82%)	8 (73%)
	Total fat mass (%)	17 (77%)	9 (82%)	8 (73%)
	Android fat mass (g)	20 (91%)	10 (91%)	10 (91%)
	Android fat mass (%)	19 (86%)	9 (82%)	10 (91%)
	Gynoid fat mass (g)	15 (68%)	7 (64%)	8 (73%)
	Gynoid fat mass (%)	5 (23%)	2 (18%)	3 (27%)
Surface anthropometry	Sum of 7 skinfolds (mm) ^a	21 (95%)	11 (100%)	10 (91%)
	Waist circumference (cm) ^b	15 (68%)	5 (45%)	10 (91%)
MRI	SAT volume (cm ³)	19 (86%)	10 (91%)	9 (82%)
	VAT volume (cm ³) ^c	21 (95%)	11 (100%)	10 (91%)

Data shown are – number of athletes (% of athletes)

DXA = dual-energy X-ray absorptiometry; MRI = magnetic resonance imaging

^a 1 athlete increased sum of 7 skinfolds (1 Polynesian)

^b 3 athletes increased waist circumference (2 Caucasian, 1 Polynesian)

^c 1 athlete increased VAT (1 Polynesian)

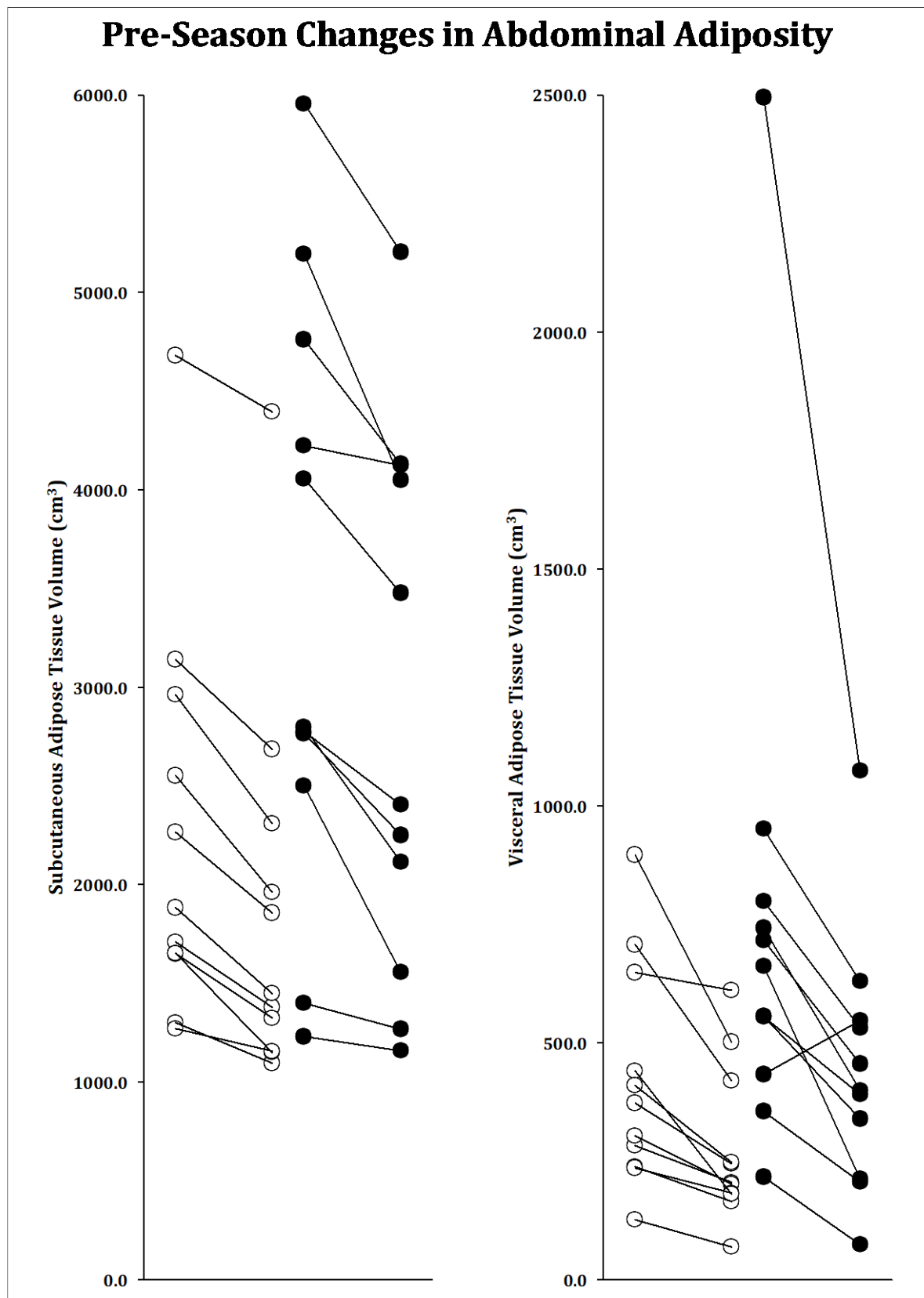


Figure 8.2. Pre-season changes in abdominal visceral (VAT) and subcutaneous (SAT) adiposity. Open circles represent Caucasians, closed circles represent Polynesians. Circles joined by lines represent each individual athlete's SAT and VAT values at the start and end of pre-season.

DISCUSSION

In this research we were the first to assess volumetric measures of VAT in an elite athlete population and to adopt an individualised approach to the analysis of pre-season adiposity changes in elite RU athletes. The main findings were that: (1) athletes of Polynesian descent had significantly different abdominal adiposity distribution and lipid profiles compared to Caucasian athletes; and (2) the majority of athletes achieved meaningful and favourable reductions in both abdominal VAT (95%) and SAT (86%) over the pre-season period.

Prior to this study, there was limited research on visceral adiposity in athletic populations. Bosch and colleagues [73] determined that NFL linemen (BM 137.1 ± 11.7 kg; BMI 37.3 ± 3.5 kg/m²; BF% 27.0 ± 6.0 %) have high levels of VAT as estimated by DXA compared to non-linemen (1.2 ± 0.6 kg vs. 0.3 ± 0.2 kg). Similarly, heavyweight judo athletes possessed relatively higher VAT measured by single slice MRI at L4/L5 compared to non-heavyweight athletes (91 ± 39 cm² vs 33 ± 14 cm²) [387], which would have placed many above the 100 cm² diagnostic threshold for increased cardiometabolic disease risk [431]. We have previously identified that 37% of athletes in an elite RU population were above the threshold for increased risk via single slice MRI, whilst no differences were found between ethnicities [619]. However, this was using reference ranges developed in older and more obese populations and, therefore, the application to well-trained athletes was uncertain. Furthermore, single slice measures may be affected by ethnicity [142], and Polynesian individuals have greater absolute and relative body fat distribution in the abdominal region [480]. In the current study, elite Polynesian RU athletes had higher VAT, and trended towards having higher SAT than Caucasians, despite no statistically significant difference in total or relative FM. It is important to note that one Polynesian athlete had a considerably higher VAT measurement than the other ten (Figure 8.2). As this was a statistical but not clinical outlier, we retained this in the primary analysis. Removal of this athlete from the group mean analysis weakened the ethnicity difference in VAT marginally (from $P = 0.043$ to $P = 0.070$). Moreover, the results for all athletes were investigated after being adjusted for stature, but this had no

effect on the outcomes, indicating the relative size of the individual did not make a difference to VAT accumulation.

“Supersized” professional strength sport athletes in unlimited body weight categories [220], NFL linemen [561], and collegiate RU forwards [264], have exhibited elevated blood lipid profiles compared to smaller stature athletes and/or non-athlete controls. Further, NFL linemen have an increased incidence of metabolic syndrome compared to non-linemen post-career (59.8% vs 30.1%; $P < 0.001$) [380], and a higher BMI and/or WC has been associated with subclinical atherosclerosis and cardiometabolic risk in retired NFL athletes [438, 558]. However, comparisons based on ethnicity in elite athlete populations have not previously been made. Although in this study the group mean of all variables were considered to be within the normal ranges, likely owing to the young age and high activity levels of the cohort, Polynesians had higher TG and LDL-C, and a trend towards higher TC, relative to Caucasians. A number of Polynesian athletes had blood lipids that were outside of the low risk targets [551], including two for TC (>6.0 mmol/L), one for TG (>1.5 mmol/L), one for HDL-C (<1.0 mmol/L), and six for LDL-C (>3.0 mmol/L). Only one Caucasian had elevated LDL-C levels. No athletes were outside the normal range for fasted insulin or glucose measures.

Published data implies that Polynesians have some of the highest rates of obesity and cardiometabolic disease risk worldwide [214, 402]. It is noteworthy that in the athletic population we studied in which all athletes were undertaking comparable training programs and nutrition support interventions, elevated lipid profiles were still recorded in Polynesians. The higher TC and LDL-C concentrations in Polynesian athletes may place them at elevated risk of post-career cardiometabolic complications when activity levels are prone to decline, as has been shown in other sports with “supersized” athletes [380, 558]. This warrants further investigation of RU athletes after retirement, particularly given the greater focus on larger athletes is a relatively new phenomenon in the sport.

Elevated VAT has been associated with dysfunctional glucose and lipid metabolism [145, 190, 471]. In our study, higher levels of VAT showed positive correlations with TC and TG levels. It has been suggested that increased physical activity acts as a protective barrier against cardiometabolic disease risk in the general population [42, 427] as well as “supersized” athletes [387]. Indeed, a recent meta-analysis in normal-weight and overweight/obese individuals reported high-intensity interval training (HIIT) has been shown to reduce VAT [354]. Specifically in athletic groups, elite sumo wrestlers have significantly lower visceral adiposity compared to obese controls, normal glucose and TG levels, and lower TC compared with non-obese controls [365]. Furthermore, the significant reduction in VAT amongst Caucasians and Polynesians in this study at both the group and individual level, coupled with the absence of significant biochemical changes in cardiometabolic risk profiles, indicates that physical activity may be protective of adverse blood biochemical changes in elite athletes during their playing career. However, given “supersized” athletes have been reported to have a higher incidence of metabolic syndrome [380] and other obesity related complications post-career [352, 438, 558], health status should continue to be monitored after retirement in conjunction with athlete follow-up and support.

The results of this study indicate that Polynesian RU athletes have higher levels of VAT and blood lipid markers than their Caucasian peers, with the underlying reasons for this possibly dating back to physiological traits that have evolved over millennia [67]. Future investigations encompassing longitudinal studies, incorporating end of season measures of VAT and blood biochemical markers to assess changes during the off-season period, would be valuable. Additionally, studies exploring cardiometabolic health and broader health issues of RU athletes post-retirement would be beneficial. This would add a holistic view to the research being undertaken on long-term health status of retired RU athletes [261, 339].

There were some limitations identified with this study. First, it was not possible to accurately quantify dietary intake over a long period [353], or the training associated energy expenditure of the athletes given the high-intensity nature of the training being undertaken [156] together with the frequent physical collisions [76]. This information may have afforded additional insight into the underlying reasons for changes and differences based on ethnicity in abdominal adiposity and blood biochemistry. In particular, it may have provided a reason for the increased VAT in a single Polynesian athlete, which was unexpected given the high training load and results of the other athletes. Secondly, information on the medical history of the athletes and their families would have allowed exploration into possible hereditary influences. This may have provided some insight into the underlying reason one athlete displayed significantly higher VAT. Of note is that the changes this athlete made to his abdominal adiposity over the pre-season were in line with previous research, namely that VAT (1421 g) was lost preferentially to SAT (631 g) [582].

CONCLUSION

This study identified significant differences in cardiometabolic disease risk factors based on ethnicity in elite RU athletes, with Polynesians having higher values for VAT and several lipid markers. Although athletes of both ethnicities had meaningful reductions in VAT as a result of pre-season training, it is possible that Polynesian athletes may be predisposed to the higher VAT and blood biochemistry markers associated with cardiometabolic disease risk. Further investigations are advocated to explore the underlying reasons for these findings, and the long-term cardiometabolic health implications in elite Polynesian athletes.

CHAPTER NINE – CONCLUSIONS

SUMMARY

The six studies presented in this thesis explored the role that ethnicity plays in the physique of elite RU athletes. Valid indices of cardiometabolic health risk potentially associated with the “supersized” status of some athletes within this population were also investigated. Despite the increased participation of Polynesians in RU at the elite level, prior to this series of studies, no detailed information was available describing the influence ethnicity had on the body composition and cardiometabolic health risk factors of these athletes. With the unique physique traits that Polynesians possess, some of which infer increased cardiometabolic risk, these investigations were timely given the trend of “supersizing” elite RU athletes in particular positions in an attempt to elicit improved performance.

As hypothesised, elite RU athletes of Polynesian descent exhibited unique morphology, particularly pertaining to regional FM and LM distribution. Additionally, Polynesian athletes possessed greater VAT based on volumetric measures, although these did in most individual cases remain within normal ranges. However, against the hypothesis, there were no whole body differences in either LM or FM observed in elite RU athletes based on ethnicity.

In regards to body composition assessment, differences were noted in the ability of SA to predict DXA changes in FM based on ethnicity, perhaps due to the dissimilarities observed in body fat distribution. However, as hypothesised SA was proven to provide an appropriate proxy for measuring longitudinal change in an elite RU population. The use of skinfold regressions equations for the prediction of absolute FM was also denounced in this multi-ethnic population of elite RU athletes. Interestingly, and against what was hypothesised, RU and

ethnicity specific skinfold regression equations created for this population were no better in predicting BF% than those previously developed. This is in line with the recommendations that SA data is kept in its raw form when interpreting changes in FM. Finally, DXA was proven not to be able to accurately quantify VAT in this population, in comparison to the criterion MRI. This may be due to the size of the athletes, and the different proportions of LM and FM they exhibit in comparison to the general population on whom the algorithms to calculate DXA VAT are created on.

As was hypothesised, significant whole body and regional body composition changes were observed, at both the team and individual level during the pre-season period. Furthermore, the tendency for Polynesian athletes to exhibit elevated VAT and blood lipid levels compared to Caucasians was identified, indicating special consideration may need to be given to the short- and long-term health status of these individuals. Finally, as hypothesised, ethnicity was found to be significantly related to changes in markers of cardiometabolic disease risk, although in the majority of individual cases the measures remained within normal limits.

The work presented fills crucial gaps in the literature and provides coaches and sports science practitioners with a valuable insight into the role ethnicity plays in body composition characteristics, adaptations, and assessment. This information has the potential to influence athlete management from a number of perspectives, including but not limited to talent identification, strength and conditioning program development, dietary interventions, medical screening and management, and end-of-career athlete counseling.

RESEARCH AIMS AND KEY OUTCOMES

Quantification of body composition traits in modern day elite rugby union athletes

Research aims

- Describe the body composition traits of modern-day elite RU athletes.
 - Compare the morphology between forwards and backs, and between Caucasian and Polynesian athletes.
 - Identify differences in regional distribution of FM and LM, in absolute and relative terms.
- Investigate levels of VAT in elite RU athletes, incorporating comparisons based on ethnicity.

Key outcomes

The unique positional requirements in RU ensures marked differences in physique traits between forwards and backs. This series of research studies has confirmed this remains within elite RU populations, with significant whole body and regional differences observed between forwards and backs. Specifically, forwards were heavier, taller, had greater levels of LM, and had greater levels of adiposity, both in absolute and relative terms. No regional LM or FM distribution differences were observed based on position. Whilst no whole body physique differences were discovered between Caucasian and Polynesian athletes, significant differences were found in DXA derived regional distribution based on ethnicity. Polynesians possessed greater relative LM and FM in peripheral (arm and leg) regions, and less in the trunk region, compared to Caucasians.

SA derived data contradicted the results obtained by DXA, and suggested Polynesians had a larger proportion of FM in their trunk. Given the majority of trunk anthropometry measures are taken around the abdomen, it was postulated

that VAT may also differ between ethnicities. This was subsequently refuted using a single abdominal slice MRI measure, which found that whilst there was an association between visceral adiposity and position with forwards tending to display higher values, no differences were found based on ethnicity. However, questions have been raised about the validity of a single slice measure being equally representative of VAT in different ethnicities. Indeed, when volumetric measures of VAT through the entire abdominal cavity were undertaken, Polynesians possessed significantly higher levels of visceral adiposity.

Body composition assessment methods in elite rugby union athletes

Research aims

- Assess the ability of currently available skinfold regression equations to estimate body composition relative to DXA in an elite RU population of different ethnic backgrounds.
- Derive ethnicity-sensitive skinfold regression equations for predicting body composition in RU athletes.
- Investigate the association between DXA and raw surface anthropometry data when measuring changes in FFM and FM in elite RU athletes, and to explore whether differences exist due to the physique traits of the athletes based on ethnicity and/or position.
- Assess the ability of DXA to estimate VAT compared to the criterion magnetic resonance imaging in a population of elite RU athletes.

Key outcomes

Body composition assessment is routinely undertaken in elite RU programs, with SA and DXA being the most commonly utilised techniques. In practice, skinfold regression equations are often used to infer whole body composition from SA data. This research has shown that neither the existing equations evaluated, nor those specifically created from this multi-ethnic population, were sufficiently reliable to estimate body composition in elite RU athletes. As such, the use of raw SA data is advocated for use within this population. Indeed, in this series of studies it was shown SA provides adequate sensitivity to track the direction of body composition change typically observed amongst RU athletes during pre-season training. When absolute whole body and regional body composition measures are desired, the use of DXA is advocated, which has the added benefit of being able to provide an estimate of VAT. Although DXA appears to underestimate VAT compared to MRI, it may still have application as a screening tool in this population, who are likely to undertake DXA scans regularly.

Assessment of cardiometabolic disease risk markers and pre-season adaptations in elite rugby union athletes

Research aims

- Explore the relationship between ethnicity, VAT, and cardiometabolic disease risk markers in elite RU athletes of Caucasian and Polynesian descent.
- Identify pre-season team and individual athlete DXA-derived body composition adaptations in elite RU athletes, with sub-group analysis to compare changes between Polynesian and Caucasian athletes.
- Assess the impact of a pre-season training program on VAT and biochemical markers of cardiometabolic disease risk in a population of elite RU athletes of Caucasian and Polynesian ethnicity.

Key outcomes

This series of research studies found that elite Polynesian RU athletes exhibited significantly higher VAT, TG, and LDL-C, whilst trending towards higher SAT and TC compared to Caucasians at the start of the pre-season period. As has been found in general populations, this infers that despite the nutrition and training interventions applied in the elite training environment, Polynesians appear to have a genetic predisposition to possess higher levels of cardiometabolic disease markers. After exposure to a pre-season training program, it was found Polynesians had greater reductions in WC and WHt, whilst Caucasians had greater reductions in TC. No differences were found in changes pertaining specifically to VAT based on ethnicity. However, the vast majority of athletes exhibited meaningful reductions in VAT over the pre-season period. Although Polynesians had higher VAT and several lipid profile markers compared to Caucasians at both the start and end of pre-season, in most cases the overall cardiometabolic risk profile remained in normal ranges. However, some Polynesian athletes were observed to have high TC (>6.0 mmol/L) and/or elevated LDL-C (>3.0 mmol/L).

Finally, significant physique changes were noted over the pre-season period. Significant decreases in FM and increases in LM were observed when athletes were grouped according to ethnicity and position, for whole body and all regional body composition measures. At an individual level, most athletes had a loss of whole body FM, whilst around one-third had an increase in whole body LM. Position and ethnicity combined did not have any significant group effects on pre-season adaptations; however, Caucasian athletes increased LM more than Polynesians. Further, when explored using the LSC model at an individual level, three times more Caucasians were able to increase LM over the pre-season period compared to Polynesians, illustrating the value of exploring individual athlete differences.

PRACTICAL APPLICATIONS AND IMPLICATIONS OF THE RESEARCH

The findings of this thesis may be utilised by sport science and sports medicine practitioners, as well as coaches, to better appreciate the role ethnicity plays in the body composition of elite RU athletes.

Body composition assessment

- The use of currently available skinfold regression equations, including the RU specific equations created in this series of investigations, cannot be advocated for use in elite RU populations, and the use of raw SA data for tracking longitudinal change is recommended.
- Raw SA measures provide a robust indication of the direction of change in FM and FFM for both Caucasians and Polynesians. However, caution needs to be applied by practitioners when interpreting the magnitude of change using SA measures, particularly with FM.
- Given that DXA underestimates VAT in this population, caution needs to be applied when interpreting these results. However, these measures may still provide practitioners with an indication of athletes at increased cardiometabolic risk due to elevated VAT levels, and initiate further screening if required.

Pre-season adaptations

- The individualised approach to assessing pre-season physique adaptations can provide coaches and sport science practitioners with specific insight to the success of their programs from a body composition perspective. This approach can also increase awareness of the way different individuals respond to the training and diet stimulus provided.

Health status

- Existing cut-offs and references ranges for VAT and abdominal adiposity risk may not be applicable to this population of elite RU athletes. Therefore, these should be used with caution when applied to athletic populations.
- The meaningful reductions in VAT over the pre-season across individuals of both ethnicities suggests the high training load undertaken within the elite training environment may be protective of health complications during an athlete's career. However, the higher VAT identified in some athletes, particularly Polynesians, suggests there may be some athletes who are at an increased risk. This may be particularly pertinent when the known cardio-protective efforts of exercise are removed, for example upon retirement from elite sport.

LIMITATIONS

Although the findings of this thesis have important implications for athlete management in elite RU populations, the following limitations from the series of investigations undertaken are acknowledged.

- This thesis reported on the physique characteristics of elite RU athletes. Given the categorisation of “elite” used throughout the thesis, that being athletes of international standard (i.e. national squad) or those participating in the top professional leagues in the world (i.e. Super Rugby), the cohort of athletes available to profile was limited. Using samples of this size confines the inferences that can be made from the data, and thus it may not be representative of, or applicable to, all professional RU athletes, or indeed those at the sub-elite and recreational level. However, increasing the sample size by profiling sub-elite athletes would reduce the specific application of the findings to the target population of elite athletes.
- Given the logistical issues associated with researching athletes from high performance programs, it was not always possible to perform all assessments on the same day. Having a more rigid testing protocol may have produced minor variances in the results. However, given that the timing of assessments in all studies were either within a short time frame (72 hours), or within 7 days during a period characterised by minimal physique changes (i.e. mid-season), it is extremely unlikely the outcomes would have been impacted. Indeed, this was confirmed with statistical analysis.
- The quantification of dietary intake and training loads would have provided the opportunity to further scrutinise the adaptations observed over a pre-season period. Unfortunately, this was simply not possible from a logistical standpoint given that the resources required to collect valid data were not available, and the burden placed on the athletes was deemed unjustifiable by the high performance staff within the organisations. Further, significant challenges exist in being able to quantify high-intensity exercise energy

expenditure, particularly in contact sports where the tools available are not suitable to wear during physical collisions. Finally, given that there is no gold standard assessment of energy intake, any method employed would be subject to considerable error, particularly over a long period in an athletic population.

- Inferences regarding the changes observed over the pre-season period, in both body composition and measures of cardiometabolic health status, may have been better understood if research was extended to include the full annual training cycle, including off-season changes. For example, injuries, off-season surgery, or intensified off-season training programs may have stimulated different adaptations during the pre-season. Also, family medical histories were unknown, as were the specific athlete goals of the training period, both of which may have impacted the observed changes during the period assessed.

FUTURE RESEARCH

From the findings of this thesis emerged several interesting and meaningful directions future research can take in this area.

- Investigations into the relationship between specific body composition characteristics and physical performance testing parameters would further inform high performance practitioners on the most important physique traits athletes need to exhibit, based on position, to improve and excel in RU. Additionally, the relationship between pre-season body composition adaptations and improved performance testing outcomes would further inform such decisions. Moreover, explorations into the relationship between specific whole body and regional body composition characteristics and on-field performance would significantly add to the literature.
- Studies with larger samples of athletes would provide additional insight into the role ethnicity plays within body composition characteristics in RU. Additionally, studies involving athletes from different levels of competition, and possibly from different countries and environments (i.e. Polynesians living in Polynesian countries), would further assist practitioners understand how ethnicity influences RU athletes from both a performance and health perspective.
- The assessment of body composition adaptations in relation to dietary intake and/or quantified training load would provide novel insight into the influence these factors have on physique change, and the underlying reasons for differences based on ethnicity. This would subsequently guide practitioners in athlete training and diet program prescription and management, from both a performance and health standpoint.

- Subsequent research examining changes in body composition over the RU off-season would complement the findings of this research, and possibly provide an explanation for the ethnicity specific results observed regarding LM adaptations over the pre-season. The role that “de-conditioning” in the off-season plays from a cardiometabolic risk assessment standpoint would also provide perspective into the unique physiology of this group of athletes of mixed-ethnicity and heterogeneous physique.
- The development of appropriate reference ranges for VAT and other markers of cardiometabolic disease risk within elite athlete populations would provide an appropriate guide for practitioners to refer to when assessing the health status of “supersized” athletes, given that currently there are no appropriate guidelines.
- Studies investigating the post-career cardiometabolic health status of elite RU athletes would provide an indication of the long-term risk within this population. Of particular interest would be exploring if differences are present in these individuals based on career playing position and/or ethnicity.

FINAL RECOMMENDATIONS

This thesis explored the relationship between ethnicity and physique characteristics in elite RU athletes, including the role that ethnicity plays in the assessment of body composition, adaptations to training stimulus, and the cardiometabolic health status of athletes. The findings from this series of investigations provides high performance sport science practitioners and coaches with valuable information to enable more informed prescription of personalised training and dietary interventions. Further, the findings provide evidence to assist with the development of body composition assessment strategies, and the interpretation of results.

Perhaps the discoveries of most importance moving forward are those pertaining to the role that ethnicity may play in cardiometabolic disease risk in elite athlete populations. Appreciating that Polynesian athletes may be at an increased risk of during- and/or post-career cardiometabolic complications provides sport science and sports medicine practitioners with the opportunity to introduce appropriate interventions to manage the potential risk. Further, the findings indicate post-career health education and follow-up may be required to ensure an athlete's health isn't compromised on leaving the high-performance training environment. This area warrants focused investigation and could be integrated into research currently being undertaken on the implications of concussion episodes for retired RU athletes.

Collectively, the findings presented in this thesis provides novel and previously undocumented information about elite Caucasian and Polynesian RU athletes pertaining to their specific physique traits. The presented findings, along with future investigations on the topics identified, will undoubtedly improve the performance outcomes and health management of these morphologically unique athletes moving forward.

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APPENDIX I – SAME-DAY VERSUS CONSECUTIVE-DAY PRECISION ERROR OF DUAL-ENERGY X-RAY ABSORPTIOMETRY FOR INTERPRETING BODY COMPOSITION CHANGE IN RESISTANCE TRAINED ATHLETES

Zemski AJ¹, Hind K², Keating SE³, Broad EM⁴, Marsh, DJ⁵, and Slater GJ¹. Same-day versus consecutive-day precision error of dual-energy X-ray absorptiometry for interpreting body composition change in resistance trained athletes. *Journal of Clinical Densitometry*. (Under review, revisions submitted September 2018).

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the manuscript including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (70%), KH/GJS (9%), SEK/EM/DJM (4%).
- Conceived and designed the experiment: AJZ, KH, GJS.
- Collected, collated and analysed the data: AJZ, KH, SEK GJS.
- Wrote/reviewed the paper: AJZ, KH, SEK, EMB, DJM, GJS.

ABSTRACT

Introduction: The application of DXA in sport science settings is gaining popularity due to its ability to assess body composition. The ISCD recommends application of the LSC to interpret meaningful and true change. This is calculated from same-day consecutive scans, thus accounting for technical error. However, this approach doesn't capture biological variation which is pertinent when interpreting longitudinal measurements, and could be captured from consecutive-day scans. The aims of this study were to investigate the impact short-term biological variation has on LSC measures, and establish if there is a difference in precision based on gender in a resistance trained population.

Methodology: Twenty-one resistance trained athletes (age 30.6 ± 8.2 years; stature 174.2 ± 7.2 cm; mass 74.3 ± 11.6 kg) with at least 12 months consistent resistance training experience, underwent two consecutive DXA scans on one day of testing, and a third scan the day before or after. ISCD recommended techniques were used to calculate same-day and consecutive-day precision error and LSC values.

Results: There was high association between whole body ($R^2 = 0.98\text{--}1.00$) and regional measures ($R^2 = 0.95\text{--}0.99$) for all same-day ($R^2 = 0.98\text{--}1.00$) and consecutive-day ($R^2 = 0.95\text{--}0.98$) measurements, excluding VAT. The consecutive-day precision error, in comparison to same-day precision error, was almost twice as large for FM (1261 g vs 660 g), and over three times as large for LM (2083 g vs 617 g), yet still remained within the ISCD minimum acceptable limits for DXA precision error. No whole body differences in precision error were observed based on gender.

Conclusion: When tracking changes in body composition, the use of precision error and LSC values calculated from consecutive-day analysis is advocated, given this takes into account both technical error and biological variation, thus providing a more accurate indication of true and meaningful change.

INTRODUCTION

DXA has historically been utilised primarily in clinical settings to quantify BMC and BMD as part of osteoporosis assessment [70]. More recently, DXA has gained popularity in sport science and fitness settings for its ability to assess body composition, incorporating measures of whole body and regional LM and FM, including VAT [2, 377].

Highly trained athletes are likely to exhibit small body composition adaptations over time [87, 228], however these minor changes can have a significant influence on performance outcomes [64]. The ability to confidently quantify these small but potentially important changes in body composition can enable better refinement of interventions, and thus, potentially enhance athletic performance. The ISCD recommends the application of the LSC in the interpretation of longitudinal body composition measurements, which is calculated using same-day repeat scans [223, 247]. LSC quantifies precision based on two consecutive scans, thus identifying the technical error inbuilt into a specific piece of equipment for a given population [223]. However, in practice, longitudinal measures are taken weeks or months apart, and despite following recommended best practice protocols [396], some level of day-to-day biological variation will be present in variables such as hydration status and muscle solute content, both of which impact results [71, 396]. It is unclear what influence these factors have on body composition LSC calculations.

Excellent precision for DXA body composition measures has been published in non-athletic adults for both whole body and regional measures [246, 346, 439, 476]. Varying degrees of precision errors have been reported in athletic populations, with elite male rugby league athletes having established higher precision errors than those reported in other athletes, suggesting size may influence precision error [37, 65, 293]. Presently, there is limited information available on female athletes. This is pertinent given that precision errors should be specific to the population studied, and athletes vary greatly in physique depending on their sport [86]. Sex-specific differences in precision have been

recognised in general populations, with precision error in males being higher for FM, and lower in LM [439]. However, it is unclear whether or not these differences exist in athletic populations given the distinctive physique characteristics resistance trained individuals possess. Furthermore, to date, biological variation has not been explored in resistance trained female athletes, and there is little information about LSC values in this sex-specific population.

The aims of this study were to 1) investigate the impact biological variation has on LSC measures using best practice protocols; 2) establish if there is a difference in precision, and day-to-day biological variation based on gender in a resistance trained population; and 3) establish precision errors specific to a population of resistance trained athletes on a given densitometer, the results of which can be used to infer LSC in future longitudinal assessments.

METHODS

Participants

Twenty-one resistance trained athletes (11 males and 10 females) participated in the study. All participants had been consistently undertaking resistance training for at least 12 months (averaging three resistance based sessions per week). Resistance training modalities included Olympic lifting, body-weight exercises, and free-weights exercises, with training focused on strength and power related enhancements. All participants provided their signed informed consent to undertake the scans, and all local radiologic safety regulations were adhered to.

Study design

Participants underwent two consecutive DXA scans on one day of testing (D1S1, D1S2), and a third scan either the day before or after (D2S1), on a Hologic Discovery A (Hologic, Bedford, MA, USA) using the auto whole body fan beam mode. Participants presented and were scanned following the Nana et al. protocol previously described [396]. Specifically, this included being scanned bladder voided in the early morning after an overnight fast in a rested state. Following the first day of assessment, participants were instructed to remain well hydrated, consume their normal diet, and refrain from exercise to minimise biological variation for the subsequent scan(s) 24 hours later. The participants were positioned on the densitometer in the position recommended by Nana et al., with foam pads utilised to ensure consistency in positioning [396]. When scans were performed on the same day, participants were re-positioned for the repeat scan after dismounting the scanning table. A single trained technologist performed all scans and ROI were manually placed according to the manufacture's instructions. The subsequent analysis was conducted using the Hologic software (Version 13.4.2:3). VAT was calculated after setting the ROI by subtracting SAT in the android region from total fat, after SAT overlaying the visceral cavity is estimated from SAT lateral to the abdominal wall musculature.

This method has been validated against criterion measures elsewhere [284]. Quality control procedures were undertaken daily using a phantom according to the manufacturer's guidelines.

Statistical analysis

Data analysis was performed using Microsoft Excel (Microsoft, Redmond, WA, USA). Descriptive data is reported as the mean $\pm$ SD. Precision is reported as the RMS-SD and %CV, and the resulting LSC with 95% confidence intervals (LSC-95% CI) is calculated following the ISCD protocol [223]. The %CV was derived from the equation $\%CV = (SD/mean) \times 100$. Coefficients of determination (R^2) were calculated between measurements to establish how well fitted lines of regression approximated the other measure. Paired t-tests were utilised to test for differences based on same-day versus consecutive-day scans, and independent t-tests were used to test for differences based on gender. Statistical significance was set at 0.05.

RESULTS

Descriptive statistics for the population are given in Table A.1. Significant sex-specific differences were observed for the majority of regional body composition measures, and whole body BMC, FM and LM.

Table A.2 displays the mean differences between same-day (technical error only) and consecutive-day (technical error and biological variation) scans, as a whole group and also based on sex. Whole body differences between same-day and consecutive-day scans are also shown in Figures A.1–A.3. Regionally, variations in trunk LM and FM, plus whole body LM and FM were significantly different between same-day and consecutive-day scans across most groups. Differences were also observed for variations in leg LM based on gender, with males exhibiting significantly greater differences across same-day (males 490 ± 421 g vs females 153 ± 99 g; $p = 0.024$) and consecutive-day measures (males 629 ± 432 g vs females 238 ± 130 g; $p = 0.013$).

Table A.3 shows the precision error for each region, represented as the %CV, with the RMS–SD and LSC–95% CI. There was excellent agreement between same-day ($R^2 = 0.99$ – 1.00) and consecutive-day measures ($R^2 = 0.98$ – 0.99) of whole body BMC, FM and LM. There was similar agreement for both same-day and consecutive-day measures of regional BMC and LM ($R^2 = 0.98$ – 1.00). Agreement between consecutive-day measures of regional FM ($R^2 = 0.96$ – 0.97) and VAT ($R^2 = 0.94$) was not as strong as same-day measures (FM $R^2 = 0.99$; VAT $R^2 = 0.96$).

Table A.1. Descriptive statistics of the participants.

	All participants (n = 21)		Males (n=11)		Females (n=10)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Age (years)	30.6 ± 8.2	21.3 – 51.1	28.1 ± 6.3	21.3 – 42.2	33.4 ± 9.4	22.6 – 51.1
Stature (cm)	174.2 ± 7.2	160.9 – 183.6	178.9 ± 3.7	173.8 – 183.6	169.1 ± 6.7 ^a	160.9 – 182.8
Mass (kg)	74.3 ± 11.6	57.9 – 98.5	82.9 ± 8.8	69.4 – 98.5	64.8 ± 4.6 ^a	57.9 – 70.9
BMI (kg/m²)	24.4 ± 2.7	19.8 – 29.3	25.9 ± 2.2	22.5 – 29.3	22.8 ± 2.4 ^a	19.8 – 26.4
Arms BMC (g)	421 ± 106	274 – 597	506 ± 61	422 – 597	327 ± 46 ^a	274 – 441
Arms FM (g)	1484 ± 570	943 – 3227	1375 ± 644	943 – 3227	1604 ± 481	1008 – 2528
Arms LM (g)	7379 ± 2453	4555 – 13070	9883 ± 1571	7697 – 13070	5174 ± 564 ^a	4555 – 6153
Trunk BMC (g)	821 ± 180	576 – 1241	934 ± 158	687 – 1241	696 ± 105 ^a	576 – 933
Trunk FM (g)	4911 ± 2109	2876 – 10187	4470 ± 2113	2876 – 10187	5395 ± 2105	3658 – 9760
Trunk LM (g)	29413 ± 5965	22125 – 42985	33748 ± 4800	27461 – 42985	24645 ± 2291 ^a	22125 – 28905
Legs BMC (g)	1023 ± 187	781 – 1370	1175 ± 112	1010 – 1370	854 ± 61 ^a	781 – 966
Legs FM (g)	5565 ± 1974	2316 – 9279	4279 ± 1522	2316 – 7583	6981 ± 1355 ^a	5258 – 9279
Legs LM (g)	19888 ± 4301	13730 – 28072	23414 ± 2496	20352 – 28072	16009 ± 1506 ^a	13730 – 18799
WB BMC (g)	2856 ± 476	2189 – 3804	3216 ± 327	2841 – 3804	2460 ± 227 ^a	2189 – 2803
WB FM (g)	12891 ± 4333	7768 – 22070	11115 ± 4152	7768 – 21988	14846 ± 3804 ^a	11212 – 22070
WB FM (%)	17.6 ± 6.6	9.3 – 31.5	13.2 ± 4.6	9.3 – 24.9	22.4 ± 4.8 ^a	17.0 – 31.5
WB LM (g)	59954 ± 12878	43660 – 87839	70081 ± 8886	59301 – 87839	48814 ± 4191 ^a	43660 – 56101
Android FM (g)	785 ± 410	457 – 1962	771 ± 463	457 – 1962	801 ± 366	485 – 1538
Android FM (%)	16.0 ± 6.9	9.5 – 33.4	13.8 ± 6.5	9.5 – 30.0	18.4 ± 6.9 ^a	13.3 – 33.4
Android FFM (g)	4808 ± 777	3073 – 5529	4642 ± 574	3953 – 5529	3463 ± 407 ^a	3073 – 4253
Gynoid FM (g)	2654 ± 969	1202 – 4789	2033 ± 673	1202 – 3588	3336 ± 772 ^a	2446 – 4789
Gynoid FM (%)	21.4 ± 8.3	9.8 – 36.3	14.9 ± 4.6	9.8 – 24.8	28.6 ± 4.6 ^a	23.2 – 36.3
Gynoid FFM (g)	10053 ± 2081	7109 – 14428	11692 ± 1428	10285 – 14428	8251 ± 684 ^a	7109 – 9664
VAT FM (g)	200 ± 84	89 – 485	252 ± 81	174 – 485	143 ± 37 ^a	89 – 194
VAT Volume (cm³)	216 ± 91	96 – 525	273 ± 88	188 – 525	154 ± 39 ^a	96 – 210
VAT Area (cm²)	42 ± 17	18 – 101	51 ± 17	36 – 101	30 ± 8 ^a	18 – 40

^a Significant difference (<0.05) between males and females.

BMI = body mass index; BMC = bone mineral content; FM = fat mass; LM = lean mass; WB = whole body; VAT = visceral adipose tissue.

Table A.2. Mean difference ($\pm$ standard deviation) between same-day scans (technical error) and consecutive-day scans (technical error and biological variation).

	Same-day (D1S1 / D1S2)			Consecutive-day (D1S1 / D2S1)		
	Technical error			Technical error & biological variation		
	All participants	Males	Females	All participants	Males	Females
Arms BMC (g)	6 $\pm$ 5	6 $\pm$ 5	6 $\pm$ 6	8 $\pm$ 6	8 $\pm$ 5	7 $\pm$ 7
Arms FM (g)	48 $\pm$ 39	55 $\pm$ 37	41 $\pm$ 41	100 $\pm$ 78 ^a	108 $\pm$ 96	92 $\pm$ 57 ^c
Arms LM (g)	113 $\pm$ 90	114 $\pm$ 80	111 $\pm$ 104	175 $\pm$ 133 ^a	167 $\pm$ 134	183 $\pm$ 139 ^c
Trunk BMC (g)	10 $\pm$ 10	14 $\pm$ 11	5 $\pm$ 5 ^d	11 $\pm$ 9	13 $\pm$ 10	8 $\pm$ 7
Trunk FM (g)	141 $\pm$ 106	128 $\pm$ 96	154 $\pm$ 121	242 $\pm$ 204 ^a	236 $\pm$ 181	248 $\pm$ 236
Trunk LM (g)	324 $\pm$ 323	414 $\pm$ 405	224 $\pm$ 167	782 $\pm$ 570 ^a	844 $\pm$ 651 ^b	714 $\pm$ 491 ^c
Legs BMC (g)	21 $\pm$ 20	21 $\pm$ 14	22 $\pm$ 25	21 $\pm$ 17	17 $\pm$ 17	25 $\pm$ 17
Legs FM (g)	185 $\pm$ 93	199 $\pm$ 79	170 $\pm$ 109	249 $\pm$ 216	212 $\pm$ 231	290 $\pm$ 201
Legs LM (g)	330 $\pm$ 350	490 $\pm$ 421	153 $\pm$ 99 ^d	443 $\pm$ 376	629 $\pm$ 432	238 $\pm$ 130 ^e
WB BMC (g)	24 $\pm$ 18	22 $\pm$ 15	27 $\pm$ 22	28 $\pm$ 22	29 $\pm$ 22	27 $\pm$ 24
WB FM (g)	295 $\pm$ 168	314 $\pm$ 137	273 $\pm$ 202	522 $\pm$ 386 ^a	463 $\pm$ 353	588 $\pm$ 428 ^c
WB LM (g)	262 $\pm$ 179	244 $\pm$ 202	281 $\pm$ 160	925 $\pm$ 538 ^a	905 $\pm$ 535 ^b	947 $\pm$ 568 ^c
Android FM (g)	27 $\pm$ 25	25 $\pm$ 24	30 $\pm$ 29	34 $\pm$ 24	40 $\pm$ 27	28 $\pm$ 19
Android FFM (g)	44 $\pm$ 38	51 $\pm$ 41	37 $\pm$ 36	97 $\pm$ 58 ^a	105 $\pm$ 52 ^b	87 $\pm$ 65
Gynoid FM (g)	66 $\pm$ 49	69 $\pm$ 56	63 $\pm$ 43	143 $\pm$ 95 ^a	109 $\pm$ 101	180 $\pm$ 76 ^c
Gynoid FFM (g)	64 $\pm$ 57	53 $\pm$ 43	77 $\pm$ 70	92 $\pm$ 64	85 $\pm$ 69	99 $\pm$ 62
VAT FM (g)	14 $\pm$ 15	10 $\pm$ 11	18 $\pm$ 18	25 $\pm$ 26	16 $\pm$ 13	34 $\pm$ 34
VAT Volume (cm ³)	16 $\pm$ 16	12 $\pm$ 12	20 $\pm$ 19	28 $\pm$ 29	19 $\pm$ 14	38 $\pm$ 37
VAT Area (cm ²)	3 $\pm$ 3	2 $\pm$ 2	4 $\pm$ 4	5 $\pm$ 5	3 $\pm$ 3	7 $\pm$ 7

Data presented mean $\pm$ standard deviation.

D1S1 = day 1 scan 1; D1S2 = day 1 scan 2; D2S1 = day 2 scan 1; BMC = bone mineral content; FM = fat mass; LM = lean mass; WB = whole body; VAT = visceral adipose tissue.

^a Significant difference (<0.05) between same-day and consecutive-day differences in all participants

^b Significant difference (<0.05) between same-day and consecutive-day differences in males

^c Significant difference (<0.05) between same-day and consecutive-day differences in females

^d Significant difference (<0.05) between males and females in the differences in same-day measures

^e Significant difference (<0.05) between males and females in the difference in consecutive-day measures

Table A.3. Precision error for each region, represented as the %CV, with the RMS-SD and LSC-95% CI.

	D1S1 / D1S2		D1S1 / D2S1	
	Technical error		Technical error & biological variation	
	RMS-SD (LSC-95% CI)	%CV (LSC-95% CI)	RMS-SD (LSC-95% CI)	%CV (LSC-95% CI)
Arms BMC (g)	5.6 (15.5)	1.1 (3.0)	6.8 (18.9)	1.3 (3.7)
Arms FM (g)	43.5 (120.5)	2.5 (6.8)	89.1 (246.8)	5.3 (14.5)
Arms LM (g)	101.1 (279.9)	1.2 (3.3)	154.1 (426.7)	1.9 (5.2)
Trunk BMC (g)	9.7 (27.0)	0.8 (2.2)	9.8 (27.1)	0.9 (2.6)
Trunk FM (g)	123.7 (342.5)	2.2 (6.0)	221.3 (612.9)	3.6 (9.9)
Trunk LM (g)	319.4 (884.7)	0.8 (2.1)	678.7 (1880.0)	1.9 (5.3)
Legs BMC (g)	20.2 (56.1)	1.5 (4.2)	18.6 (51.6)	1.5 (4.1)
Legs FM (g)	146.0 (404.4)	2.7 (7.5)	230.7 (639.1)	3.4 (9.5)
Legs LM (g)	335.6 (929.6)	1.1 (3.0)	406.5 (1126.0)	1.5 (4.1)
WB BMC (g)	21.3 (59.0)	0.6 (1.7)	25.2 (69.8)	0.7 (1.9)
WB FM (g)	238.4 (660.4)	1.8 (5.1)	455.2 (1261.0)	2.9 (8.0)
WB LM (g)	222.7 (616.8)	0.3 (0.9)	752.0 (2083.0)	1.1 (3.2)
Android FM (g)	26.1 (72.3)	2.6 (7.3)	29.0 (80.5)	3.5 (9.7)
Android FFM (g)	40.9 (113.4)	0.8 (2.1)	79.1 (219.2)	1.7 (4.7)
Gynoid FM (g)	57.8 (160.1)	2.1 (5.8)	120.2 (333.0)	4.0 (10.9)
Gynoid FFM (g)	60.1 (166.5)	0.5 (1.4)	78.4 (217.3)	0.7 (1.9)
VAT FM (g)	12.7 (35.0)	5.3 (15.3)	18.0 (50.0)	7.2 (20.0)
VAT Volume (cm³)	13.7 (37.9)	5.5 (15.4)	19.5 (54.1)	7.3 (20.2)
VAT Area (cm²)	2.6 (7.3)	5.5 (15.3)	3.7 (10.4)	7.3 (20.2)

RMS-SD = root-mean-square standard deviation; %CV = percent coefficient of variation; LSC = least significant change; D1S1 = Day 1 Scan 1; D1S2 = Day 1 Scan 2; D2S1 = Day 2 Scan 1; BMC = bone mineral content; FM = fat mass; LM = lean mass; WB = whole body; VAT = visceral adipose tissue.

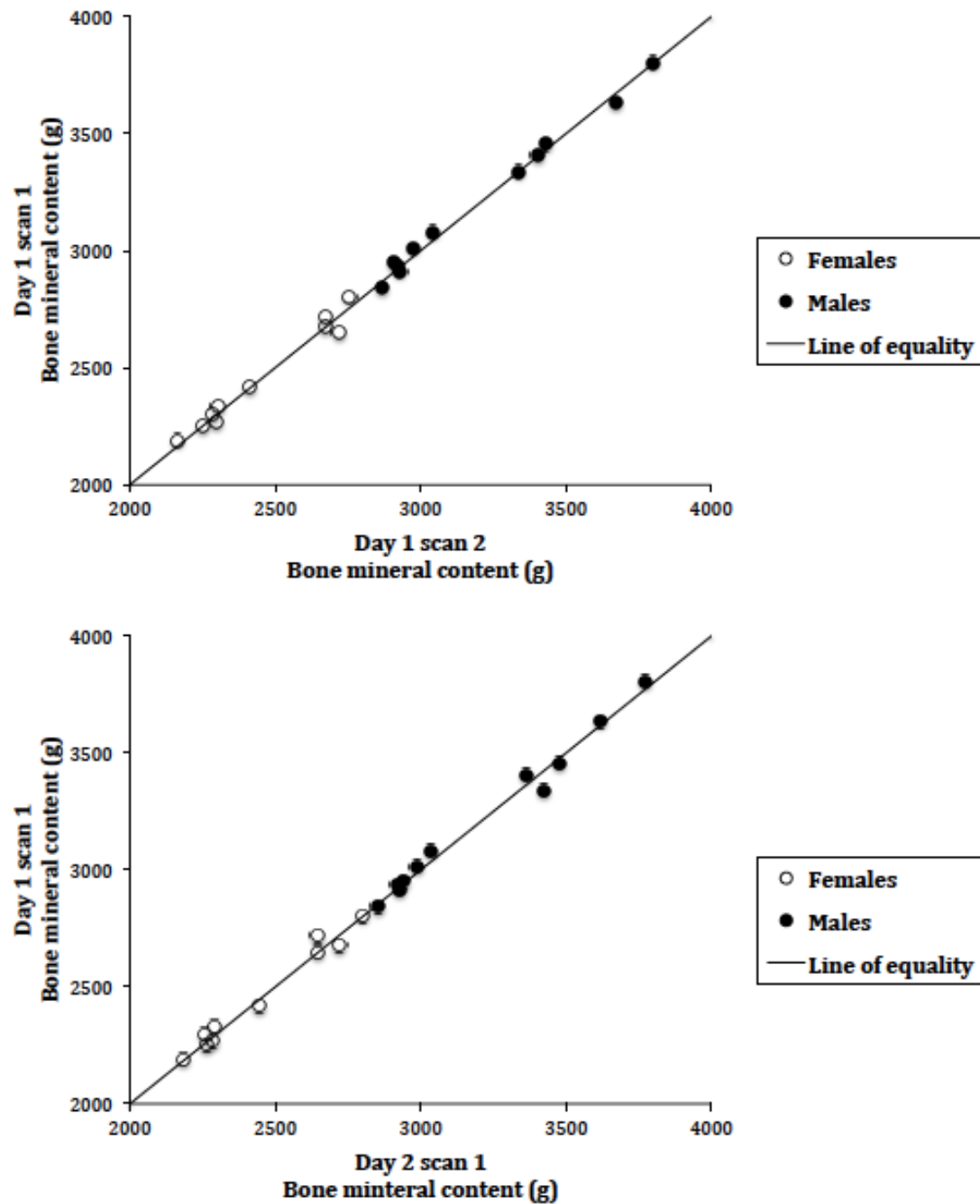


Figure A.1. The regressions between measures of bone mineral content for same-day (top) and consecutive-day (bottom) precision.

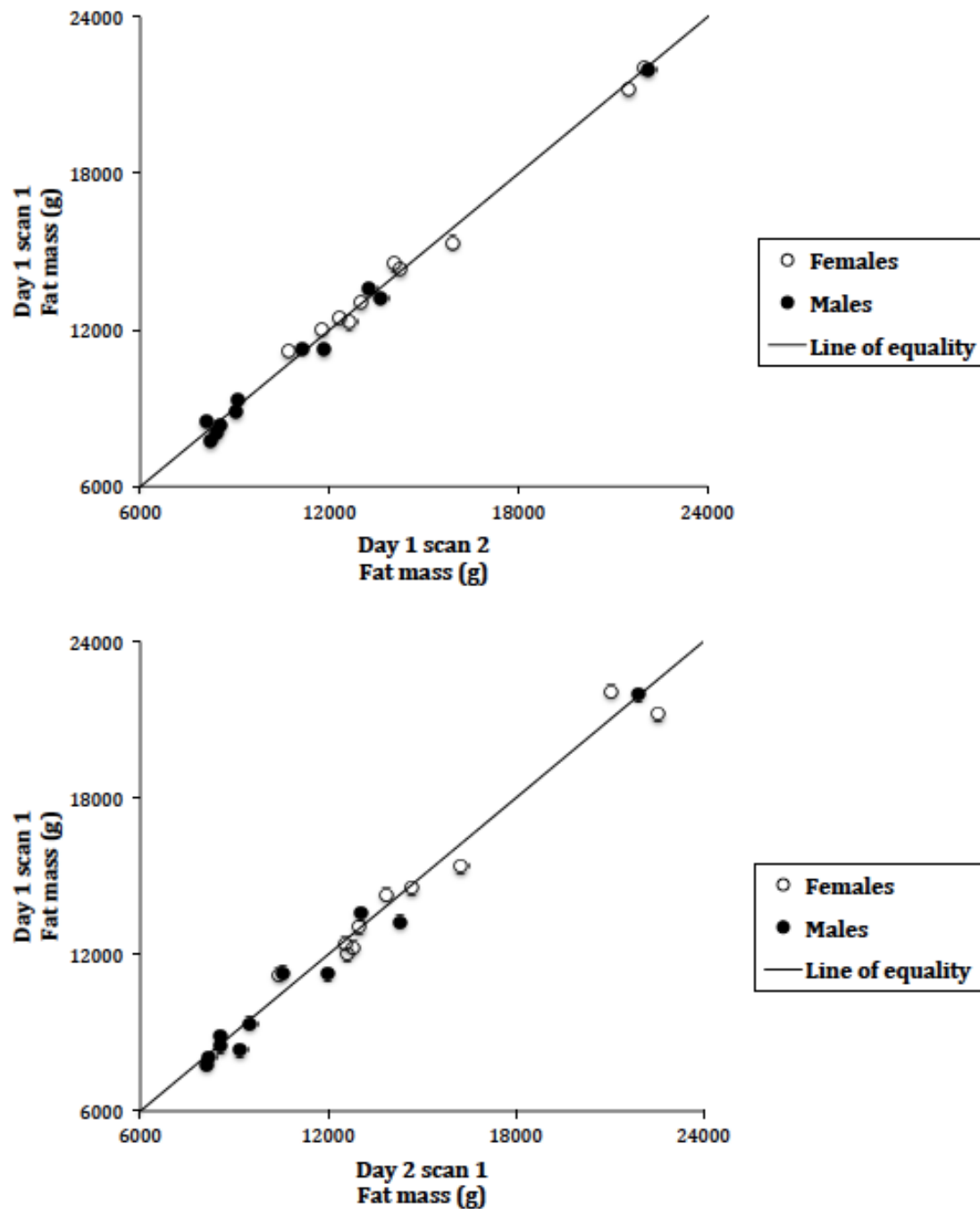


Figure A.2. The regressions between measures of fat mass for same-day (top) and consecutive-day (bottom) precision.

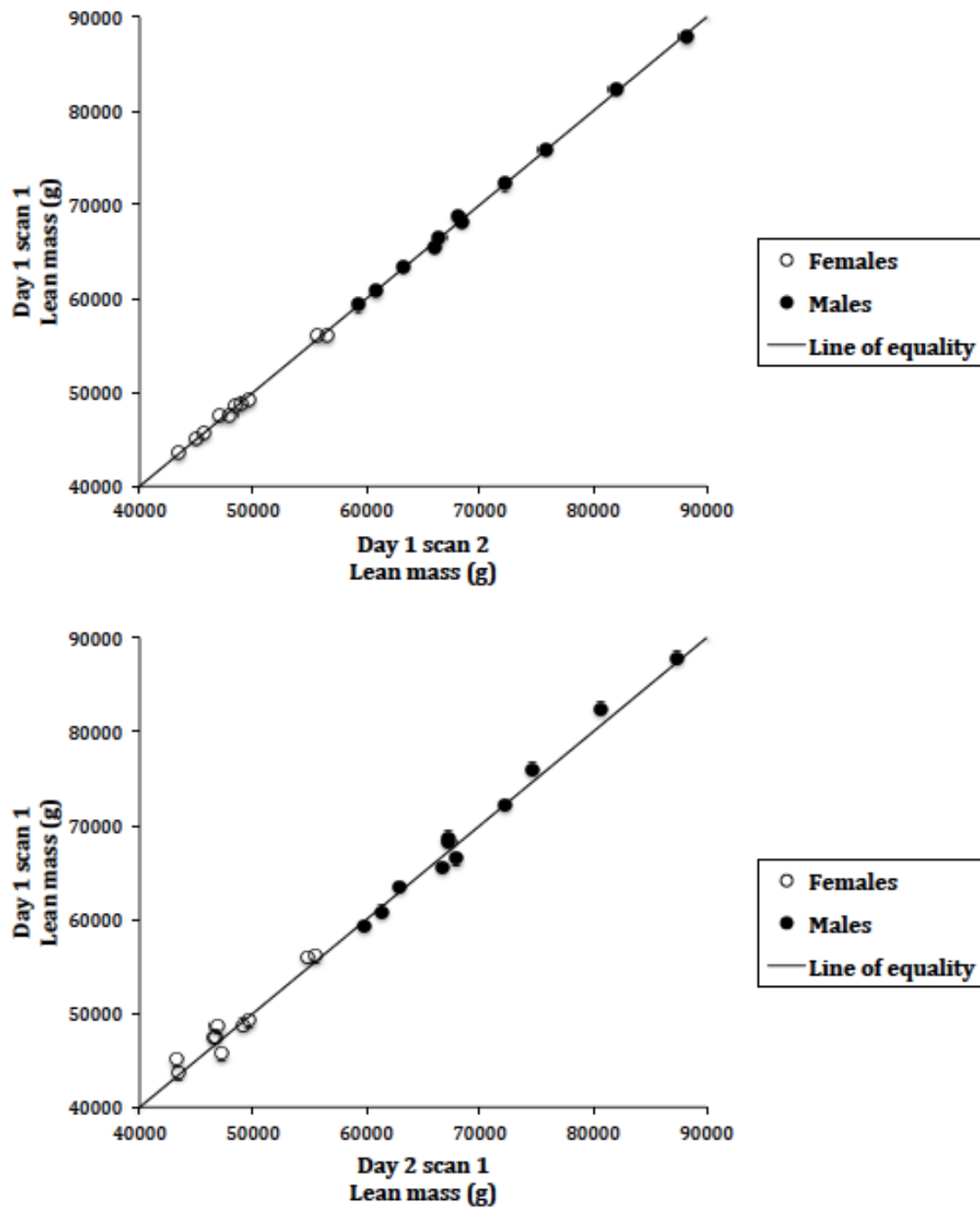


Figure A.3. The regressions between measures of lean mass for same-day (top) and consecutive-day (bottom) precision.

DISCUSSION

The primary finding of this study was that substantial differences were observed between same-day (technical error) and consecutive-day precision error (technical error and biological variation) for body composition in a resistance trained population. Consecutive-day precision error was almost twice as large for FM, and over three times as large for LM. Given that longitudinal monitoring of body composition will include both technical error and biological variation, the use of consecutive-day precision error is advocated.

Same-day precision was excellent for whole body BMC (CV 0.6%, LSC 1.7%) and LM (CV 0.3%, LSC 0.9%), and higher for FM (CV 1.8%, LSC 5.1%). Previously, studies have investigated either short-term (same-day) precision, which measures technical error [37, 246, 293], or long-term precision, which takes into account both technical error and biological variation [439]. Same-day precision errors were similar to those found on a Lunar iDXA for BMC (CV 0.6%, LSC 1.7%) and LM (CV 0.5%, LSC 1.4%), however, FM on the iDXA was considerably lower (CV 0.8%, LSC 2.3%) [246]. In comparison, the short-term precision (same-day and consecutive-day) identified in this study is better than the long-term precision errors previously reported when inferred over periods of 3-51 days [439]. This is unsurprising given significant body composition adaptations can be achieved in as little as 4-weeks in elite athletes [17], drawing into question the validity of such long-term precision error estimates.

The ISCD advocates LSC is calculated for body composition indices before any quantitative statement of change can be made for FM and LM measures [223]. To our knowledge this is the first study to explore short-term biological variation as part of LSC calculations on body composition, to account for possible biological variation observed over 24 hours, in conjunction with technical error. Biological variation can arise from fluctuations in gastrointestinal content, total body water content, and glycogen reserves, in particular on the measurement of LM [71, 293, 393, 553]. This is particularly relevant in resistance trained individuals who have the potential for larger fluctuations in hydration status and intramuscular

solutes such as creatine and glycogen over a short time frame [71, 433]. Our consecutive-day testing resulted in wider precision errors for FM (CV 1.8% vs 2.9%, LSC 5.1% vs 8.0%) and LM (CV 0.3% vs 1.1%, LSC 0.9% vs 3.2%), indicating small amounts of biological variation despite use of best practice protocols [396], and instructions to the participants to eat normally and not exercise between consecutive-day scans. Nevertheless, it should be noted that the consecutive-day precision errors in the current study were within the acceptable limits for DXA precision as identified by the ISCD which are 3% for FM and 2% for LM [223]. Further, the precision error values were similar to those found in a number of studies as recently reviewed [247].

Accounting for biological variation in addition to technical error significantly widened the LSC for LM and FM, but not for BMC, in this resistance trained population (Table A.3). However, we consider it valid to incorporate the biological variation observed over a single day into LSC values, to ensure that when longitudinal changes are being interpreted, true changes are able to be identified. Indeed, the consecutive-day LSC values presented here have successfully been used to interpret changes in physique traits in resistance trained individuals over a 12 week period [618]. Furthermore, these findings are similar to those reported for bone mineral density, in that same-day precision underestimated true variability, which could potentially result in an incorrect interpretation of longitudinal change [296].

Same-day regional precision in this study was similar to that observed in previous studies performed in a general population [245], student athletes [86] and elite rugby league athletes [37]. Precision was better for BMC (CV 0.8–1.5%) and LM (CV 0.8–1.2%) in all regions compared to FM (CV 2.1–2.7%). Further, the trunk region exhibited the greatest regional variation, which agrees with reports elsewhere [37, 340]. VAT measures had moderate same-day and consecutive-day precision errors (CV same-day 5.3% vs consecutive-day 7.2%), with a high LSC (same-day 15.3% vs consecutive-day 20.0%). In this study, consecutive-day regional precision was similar to same-day precision for BMC in all areas,

however the CV was considerably higher for regional FM (CV 3.4–5.3%) and LM (CV 1.5–1.9%) measures.

It has been advocated that the LSC values applied should be specific to the athletic population being assessed [86]. Given the potential for marked differences in physique between males and females, sex-specific precision should be explored. No whole body differences in same-day or consecutive-day precision error were observed between males and females. Prior to our study there has only been one investigation of the short-term precision of DXA for body composition assessment in female athletes. The reported precision errors in that study for LM (CV 0.8%) and FM (CV 2.1%) were similar to that found in this present study, although in the previous investigation only 3 athletes were tested using a same-day protocol [523]. In the present study, whole body BMC, FM and LM precision errors were not significantly different to males, with the only sex-specific differences occurring for leg LM and trunk BMC (Table A.2). This is perhaps in part due to similarities in training of the participants. Despite this, the quantification of precision error specific to the athletic population being investigated likely remains warranted, especially in populations with physique extremes [247].

CONCLUSION

In a population of resistance trained athletes, consecutive-day precision error was almost twice as large for whole body FM, and over three times as large for whole body LM. Despite this, the Hologic Discovery A Densitometer provided acceptable precision error for whole body measures of BMC, LM, and FM, which remained within the ISCD minimum acceptable limits. When tracking changes in body composition, it would seem pertinent to use precision error and LSC values calculated from consecutive-day analysis, given this takes into account both technical error and biological variation, and both contribute to precision when interpreting longitudinal change.

APPENDIX II – POSTER PRESENTATION, INTERNATIONAL SPORT AND EXERCISE NUTRITION CONFERENCE 2012. NEWCASTLE, UK

Zemski AJ^{1,2}, Slater GJ^{2,3} and Broad EM¹. Estimating body composition in elite rugby union athletes using surface anthropometry. *International Journal of Sport Nutrition and Exercise Metabolism*. 2013; 23: S7-8.

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the poster/abstract including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (80%), GJS/EMB (10%).
- Conceived and designed the experiment: AJZ, GJS, EMB.
- Collected and collated the data: AJZ, GJS.
- Analysed the data: AJZ, GJS, EMB.
- Wrote/reviewed the poster/abstract: AJZ, GJS, EMB.

ABSTRACT

Body composition monitoring is routinely performed in elite athlete populations due to its well reported relationship to competitive success. Due to its low cost, portability and practicality, SA is the preferred method of body composition measurement in the field. However, the validity of generic equations for estimating body composition from anthropometric data has been questioned. The present study aims to compare available “skinfold equation” derived data against DXA data on a group of international RU athletes. Between May 2009 and August 2012 anthropometric data was collected on seventy-five professional RU athletes. This was collected between one and seven times on each athlete according to ISAK standards, by a single experienced anthropometrist, using a standardised protocol. On each occasion anthropometric data was collected a DXA scan was undertaken within seven days. The DXA scans were done using either a loosely standardised protocol, or a well standardised protocol. The skinfold data was used to predict BF% using equations specific to males derived using Harpenden calipers and sites specified by ISAK, and compared to the corresponding DXA generated BF%. Statistical analysis was undertaken using the Bland Altman method for assessing agreement between two methods of measurement taking into account multiple observations per individual. Data analysis revealed using the majority of equations available anthropometric data underestimated BF% compared to DXA. The analysis also suggested that using a well standardised DXA protocol decreases variability between the two methods. The results indicate specific equations should be established to predict BF% from SA data in professional RU athletes, using a well standardised DXA protocol to increase the strength of the derived equations.

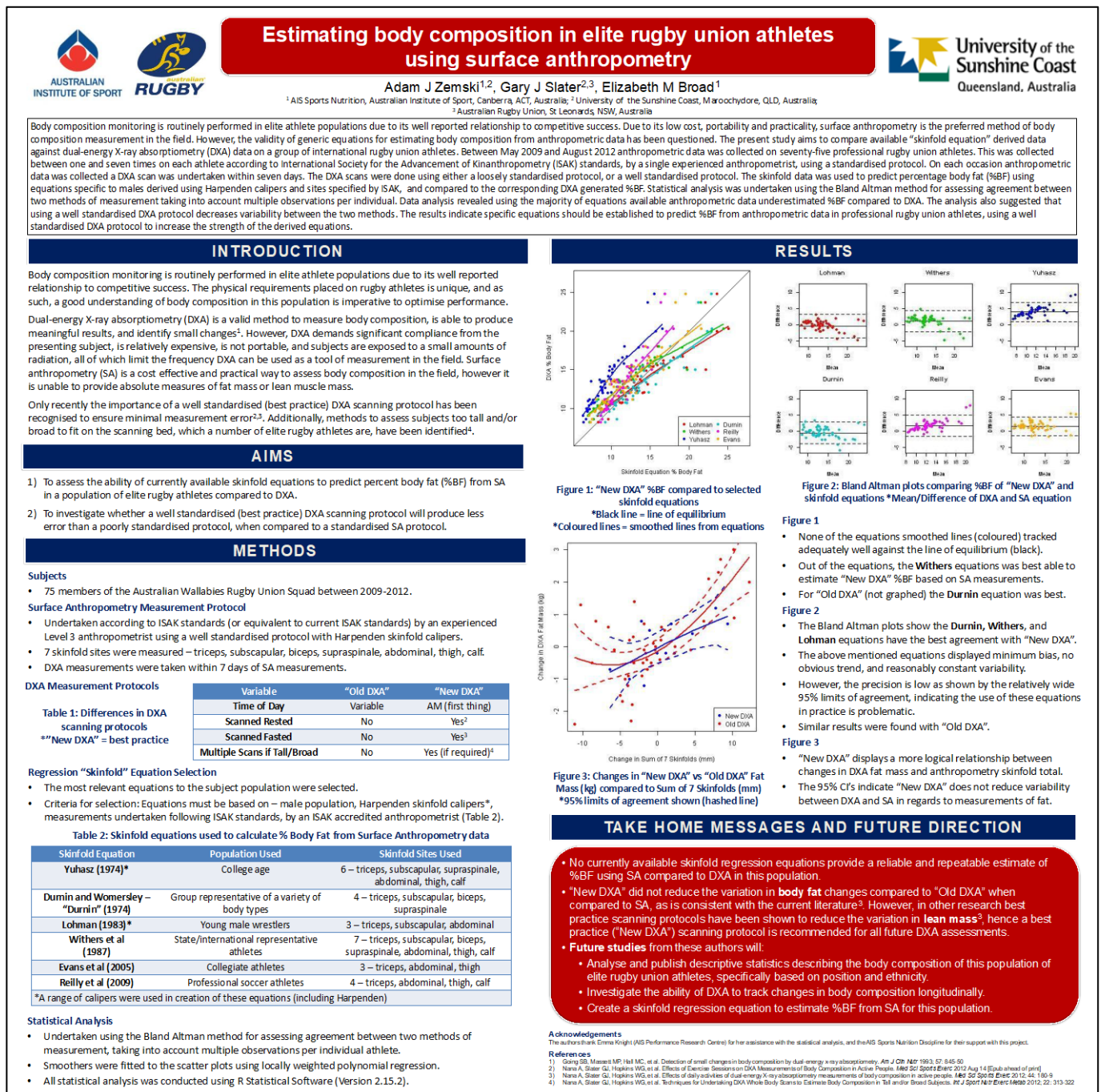


Figure A.4. Poster presented at the International Sport and Exercise Nutrition Conference 2012, Newcastle, UK.

APPENDIX III – POSTER PRESENTATION, SPORTS DIETITIANS AUSTRALIA CONFERENCE 2013. MELBOURNE, AUSTRALIA

Zemski AJ^{1,2}, Slater GJ^{2,3}, Broad EM¹, and Chaseling J⁴. Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity.

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Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the poster including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: AJZ (75%), GJS/EMB (10%), JC (5%).
- Conceived and designed the experiment: AJZ, GJS, EMB.
- Collected and collated the data: AJZ, GJS.
- Analysed the data: AJZ, GJS, JC.
- Wrote/reviewed the poster: AJZ, GJS, EMB.



Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity



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Introduction: Body composition monitoring is routinely performed on elite rugby athletes due to its well reported relationship to competitive success. Differences according to playing position – forwards (F) and backs (B) – have been previously described, however little is known about the body composition differences between Caucasian (C) and non-Caucasian (NC) athletes. **Methodology:** Body composition data was collected on forty professional rugby union athletes. Anthropometric measurements were taken in conjunction with a dual-energy X-ray absorptiometry (DXA) scan. Differences according to playing position and ethnicity were investigated using a factorial analysis of variance with age as a covariate. Three athletes were identified as outliers and removed from the analysis. **Results and Discussion:** Differences were found between F and B across a number of anthropometric and DXA measures. There were no differences between C and NC athletes when assessed for whole body composition. Using absolute measures of lean and fat mass, significant main effect differences were found according to position, with no differences noted according to ethnicity. Using DXA, according to position, few differences in regional distribution patterns of lean and fat mass were found, but there were differences found according to ethnicity. C and NC athletes had different peripheral lean mass (48.6 ± 1.2 vs 49.7 ± 1.2 kg; $p=0.040$) and fat mass (51.3 ± 3.1 vs 53.1 ± 3.7 kg; $p=0.052$) distribution, and trunk lean mass (46.8 ± 1.1 vs 45.6 ± 1.0 kg; $p=0.020$) and fat mass (39.5 ± 3.5 vs 37.2 ± 3.0 kg; $p=0.019$) distribution. These regional fat mass distribution differences were not seen when using surface anthropometry skinfolds as the measure, indicating that C and NC athletes may have different regional storage patterns of visceral and subcutaneous fat mass. **Conclusion:** The distribution of regional body composition appears to be different between ethnicities. This warrants further investigation, especially in relation to the potential impact on performance traits such as running economy and peak speed. It also brings into question the use of non-ethnic specific regression equations using surface anthropometry to infer total body composition.

INTRODUCTION

Rugby union is a full contact team sport characterised by short bursts of high intensity running, heavy tackling and body contact, interspersed with periods of recovery. It requires a unique combination of strength, skill, speed and endurance from the athletes¹.

Body composition monitoring is routinely performed in elite rugby populations due to its well reported relationship to competitive success. The assessment techniques of choice are dual-energy X-ray absorptiometry (DXA) and surface anthropometry.

Body composition differences according to playing position have previously been described². Body composition differences between sedentary people of different ethnicities have been reported³, but this has not been investigated in elite athletic populations.

The physical requirements placed on rugby athletes are unique, and as such, a good understanding of body composition traits according to playing position and ethnicity in this population is imperative to manipulate training and dietary programs to optimise performance.

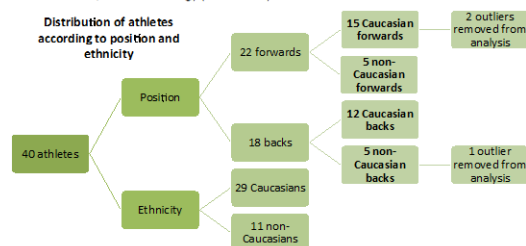
AIM

To ascertain the differences in body composition – including regional lean mass and fat mass absolute amounts, and distribution – between elite Caucasian and non-Caucasian rugby athletes of different on-field playing positions.

METHODS

Subjects

Body composition data was collected on forty professional rugby union athletes from the Australian national squad, the Wallabies, in the year 2012. Three athletes were identified as outliers and removed from the statistical analysis, leaving thirty-seven athletes (25.4 ± 3.1 yrs, 187.2 ± 7.9 cm, 102.5 ± 12.2 kg) (mean $\pm$ SD).



Body Composition Measurement Protocol

	DXA	Surface Anthropometry
Equipment	Hologic Discovery A scanner Apex 12.7.3 software	Harpenden skinfold callipers A&D Mercury electronic scales
Equipment Calibration	Daily before measurement using phantoms as per manufacturer guidelines	As per manufacturer guidelines
Technician	Single qualified and experienced DXA scanning technician	Single experienced and Level 3 ISAK accredited anthropometrist
Measurement Protocol	As per techniques described to maximise technical reliability and minimise error ^{4,5}	As per ISAK standards – using 7 skinfold sites (triceps, subscapular, biceps, supraspinale, abdominal, mid thigh, medial calf) and duplicate/triplicate measures
Time Of Day	First thing in the morning prior to food, fluid, or exercise	Mass taken first thing in the morning prior to food, fluid, or exercise Skinfolds taken mid-afternoon
Proximity To Other Measure	Measurements were taken within 7 days of each other	

Classification Of Ethnicity

Ethnicity was self described by the athletes, with either three or four grandparents being of the chosen ethnic descent.

Statistical Analysis

A factorial analysis of variance using age as a covariate was undertaken on the data. The means reported are arithmetic means, whilst the testing was done on the adjusted means. Three athletes were removed from the statistical analysis as they were identified as outliers.

RESULTS

Whole Body Composition Results (mean $\pm$ SD)

- Statistically significant differences were found between forwards (F) and backs (B) using both surface anthropometry and DXA measures, similar to what has been previously described².
- No significant differences were seen between Caucasians (C) and non-Caucasians (NC).

	Position		Ethnicity	
	F	B	C	NC
Height (cm)	191.0 $\pm$ 7.5	182.6 $\pm$ 5.6	187.8 $\pm$ 7.3	185.5 $\pm$ 9.5
Mass (kg)	111.7 $\pm$ 8.0	91.7 $\pm$ 5.6	101.4 $\pm$ 10.8	105.3 $\pm$ 15.9
BMI	30.6 $\pm$ 2.2	27.5 $\pm$ 1.4	28.7 $\pm$ 1.9	30.5 $\pm$ 3.2
Sum 7 Skinfolds (mm)	73.1 $\pm$ 12.2	49.0 $\pm$ 7.4	62.0 $\pm$ 15.9	62.1 $\pm$ 16.6
LMI	61.3 $\pm$ 4.2	53.3 $\pm$ 3.6	57.1 $\pm$ 5.0	59.1 $\pm$ 7.1
Bone Mass (kg)	4.5 $\pm$ 0.4	3.9 $\pm$ 0.4	4.1 $\pm$ 0.5	4.4 $\pm$ 0.7
Bone Mass %	4.0 $\pm$ 0.3	4.2 $\pm$ 0.3	4.0 $\pm$ 0.3	4.1 $\pm$ 0.3
Lean Mass (kg)	92.2 $\pm$ 6.1	79.1 $\pm$ 5.2	85.3 $\pm$ 7.7	88.6 $\pm$ 11.1
Lean Mass %	81.8 $\pm$ 1.8	85.2 $\pm$ 1.4	83.4 $\pm$ 2.3	83.2 $\pm$ 2.7
Fat Mass (kg)	16.1 $\pm$ 2.7	9.9 $\pm$ 1.6	13.1 $\pm$ 3.6	13.8 $\pm$ 4.7
Fat Mass %	14.2 $\pm$ 1.7	10.7 $\pm$ 1.5	12.6 $\pm$ 2.3	12.6 $\pm$ 2.8

Interaction Effect for Position*Ethnicity ($p<0.05$)
Main Effect for Position ($p<0.05$)
Main Effect for Ethnicity ($p<0.05$)

BMI = Body Mass Index
mass (kg) / height² (cm)
LMI = Lean Mass Index
mass (kg) / sum 7 skinfolds^{0.14} (mm)

Regional Body Composition Results (mean $\pm$ SD)

- Statistically significant differences were found according to position when looking at regional body composition distribution of lean and fat mass in absolute amounts (kg), in both the peripheral and trunk regions.
- There is a significant interaction between position and ethnicity in absolute lean peripheral (kg), with NC F having a greater absolute amount than C F (49.6 ± 1.9 kg, 43.8 ± 2.8 kg; $p=0.22$).
- According to ethnicity, significant differences were found in proportional regional distribution patterns (%) of lean and fat mass in both the peripheral and trunk regions.

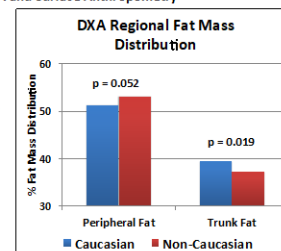
		Position		Ethnicity	
		F	B	C	NC
Peripheral (Arms + Legs)	Lean (kg)	45.3 $\pm$ 3.7	38.5 $\pm$ 2.6	41.4 $\pm$ 3.8	44.0 $\pm$ 6.3
	Lean %	49.1 $\pm$ 1.5	48.7 $\pm$ 1.0	48.6 $\pm$ 1.2	49.7 $\pm$ 1.2
	Fat (kg)	8.5 $\pm$ 1.6	5.0 $\pm$ 0.9	6.7 $\pm$ 1.9	7.4 $\pm$ 2.8
	Fat %	52.8 $\pm$ 3.8	50.7 $\pm$ 2.2	51.3 $\pm$ 3.1*	53.1 $\pm$ 3.7*
Trunk	Lean (kg)	42.7 $\pm$ 2.8	36.8 $\pm$ 2.7	39.9 $\pm$ 3.9	40.3 $\pm$ 4.6
	Lean %	46.4 $\pm$ 1.4	46.5 $\pm$ 1.0	46.8 $\pm$ 1.1	45.6 $\pm$ 1.0
	Fat (kg)	6.4 $\pm$ 1.4	3.8 $\pm$ 0.7	5.2 $\pm$ 1.7	5.2 $\pm$ 1.9
	Fat %	39.5 $\pm$ 4.0	38.1 $\pm$ 2.7	39.5 $\pm$ 3.5	37.2 $\pm$ 3.0

Interaction Effect for Position*Ethnicity ($p<0.05$)
Main Effect for Position ($p<0.05$)
Main Effect for Ethnicity ($p<0.05$)

* Narrowly missed significance ($p=0.052$)

Regional Fat Mass Distribution Patterns Using DXA and Surface Anthropometry

- When looking at fat mass regional distribution patterns there were no significant differences found according to position between F and B.
- No significant differences were seen in fat mass regional distribution patterns between C and NC using surface anthropometry, however some differences were seen when using DXA measures (see graph).
- This may be due to the fact surface anthropometry only measures subcutaneous fat mass, indicating athletes from different ethnicities may have different regional subcutaneous and visceral fat storage patterns.



TAKE HOME MESSAGES

- As previously reported, forwards and backs have very different body composition traits to allow them to perform their position specific on-field tasks.
- Caucasian and non-Caucasian athletes have significantly different regional lean mass and fat mass distribution patterns in the peripheral and trunk body regions.
- As DXA and surface anthropometry measures of fat distribution differ between C and NC athletes, there may be differences in the regional storage of fat deposits in terms of subcutaneous and visceral fat.
- Future investigation is warranted due to potential impact on performance traits such as running economy and peak speed. It also brings into question the use of non-ethnic specific regression equations using surface anthropometry to infer total body composition.

Acknowledgements

The authors thank Emma Knight (AIS Performance Research Centre) for her assistance with the statistical analysis, and the AIS Sports Nutrition Discipline for their support with this project.

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Figure A.5. Poster presented at the Sports Dietitians Australia Conference 2013, Melbourne, Australia.

APPENDIX IV – ORAL PRESENTATION, SPORTS MEDICINE AUSTRALIA CONFERENCE 2017. LANGKAWI, MALAYSIA

Keating SE¹, Zemski AJ^{2*}, Broad EM³, Marsh DJ⁴, and Slater GJ^{2,5}. Ethnic differences in visceral adipose tissue and markers of cardiometabolic disease risk in elite rugby union athletes. *Journal of Science and Medicine in Sport*. 2017; 20: 62.

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*Study forms part of the research towards PhD

Student contribution to work – involved in the conception of the study, involved in the collection and collation of all data, analysed and interpreted data, was responsible for writing the first draft of the presentation/abstract including preparation of all figures/tables, and modified drafts following co-author recommendations.

- Intellectual contribution: SEK/AJZ (41%), EMB/DJM/GJS (6%).
- Conceived and designed the experiment: SEK, AJZ, DJM, GJS.
- Collected and collated the data: SEK, AJZ, DJM, GJS.
- Analysed the data: SEK, AJZ.
- Wrote/reviewed the presentation/abstract: SEK, AJZ, EMB, DJM, GJS.
- Delivered the presentation: SEK.

ABSTRACT

Background: RU athletes display unique, position-specific body composition characteristics. Evidence suggests that Caucasian and Polynesian athletes exhibit differences in regional FM distribution; however, specific differences in SAT and metabolically detrimental VAT have not been explored. While some evidence suggests that heavy-weight athletes have higher VAT than other athletes, no studies have quantified VAT in RU players using gold-standard imaging methods. We investigated the differences in VAT and SAT volume, and markers of cardiometabolic risk, in elite Caucasian and Polynesian RU athletes at the commencement of pre-season.

Methods: Twenty-two elite male RU athletes (age 22.8 ± 3.2 years, stature 186.8 ± 8.4 cm, BM 101.5 ± 13.7 kg; forwards $n = 11$, backs $n = 11$) of Caucasian ($n = 11$) and Polynesian ($n = 11$) descent were recruited. VAT and SAT volumes were quantified via MRI. Total-body and regional FM were quantified via DXA. Blood samples were collected after an overnight fast for: TC, HDL-C and LDL-C, TG, glucose and insulin. Independent t-tests evaluated differences between ethnicities and between positions. Pearson correlations determined associations between VAT and blood markers.

Results: When compared with Caucasian participants, Polynesians exhibited significantly higher levels of VAT (777 ± 611 cm³ vs 425 ± 236 cm³, $P = 0.04$) and android fat ($19.4 \pm 5.0\%$ vs $14.5 \pm 3.8\%$, $P = 0.02$) and tended to have higher levels of SAT (3423 ± 1529 cm³ vs 2289 ± 1025 cm³, $P = 0.056$), but not total FM ($P = 0.30$). LDL-C was significantly higher in Polynesian participants ($P = 0.02$) with trends for higher TC ($P = 0.057$) and TG ($P = 0.051$); however, means were within normal reference ranges. When grouped by position, forwards had significantly higher SAT than backs (3727 ± 1415 cm³ vs 1986 ± 652 cm³, $P = 0.002$), but there were no differences in VAT ($P = 0.455$). Higher VAT was associated with higher TC ($r = 0.62$, $P = 0.002$), LDL-C ($r = 0.52$, $P = 0.01$) and TG ($r = 0.60$, $P = 0.003$).

Discussion: Ethnicity-specific differences exist in the distribution of body fat in elite RU athletes, with Polynesians exhibiting higher VAT than Caucasians, which was associated with higher levels of blood lipids and lipoproteins. Given differences in overall body fat was not seen between the ethnicities, and higher VAT levels were not linked with the larger athletes (forwards), ethnicity may specifically play a role in increased metabolic risk, even in elite athletic populations. While adiposity levels were below values for increased risk, this may have implications post-career for Polynesian athletes.

APPENDIX V – DATA COLLECTION METHODOLOGY: SURFACE ANTHROPOMETRY

This methodology has been adapted from other sources [121, 357, 410]. Images to accompany the descriptions included in this Appendix are available within these references for those unfamiliar with the protocols, anatomy and terminology.

Person to take measurement

Anthropometrist with Level 3 ISAK qualifications.

Place measurement taken

An area within the training facility where there is adequate room for the testing to be undertaken.

Materials required

- Skinfold calipers (Harpender calipers, British Indicators, Hertfordshire, UK)
- Self-retracting, flexible metal anthropometry tape (Lufkin W606 2 m tape measure, Maryland, USA)
- Stadiometer (Seca 213, Birmingham, UK)
- Body mass scales (A&D Mercury, Adelaide, Australia)
- Segmometer
- Anthropometry box (dimensions 40 cm x 50 cm x 30 cm), or similar
- Marker pen
- Alcohol swabs

Procedure

Pre-test protocol

For the measurement of body mass and stature, participants were instructed to present in a well-hydrated state after an overnight fast, with no physical activity for the previous 8 hours. The bladder was emptied and all metal objects removed. Body mass and stature measurements were made at the same time of day, upon waking, before breakfast or training, but after voiding the bladder. Measurements were taken wearing minimal clothing so as to minimise the influence of extraneous factors that could impact on body mass.

For the assessment of anthropometric measures appropriate clothing was worn. This included minimal clothing that allowed access to the skin on the upper thigh, stomach and upper back. Thin material shorts (i.e. bike shorts) were worn to improve the accuracy of girth measurements. The time of day anthropometric measures were taken was kept consistent.

Marking up

Specific anatomical landmarks were identified and marked on the participant's body before measuring and recording the subcutaneous skinfold thickness at each site. The protocol for the collection and use of surface anthropometry data was developed by ISAK. It relates specifically to the measurement of subcutaneous fat thickness via the use of skinfold measures. All measurements were taken on the right side of the body.

Acromiale

- Definition: the point on the superior aspect of the most lateral part of the acromion border.
- Location: the anthropometrist stood behind and on the right side of the participant, and palpated along the spine of the scapula to the corner of the acromion. This represents the start of the lateral border which usually runs anteriorly, slightly superiorly and medially. The straight edge of a pen was applied to the lateral and superior aspect of acromion to confirm the location of the most lateral part of the border. The anthropometrist palpated superiorly to the top margin of the acromion border in line with the most lateral aspect and marked this most lateral aspect. NB: the most lateral part of the acromion border was typically slightly posterior to the midline of the shoulder.

Radiale

- Definition: the point at the proximal and lateral border of the head of the radius.
- Location: the anthropometrist palpated downward into the lateral dimple of the right elbow. It was possible to feel the space between the capitulum of the humerus and the head of the radius. The thumb was moved distally onto the most lateral part of the proximal radial head, and a small indentation on the skin was made at this point with the thumbnail for accurate marking. Correct location was checked by slight rotation of the forearm which caused the head of the radius to rotate.

Acromiale-radiale

- Definition: the linear distance between the acromiale and radiale sites.
- Location: the participant assumed a relaxed standing position with the arms hanging by their sides and the right forearm pronated. Using a segmometer instead of a tape allowed for clearance of the deltoids. One branch of the segmometer was anchored on the acromiale while the other branch was placed on the radiale. This represented the upper arm length. This length was needed to identify the mid-acromiale-radiale landmark.

Mid-acromiale-radiale

- Definition: the mid-point of the straight line joining the acromiale and the radiale.
- Location: the linear distance between the acromiale and radiale was measured with the arm relaxed and extended by the side. This distance was measured using a segmometer as it was not acceptable to follow the curvature of the arm with a tape measure. The lower edge of the segmometer was brought up to the level of the mid-point between these two landmarks and a small indentation on the skin with the instrument was made. A small horizontal mark was made at this point.

Triceps skinfold site

- Definition: the point on the posterior surface of the arm in the mid-prone position, in the mid-line, at the level of the marked mid-acromiale-radiale landmark.
- Location: using a tape measure, the mid-acromiale-radiale site was projected perpendicularly to the long axis of the arm around the back of the arm. The projected line intersected with a vertical line in the middle of the arm when viewed from behind.

Biceps skinfold site

- Definition: the point on the anterior surface of the arm, in the mid-prone position, at the level of the mid-acromiale-radiale landmark, in the middle of the muscle belly.
- Location: similar to the triceps skinfold site, using a tape measure, the mid-acromiale-radiale site was projected perpendicularly to the long axis of the arm around to the front of the arm, and intersected with a projected vertical line in the middle of the muscle belly when viewed from the front. NB: this may be medial from the mid-line of the anterior surface of the arm.

Subscapulare

- Definition: the under most tip of the inferior angle of the scapula.
- Location: the participant maintained a relaxed standing position as the skin at this site is quite pliable and prone to error with participant movement. The anthropometrist palpated the inferior angle of the scapula with the left thumb starting medially and running the thumb under the under most tip of the scapula. If there was extreme difficulty locating the inferior angle of the scapula, the participant slowly reached behind the back with their right arm. The inferior angle of the scapula was felt continuously as the hand is again placed by the side of the body. A final check of this landmark was made ensuring the arm was released completely back to the relaxed position.

Subscapular skinfold site

- Definition: the site 2 cm along a line running laterally and obliquely downward from the subscapular landmark at a 45° angle.
- Location: a tape measure was used to locate the point 2 cm from the subscapular in a line 45° laterally downward.

Iliocristale

- Definition: the point on the iliac crest where a line drawn from the mid-axilla (middle of the armpit), on the longitudinal axis of the body, meets the ilium.
- Location: the participant was asked to put their right hand on their left shoulder. The anthropometrist used their left hand to stabilise the body by providing resistance on the left side of the pelvis. The general location of the top of the iliac crest was found with the right hand by rolling the heel of the thumb or using the palms of the fingers. Once the general position had been located, the specific edge of the crest was located by horizontal palpation with the tips of the fingers. Once identified, a horizontal line was drawn at the level of the iliac crest. An imaginary line was then drawn from the mid-axilla down the mid-line of the body. The landmark was at the intersection of the two lines.

Iliospinale

- Definition: the most inferior or under most part of the tip of the anterior superior iliac spine.
- Location: as this landmark is usually below the level of the waistband, the participant was asked to assist with the identification of this site by lowering their pant-line on the right side. The superior aspect of the ilium was palpated, and followed anteriorly and inferiorly along the crest until the prominence of the ilium runs posteriorly. The landmark was marked at the lower margin or edge where the bone could just be felt. Difficulty in appraising the landmark was assisted by the participant lifting the heel of the right foot and rotating the femur outward. Because the sartorius muscle originates at the site of the iliospinale, this movement of the femur enabled palpation of the muscle and tracing to its origin.

Supraspinale skinfold site

- Definition: the point at the intersection of two lines: (1) the vertical line from the marked iliospinale to the anterior axillary border; and (2) the horizontal line at the level of the marked iliocristale.
- Location: using a tape measure, the line that runs from the anterior axillary border (i.e. the front of the armpit) to the iliospinale was located, and a short line was drawn along the side roughly at the level of the iliocristale. It was useful to ask the participant to hold the tape at the anterior axillary border with their left hand. The tape was then run horizontally around from the marked iliocristale to intersect the vertical line.

Abdominal skinfold site

- Definition: the point 5 cm horizontally to the right-hand side of the omphalion (mid-point of the navel).
- Location: using a tape measure, this site was measured horizontally across 5 cm to the right from the mid-point of the navel.

Front thigh skinfold site

- Definition: the mid-point of the linear distance between the inguinal point (the point at the intersection of the inguinal fold and the mid-line of the anterior thigh) and the patellare (the mid-point of the posterior superior border of the patella).
- Location: the participant assumed a seated position with the torso erect and the arms hanging by the sides. The knee of the right leg was bent at a right angle. The anthropometrist stood facing the right side of the seated participant on the lateral side of the thigh. If there was difficulty locating the inguinal fold (the crease at the angle of the trunk and the anterior thigh) the participant flexed the hip to make a fold. Using a segmometer, a measure was taken from the inguinal fold to the posterior superior border of the patella. The point that was equidistant between these two landmarks in the mid-line of the thigh was marked.

Medial calf skinfold site

- Definition: the point on the most medial aspect of the calf at the level of the maximal girth.
- Location: the participant was asked to stand on top of an anthropometric box with their feet separated and their body mass evenly distributed. Using a tape measure, the maximum circumference of the calf was found. Girths proximal to this were measured using the middle fingers to manipulate the position of the tape in a series of distal and proximal movements. Once the maximal level was located, the point was marked on the medial aspect of the calf.

Measurements

Stature (stretch)

1. The participant was asked to remove their shoes.
2. The participant then stood directly under the stadiometer with their feet together and their heels, buttocks, and upper part of their back touching the stadiometer.
3. The participant's head was positioned in the Frankfort plane. The Frankfort plane was achieved by placing the tips of the thumbs on each orbitale, and the index fingers on each tracion, then horizontally aligning the two. The thumbs were then relocated posteriorly towards the participant's ears, and far enough along the line of the jaw to ensure that upward pressure, when applied, was transferred through the mastoid processes.
4. The participant was instructed to take in and hold a deep breath while keeping the head in the Frankfort plane.
5. A gentle upward lift was applied through the mastoid processes.
6. The recorder then brought the stadiometer tape down until it was placed firmly on the vertex, crushing the participant's hair as much as possible. It was ensured that the heels did not leave the floor and that the position of the head was maintained in the Frankfort plane.
7. The measurement was taken at the end of a deep inward breath.

Body mass

1. The bladder was voided prior to assessment.
2. The scales were positioned where they were able to be read.
3. The scales were calibrated to ensure they were reading zero.
4. The participant was dressed in minimal clothing with shoes removed and pockets emptied.
5. The participant was asked to stand on the centre of the scales without support and with their body mass evenly distributed on both feet.
6. The participant was asked to look directly ahead.
7. When the body mass measure stabilised, the result was recorded.

Skinfold measures (general instructions)

1. The fold was picked up with the near edge of the thumb and finger in line with the marked site, and the back of the hand facing the anthropometrist. The fold was grasped and lifted so that a parallel, double-fold of skin (including the underlying subcutaneous adipose tissue) was held between the thumb and index finger of the left hand. Note: grasping large folds creating a “mushroom” effect was avoided, as were small folds where the caliper may have slipped off and caused pain and discomfort.
2. The nearest edge of the caliper was applied 1 cm away from the edge of the thumb and finger. The centre of the caliper faces was placed at a depth of approximately mid-fingernail.
3. The caliper was held at 90° to the surface of the skinfold in the three spacial planes at all times. It was ensured the fold was held while the caliper was in contact with the skin.
4. Measurement was taken 2 seconds after full pressure of the caliper was applied. Note: the caliper handles were released during measurement.
5. Skinfold sites were measured in succession (i.e. one set of each skinfold measure was taken before returning to each site for the duplicate measure, reducing the effects of skinfold compressibility and technician bias).

Triceps skinfold site

- Definition: the skinfold measurement taken parallel to the long axis of the arm at the triceps skinfold site.
- Location: the right arm of the participant was relaxed with the shoulder joint slightly externally rotated to the mid-prone position and elbow extended by the side of the body. The skinfold was raised with the left thumb and index finger on the marked posterior mid-acromiale-radiale line. The fold was vertical and parallel to the line of the upper arm. The participant was asked to extend, then relax, and then take the skinfold measurement was taken.

Subscapular skinfold site

- Definition: the skinfold measurement taken with the fold running obliquely downwards at the subscapular skinfold site.
- Location: the skinfold was taken at the subscapular skinfold site which was marked 2 cm laterally and obliquely downward from the subscapular landmark at a 45 degree angle as determined by the natural fold lines of the skin.

Biceps skinfold site

- Definition: the skinfold measurement taken parallel to the long axis of the arm at the biceps skinfold site.
- Location: the right arm of the participant was relaxed with the shoulder joint slightly externally rotated to the mid-prone position, and elbow extended by the side of the body. The skinfold was raised with the left thumb and index finger on the marked anterior mid-acromiale-radiale line. The fold was vertical and parallel to the line of the upper arm. The skinfold was taken while the arm was relaxed. As the bicep skinfold is generally a small skinfold, care was taken not to pinch too deep causing a triple fold of the skin.

Supraspinale skinfold site

- Definition: the skinfold measurement taken with the fold running obliquely and medially downward at the supraspinale skinfold site.
- Location: the participant assumed a relaxed standing position with the arms hanging by the sides. The fold runs medially downward and anteriorly at about a 45° angle as determined by the natural fold lines of the skin.

Abdominal skinfold site

- Definition: the skinfold measurement taken vertically at the abdominal skinfold site.
- Location: the participant assumed a relaxed standing position with the arms hanging by their sides. This was a vertical fold raised 5 cm from the right-hand side of the mid-point of the navel. Fingers were not placed inside the navel. If the skinfold was thick enough for this to occur, the mark was moved over to the right so the fingers were placed beside the navel. The distance from the mid-point of the fold to the mid-point of the navel was recorded for re-test measures.

Front thigh skinfold site

- Definition: the skinfold measurement taken parallel to the long axis of the thigh at the front thigh skinfold site.
- Location: the participant assumed a seated position at the front edge of the anthropometric box with the torso erect, the arms supporting the hamstrings and the leg extended. The anthropometrist stood facing the right side of the participant on the lateral side of the thigh. Note that the site was marked while the knee is bent; however, the skinfold measurement is taken with the leg extended. The participant assisted (if needed) by raising the underside of the thigh to relieve the tension of the skin. The anthropometrist then raised the skinfold at the marked site and took the measurement.

Medial calf skinfold site

- Definition: the skinfold measurement taken vertically at the medial calf skinfold site.
- Location: the participant assumed a relaxed standing position with the right foot placed on a box and calf relaxed. The right knee was bent at 90°. Note that the site was marked with the participant standing on the anthropometric box; however, the skinfold measurement was taken with the right foot placed on the box. The vertical fold was raised on the medial aspect of the calf at a level where it had maximal circumference. The fold was parallel to the long axis of the leg.

Waist circumference girth measure

- Definition: the circumference of the abdomen at its narrowest point between the lower costal (10th rib) border and the top of the iliac crest, perpendicular to the long axis of the trunk.
- Location: the participant was asked to fold their arms across their chest with their hands on opposite shoulders. The anthropometrist stood in front of the participant and passed the tape around the abdomen. The stub of the tape and the housing were then both held in the right hand while using the left hand to adjust the level of the tape at the back to the adjudged level of the narrowest point. Control was resumed of the stub with the left hand using the cross-hand technique, and the tape was positioned in front at the target level. The participant breathed normally and the measurement was taken at the end of a normal expiration (end tidal). When there was no obvious narrowing the measurement was taken at the mid-point between the lower costal (10th rib) border and the iliac crest.

Analysis

Testing was performed for two rotations (trial 1 and trial 2) of all measures. If there was $\leq 1\%$ difference between the two measures for body mass, stature, or waist circumference, or a $\leq 4\%$ difference between the two measures for skinfolds, the mean was recorded of these measures. If there was a difference between the two measures greater than those stated above, a third measure was performed, and the median was recorded.

From the results a S7SF was calculated by adding up the results from each measure. The S7SF, or a combination of various skinfold measures, can be applied to a variety of regression equations to provide an estimate of BF%. Details on the equations used in this research can be found in Table A.4.

The BMI was calculated by applying the formula:

$$\text{BMI} = \text{mass (kg)} / \text{stature (m)}^2$$

The LMI [166, 511], which is an empirical measure of proportional variations in FFM, was calculated by applying the formula below, where the exponent x was 0.14 for forwards, and 0.13 for backs:

$$\text{LMI} = \text{mass (kg)} / \text{S7SF}^x$$

Table A.4. Details of previously published regression equations used in this research [162, 179, 347, 459, 608].

Author (year)	Sample Size	Demographics (mean ± SD)	Skinfold Sites Used	Reference Assessment Used	Equation As Applied To This Study
Evans (2005)	78 male collegiate athletes	Age 20.9 ± 1.7 years Stature 184.0 ± 7.9 cm Mass 93.1 ± 21.6 kg	Tricep, abdominal, mid-thigh	4-compartment model	$BF\% = 8.997 + (0.24658 \times (\text{triceps} + \text{abdominal} + \text{mid-thigh})) - 6.343$
Reilly (2009)	45 male professional soccer players	Age 24.2 ± 5.0 years Stature 182.0 ± 7.0 cm Mass 82.0 ± 8.5 kg	Tricep, abdominal, mid-thigh, medial calf	DXA	$BF\% = 5.174 + (0.196 \times \text{triceps}) + (0.147 \times \text{abdominal}) + (0.124 \times \text{mid-thigh}) + (0.130 \times \text{medial calf})$
Lohman (1981)	149 male subjects from a combination of studies	Group demographics unknown	Tricep, subscapular, abdominal	Hydrodensitometry	$BD = 1.0982 - 0.000815X + 0.0000084X^2$ X = sum of triceps, subscapular, abdominal $BF\% = (4.95/BD - 4.50) \times 100$

Withers (1987)	207 state and international athletes from a range of sports	Age 24.2 ± 4.7 years Stature 180.0 ± 8.3 cm Mass 74.5 ± 10.5 kg	Triceps, subscapular, biceps, supraspinale, abdominal, mid-thigh, medial calf	Hydrodensitometry	$BF\% = (495 / (1.0988 - (0.0004 \times S7SF))) - 450$
Durnin and Womersley (1974)	92 males with a variety of body types aged between 20-29	Age 20 – 29 years Stature 177 ± 6.9 cm Mass 70.1 ± 12.2 kg	Tricep, subscapular, bicep, supraspinale	Hydrodensitometry	$BD = 1.1631 - (0.0632 \times L)$ $L = \log(\text{triceps} + \text{subscapular} + \text{bicep} + \text{supraspinale})$ $BF\% = (4.95 / BD - 4.50) \times 100$

APPENDIX VI – DATA COLLECTION METHODOLOGY: DUAL-ENERGY X-RAY ABSORPTIOMETRY

This methodology has been adapted from other sources [178, 223, 396].

Person to take measurement

Qualified and experienced densitometrist who has completed the Australian and New Zealand Bone and Mineral Society (ANZBMS) Clinical Densitometry Training Course, and holds a valid Radiation Use License.

Place measurement taken

Physique Science, Suite 2a 76 Commercial Road, Newstead, QLD, Australia.

Materials required

- Hologic Discovery A fan-beam densitometer (Hologic, Bedford, MA, USA)
- Apex 13.4.2:3 software (Hologic, Bedford, MA, USA)
- Specialised foam pads and Velcro straps used for positioning
- Spine phantom used for calibration

Procedure

Pre-test protocol

The day prior to testing, participants were requested to remain well hydrated and consume their normal diet, including their normal intake of carbohydrates. Participants presented for the test without having undertaken any exercise, and having not consumed any food or fluid. Participants changed into appropriate

clothes for the scan (sports shorts and a t-shirt/singlet), and removed all attenuating material such as jewelry, watches, and clothing with zips, buckles, belts, and buttons. Prior to the scan, participants were required to empty their bladder.

Measurements

Participants were positioned on the scanning table using the Nana et al. protocol. Specifically, the head was positioned in the Frankfort plane, the arms were separated from the body using specialised foam pads, and the hands were positioned vertically being supported by additional specialised foam pads, which also separated the hands from the body. The upper body was held in position via a piece of Velcro which wraps around the body approximately at the mid-forearm level. The feet were placed on a specialised foam pad to support them in an upright position and separate them from each other. The feet were held in position by a piece of Velcro wrapped around the ankles. An example of the Nana et al. positioning can be seen in Figure A.6.

If the participant was taller than the defined scanning area of 196 cm they received two scans. The first scan captured the body from the menton (the inferior point of the mandible) down whilst the head was positioned in the Frankfort plane. After body repositioning on the scanner and realignment of the head into the Frankfort plane, a second scan was taken to capture from the menton up to the vertex of the head.

During the scan the participant was instructed to remain relaxed, as still as possible, and breathe normally. The same experienced and qualified densitometrist performed all scans to ensure consistent positioning.

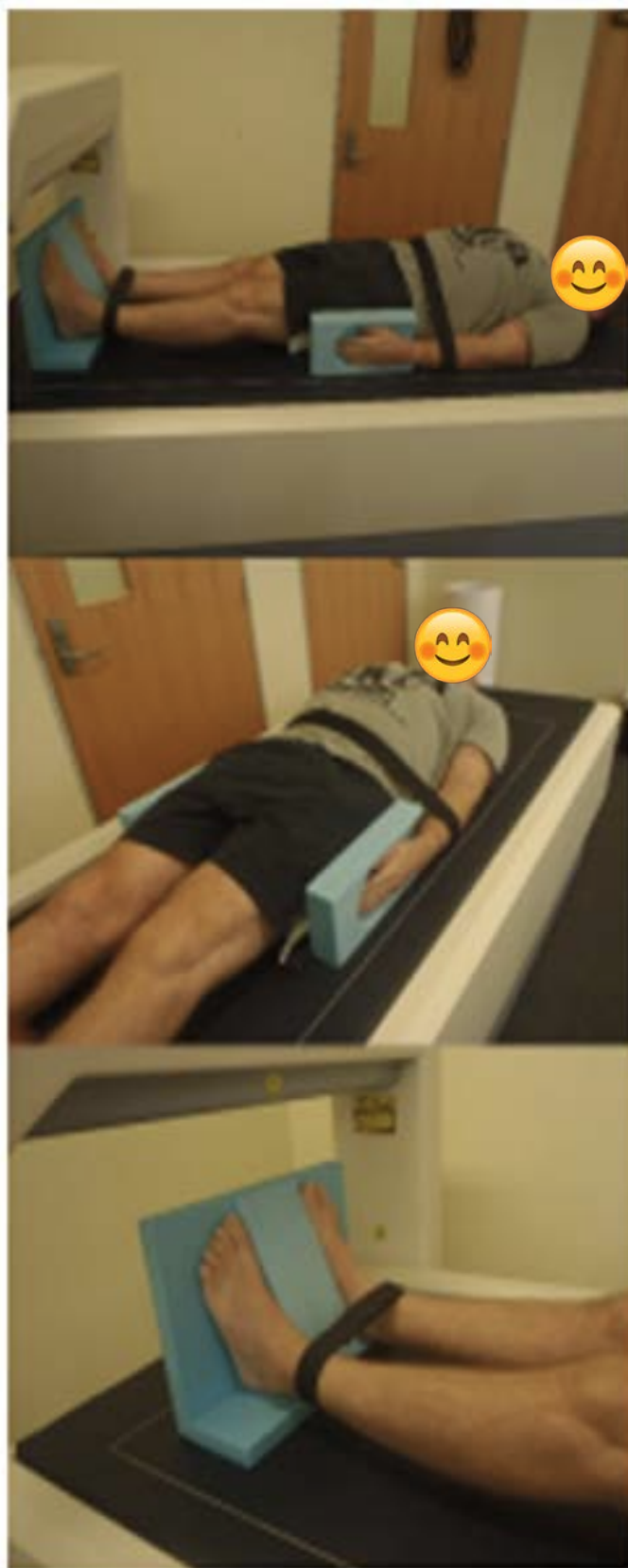


Figure A.6. Example of the Nana et al. positioning protocol with the use of foam positioning pads. Adapted with permission from Kerr et al. (2016) [294].

Analysis

Post scan analysis was undertaken using Apex 13.4.2:3 software (Hologic, Bedford, MA, USA). The same experienced and qualified densitometrist performed all post-scan analysis to ensure consistent positioning of cut lines in the regional analysis. ROI were automated by the software, with all cut locations checked to ensure they were put through the appropriate anatomical landmarks, specifically (Figure A.7):

- Neck – separates the head from the neck. Position the cut just below the chin whilst the head is in the Frankfort plane.
- Arms – should be separated from the trunk. The cut should be positioned so it passes through the centre of the humeral socket to the axilla fold. It should be as close as possible to the body without touching the ribs, pelvis, or greater trochanter.
- Pelvis – a triangular cut that separates the pelvis from the upper body and legs. The cut is positioned just above the pelvis. Two angled lines separating the pelvis from the legs should pass through the femoral necks. The position of the angled lines depends on the position of the pelvis cut.
- Legs – should be separated from each other via a line going down the centre of the lower body.

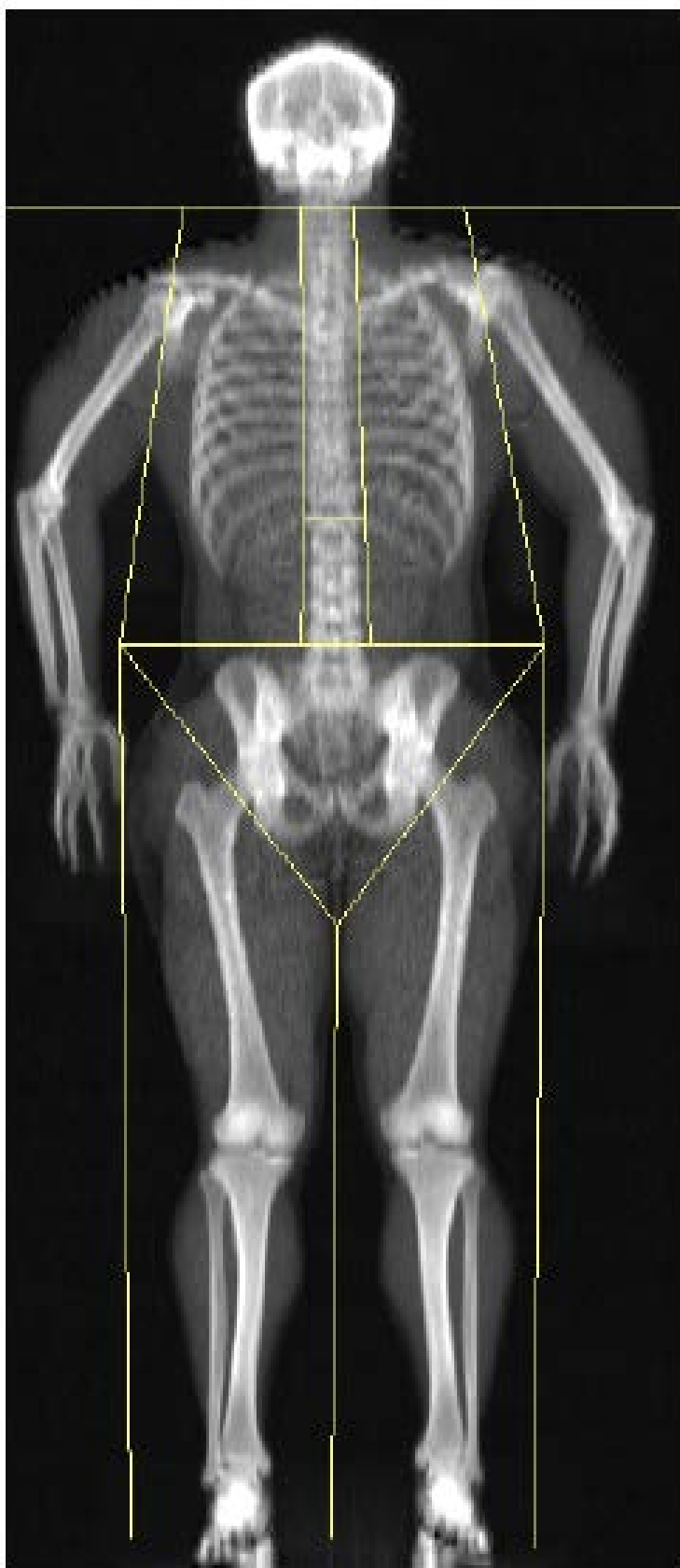


Figure A.7. Dual-energy X-ray image with region of interest cut lines put through the appropriate anatomical landmarks.

VAT area was calculated using the auto-positioning function of the software, with manual adjustments made to the edge of the subcutaneous fat placement and visceral cavity area if required (Figure A.8). The android region included the cut of the pelvic region to 20% of the distance between the pelvic cup and the bottom of the neck line, excluding the arms. The gynoid measure included the height equal to two times the height of the android region.

If required due to the stature of the participant, the results from their two scans were combined to elicit whole body composition values.

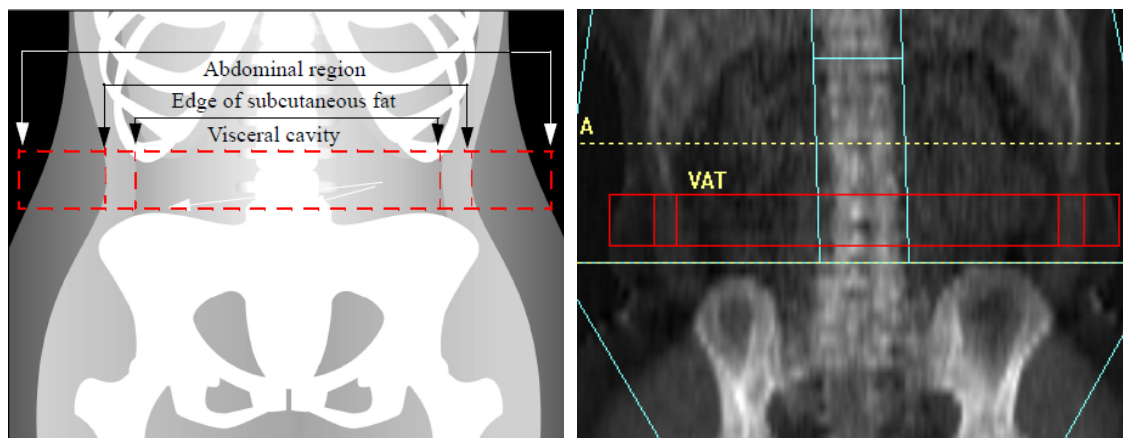


Figure A.8. Correct placement of region of interest cut lines to identify the visceral cavity, which is used to calculate the visceral adipose tissue area using dual-energy X-ray absorptiometry.

APPENDIX VII – DATA COLLECTION METHODOLOGY: MAGNETIC RESONANCE IMAGING

Person to take measurement

University qualified radiographer, with Level 2 MRI qualifications from the Australian Institute of Radiography.

Place measurement taken

Herston Imaging Research Facility, Royal Brisbane and Women's Hospital, Brisbane, Queensland, Australia.

Materials required

- PRISMA 3T MRI (Siemens Healthineers, Erlangen, Germany)
- Slice-O-matic software (version 5.0; Tomovision, Montréal, Canada)
- Hospital gowns
- Hospital patient consent forms

Procedure

Pre-test protocol

After completion of the consent form, participants were provided a hospital gown to change into, and instructed to remove any jewelry. Prior to the scan, each participant sat down with a radiographer to complete a series of questions to ensure they were able to undertake the scan, including questions pertaining to the insertion of metal plates during recent surgery. Once cleared for the scan, the participant was positioned on the scanning bed either head first or feet first

depending on their body habitus. This position was repeated at all subsequent scans.

Measurements

Scout lines were used on sagittal localisation scans to locate L5/S1 prior to analysis. A 32-channel spine array coupled with a 30-channel body array was utilised to perform the examination on a PRISMA 3T MRI (Siemens Healthineers, Erlangen, Germany). Coverage extended from the diaphragm to the L5/S1 junction. Following localisation two sequences were performed, T2 HASTE axial and a T1 Dixon axial including both fat, water, in and out of phase images. The Haste images were acquired using multiple breath holds and the T1 Dixon was acquired in a single breath hold. Table A.5 demonstrates the factors used in this acquisition.

Table A.5. Details of factors used in the acquisition of MRI images.

Sequence	FOV	TA	Slice Thickness	No of Slices	TR	TE	Flip Angle	BW	Matrix
T2 Haste Axial	450	1:10	10 mm	34	2000	54	114	781	320 x 240
T1 Dixon Axial	450	0:16	4 mm	88	3.97	1.23/ 2.46	9	1040	320 x 240

Analysis

Cross-sectional areas and volumes of both abdominal SAT and VAT from L5/S1 to the diaphragm were measured by semi-automated specialised software Slice-O-matic software (version 5.0; Tomovision, Montréal, Canada). SAT was quantified using the “mathematical morphology” function and VAT using the “region growing” function, with thresholds adjusted manually for each slice. All images were analysed by a single trained observer who was blinded to the identity and all information pertaining to the athlete.

APPENDIX VIII – DATA COLLECTION METHODOLOGY: BLOOD BIOCHEMICAL METABOLIC PARAMETERS

Person to take measurement

Qualified phlebotomist from an accredited commercial laboratory (QML Pathology, Specialist Diagnostic Services Pty Ltd, NSW, Australia).

Place measurement taken

Medical rooms in the training facility.

Materials required

- QML Pathology request forms
- Serum separator tubes (SST)
- Blood draw equipment – tourniquet, alcohol wipes, sterile gloves, Vacutainer double-sided needle and protector, butterfly needles (21 gauge)
- Surgical tape to keep needle in place
- Cotton balls
- Band-Aids
- Sharps disposal unit
- Biohazard/pathology bags
- Esky and ice

Materials were provided by the commercial laboratory (QML Pathology, Specialist Diagnostic Services Pty Ltd, NSW, Australia).

Procedure

Safety precautions were followed, including the wearing of appropriate protective equipment. The participant was seated comfortably, and made aware of the procedure prior to signing the request form. Venous blood was be collected after an overnight fast (>10 hours) into one serum separation tube from the antecubital vein. Blood in the serum separation tube was stored at 4°C for ~1-2 hours prior to analysis, during which time the gel contained in the tube assisted the blood in clotting. All bloods were stored in a biohazard bag and kept in the esky at the required temperature during transport to the laboratory, along with the signed request forms. All needles were disposed of in a sharps disposal unit, and other equipment disposed of in a designated biohazard bag.

Analysis

Analysis was undertaken on the same day as collection at an accredited commercial laboratory (QML Pathology, Specialist Diagnostic Services Pty Ltd, NSW, Australia) on a Siemens ADVIA 1800 Chemistry System (Siemens Healthineers, Erlangen, Germany) with the associated Siemens testing kit and recommended reagents. Blood was centrifuged for 10 minutes at 3000 g. This allowed the red blood cells to be collected at the bottom of the tube below the gel, and the serum to be collected at the top of the tube. The serum was analysed to test fasting glucose and insulin, and a full lipid profile, which included TG, TC, HDL-C and LDL-C. These results were used as markers of cardiometabolic disease risk. The results were communicated to the researchers via email.