Energy Requirements and Body Composition of Professional Team-Sport Athletes

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Masters Nutrition and Dietetics

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Student Declaration

I, Emily J Walker, declare that the PhD thesis entitled *Energy Requirements and Body Composition of Professional Team Sport Athletes* is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signed: [redacted] Date: 1/7/16

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Abbreviations

ADL	Activities of daily living
AF	Australian Football
ANOVA	Analysis of variance
ATP	Adenosine triphosphate
au	Arbitrary units
BF	Body fat
BM	Body mass
BMC	Bone mineral composition
BMD	Bone mineral density
BMR	Basal metabolic rate
CHO	Carbohydrate
CI	Confidence interval
CL	Confidence limits
cm	centimetre
CO_2	Carbon dioxide
DXA	Duel-energy x-ray absorptiometry
DLW	Doubly labelled water
EE	Energy Expenditure
EI	Energy intake
EPOC	Exercise post oxygen consumption
FM	Fat mass
FFM	Fat free mass
FSR	Fractional synthetic rate
g	grams
GPS	Global positioning system
Hz	Hertz
hr	hour
hrs	hours
kJ	kilojoules
kg	kilograms

km	kilometre
LM	Lean mass
m	metre
min	minute
mins	minutes
mm	millimetre
mmol	millmole
MPS	Muscle protein synthesis
NEAT	Non-exercise activity thermogenesis
O_2	Oxygen
PAL	Physical activity level
PCr	Phosphocreatine
REDs	Relative energy deficiency
RMR	Resting metabolic rate
RQ	Respiratory quotient
SD	Standard deviation
SEM	Standard error of the mean
TDEE	Total Daily Energy Expenditure
TE	Typical error
TEF	Thermic effect of food
$\dot{V}O_{2max}$	Maximal oxygen consumption
w.w	wet weight
3D	3-dimensional
$kJ \times kg^{-1}$ $BM \times d^{-1}$	kilojoules per kilogram of body mass per day
$g \times kg^{-1}$ $BM \times d^{-1}$	grams per kilogram of body mass per day

Publications and presentations relevant to this thesis

Publications

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Abstract

Team sports include repeated bouts of high-intensity activity interspersed with periods of low-intensity activity, contacts and skill execution. Optimal energy and nutrient intake is necessary for development, health, performance and for body composition goals in athletes. Study one determined total daily energy expenditure and match expenditure of Australian Football (AF) players. Accelerometers were utilised to capture daily physical activity and expenditure on the field during training and matches. Approximately 85% of the energy expended was from activity outside of training. Study two, conducted concurrently with study one, determined dietary energy and nutrient intake of AF players and whether they matched expenditure and met nutrient recommendations. Seven-day food diaries were completed leading into a match. Players did not consume enough energy on high expenditure days and did not periodise carbohydrate across the week to meet recommendations for match preparation. Study three assessed seasonal body composition changes of AF, Soccer and Rugby players using anthropometric measures including height, body mass and skinfolds, Dual-energy x-ray absorptiometry (DXA) and 3-dimensional (3D) scan technologies. The greatest change in body composition occurred in the pre-season when training volume tends to be higher with Rugby players experiencing the greatest changes. Skinfolds and DXA measured body fat had a moderate to strong correlation while DXA and 3D scan measures were poorly correlated. Study four longitudinally assessed the body composition changes of 16-18-year-old development AF players and whether body composition factors had an impact on selection. Anthropometric measures, skinfolds, DXA and 3D scans were used. The greatest changes occurred from 16-17 years of age. Skinfolds did not change while DXA showed significant losses in fat mass and gain in lean muscle. It was unable to be determined whether body composition had an impact on selection.

Chapter 1. Review of the literature

Energy expenditure (EE), dietary intake and body composition are interrelated and play an important role in maximising athlete performance in sports. Measurement of these factors are necessary to allow for appropriate prescription of nutrition for health, performance and body composition. The first part of this chapter will provide an overview of the literature surrounding energy metabolism, the components of EE and the history of EE measurement through to modern studies of EE in sport. The methods of measuring EE will not be extensively reviewed, but rather will be discussed in the context of the difficulty of measurement in the field. Football codes played professionally in Australia including Australian Football (AF), Soccer, Rugby and Rugby League will be the predominant focus of this review and an overview of the activity profile of these sports will be provided. Sports nutrition principles will be reviewed and how football athletes adhere to these. The importance of body composition in sport will be discussed, how it is used in identifying talented athletes and monitoring growth and development and the changes that occur throughout training and competition periods. In addition, the body composition requirements of football athletes will be defined, with reference to changes throughout development and the season and whether body composition impacts selection in these teams.

1.1 Energy Metabolism and expenditure

1.1.1 Energy, metabolism and units of measurement

Energy can be described as the capacity to do work while metabolism refers to the chemical reactions occurring in the body to allow work to occur. The metabolism of energy by living cells allows the body to live, grow and repair. This energy is obtained from the chemical energy of food constituents, namely carbohydrate, protein, fat and alcohol. Energy use can then be measured from the production of heat, consumption of oxygen and production of carbon dioxide (Da Poian, El-Bacha & Luz 2010). The energy obtained from a nutrient released by oxidation is partially lost as heat and the heat produced by the oxidation of molecules is measured in Calories. A Calorie is the amount of heat required to increase the temperate of one kilogram of water by one degree Celsius from zero to one degree (Favre & Silbermann 1952; Mayer 1848). The Calorie is now referred to as the kilocalorie (kcal) however the *System International des Unites* (SI) defines joule as the only unit of energy in the SI system while in Australia the kilojoule (kJ) is used and 1 kcal is equivalent to 4.186 kJ (Hargrove 2007).

1.1.2 Why measure energy expenditure and intake?

The balance between EE and energy intake (EI) determines energy stores (Galgani & Ravussin 2008). Maintaining this energy balance in the long-term is necessary for health and in the case of athletes, performance. This balance is particularly important in athletes required to alter their body composition for performance or to meet a body mass requirement for their sport. When EI and EE are equal, this is referred at energy balance and should result in the maintenance of body mass. If intake is less than expenditure, mass loss will result. The opposite is true for mass gain, if intake exceeds expenditure, mass gain will occur (Manore & Thompon 2007). Diet composition, physiological, environmental, behavioural and genetic factors will also impact body composition however long-term energy balance is the main influencing factor (Jequier & Tappy 1999). If EI is not sufficient to meet the energy needed for training or competition, performance, recovery and health of the athlete are compromised (Manore & Thompon 2007). The macronutrient composition of this energy will determine what energy stores are available for use during rest and physical activity.

1.1.3 Measurement of energy expenditure

Energy expenditure can be measured by direct calorimetry, indirect calorimetry or by non-calorimetric methods (Levine 2005). The methods of energy measurement have evolved since the beginning of the 20th century. Direct calorimetry measures total heat lost from the body when a participant is placed in a thermally-isolated chamber and the heat dissipated is recorded. This method is the most accurate and precise however it is expensive and does not allow for typical activity performed in the free-living environment (Ainslie, Reilly & Westerterp 2003; Leonard 2012; Levine 2005). Indirect calorimetry measures oxygen consumption and carbon dioxide production and is converted to energy expended using a determined formulae (Levine 2005). Non-calorimetric methods predict EE from variables related to EE such as measuring carbon dioxide production with doubly labelled water (DLW) or the flex heart rate method. Both of these are often correlated with calorimetric methods (Ainslie, Reilly & Westerterp 2003; Leonard 2012; Levine 2005). The DLW method has now become the ‘gold standard’ method to measure total daily energy expenditure (TDEE) and has been used in humans since the 1980’s (Schoeller & van Santen 1982).

1.1.4 History of the measurement of energy metabolism

Some of the earliest studies determining the specific heating of water and other materials were conducted in the late 1700’s by Antoine Lavoisier (Lavoisier 1780). Lavoisier determined that heat production could be predicted from oxygen consumption (Lavoisier 1780). Heat production can be calculated from the ratio of the rate of carbon dioxide production to oxygen consumption, which is referred to as the non-protein respiratory quotient (RQ). The RQ is the ratio between the oxidation of carbohydrate and lipid which can then be used to estimate EE based on the assumption that one litre of oxygen consumed is equal to approximately 4.81 kcal (McArdle, Katch & Katch 2001). It was not until the 1860’s that indirect calorimetry was used by European scientists, Pettenkofer and Voit to study human and animal respiration (Pettenkofer & Voit 1866; Voit 1866). Around the same time Rubner constructed a bomb calorimeter to measure the heat combustion of macronutrients from which he then calculated the energy value of foods for humans (Rubner 1885a, 1885b). After visiting Voit and Rubner in Europe, the American scientist, Wilbur Atwater began conducting significant research in the area of EE and intake (Atwater & Benedict 1905).

Atwater utilised the knowledge obtained from Voit and Rubner and published tables in 1894 on the energy content of American foods (Atwater 1894). Atwater, Rosa and Benedict then developed a more sophisticated closed circuit indirect calorimeter contained in a specialised room which enabled the measurement of human EE (Atwater & Benedict 1905). In the early 1900’s Douglas developed the Douglas bag where exhaled air was collected in a rubber bag or Tissot tank and this allowed for measurement of activities outside of the specialised room (Douglas 1911). It was identified that a method was needed that was able to measure respiration in the free-living environment and in 1906 Zuntz developed a more portable machine to measure maximal oxygen consumption ($\dot{V}O_2$) during exercise (Zuntz & Leowy 1909). It was now possible to simultaneously measure both EE of daily tasks and EI.

1.1.5 Energy expenditure and energy intake research conducted early in the 20th century

Early in the century, studies were conducted to determine the EE of a variety of activities and expenditure over the day. One of the first studies in 1910, Lieutenant Colonel Melville studied 20 infantry soldiers and calculated their EE to be approximately 17,000 kJ with about 4,300 kJ from carrying 24 kg while marching 13 miles (Melville 1910). In 1918 the energy metabolism was estimated for four groups of female munition workers with differing responsibilities (Greenwood, Hudson & Tebb 1919). Energy ranged from 418 - 753 kJ per square meter per hour with a TDEE ranging from 11,720 – 15,907 kJ (Greenwood, Hudson & Tebb 1919). Other studies measured the expenditure of discrete tasks so these could then be used to tally up expenditure over the day. Sleeping only required 2.8 kJ·min^{-1}, washing and dressing 8.2 kJ·min^{-1}, polishing 10.1 kJ·min^{-1} while ironing required twice that of polishing at 17.6 kJ·min^{-1} (Edholm et al. 1955; Passmore & Durnin 1955). It was also noted that as machines replaced people in manual labour jobs, that EE was reduced. For example, men assembling agricultural machinery used 21.8 to 6.426.8 kJ·min^{-1} and when a conveyer belt was introduced the expenditure was reduced (7.5 – 19.8 kJ·min^{-1}) (Kagan et al. 1928).

In 1894 Atwater published the nutritive value of foods (Atwater 1894). These guidelines were based on protein, carbohydrate and fat rather than specific minerals and vitamins, which had not been identified at the time. The energy value of each nutrient was provided suggesting the kilojoules in 450 grams of nutrient: protein 7,786, fat 17,665 and carbohydrate 7,786 kJ. Proportions of these were recommended depending on the person. For example, a man hard at work would require 145 grams of protein, 100 grams of fat and 450 grams of carbohydrate totalling 14,107 kJ while a man with little physical exercise would require 91 grams of protein, 91 grams of fat and 300 grams of carbohydrate totalling 10,256 kJ (Atwater 1894).

Once it became possible to measure the EE of humans, energy balance studies could be conducted. One of the first energy balance studies was conducted in school children from 1919 - 1921 (Bedale 1922). It was found that children in a boarding schooling situation over consumed energy when compared to expenditure however they acknowledged some limitations such as methods of measurement and that expenditure was only estimated for one day. A later study compared the expenditure and intake of a highly physical job versus a less active job (Garry et al. 1952). Miners expended ~15,372 kJ and consumed ~16,926 kJ while clerks expended 25% less energy at ~11,760 kJ and consumed ~12,768 kJ (Garry et al. 1952).

1.1.6 Energy expenditure and energy intake research conducted later in the 20th century

Research conducted after the 1950s was firstly directed toward measuring TDEE not just expenditure of activities, studies in civilians (non-military) and also obesity research as the condition became more prevalent. Early therapeutic programs were not succeeding and interest increased in researching the aetiology of obesity (Curtis & Bradfield 1971). There was uncertainty around why individuals could have such different energy metabolism (Widdowson 1962). Obesity was becoming increasing prevalent in the middle to high income earners prior to World War II however post war, obesity began to rise in low income earners. Energy expenditure was reduced by increased automation in daily life with machines taking over the workplace and home, there was less physical activity in leisure time and an increased intake of energy from greater food access (Caballero 2007; Durnin 1967). Industrialisation has nearly halved EE and was nicely demonstrated in a study comparing the EE of a hunter-gatherer tribe in Peru to men from the United States. Tribesmen had a mean expenditure of approximately 252 $kJ \cdot kg \cdot d^{-1}$ compared to 164 $kJ \cdot kg \cdot d^{-1}$ in men from the United States

(Montgomery 1978). Soon after the war it was observed that men who were involved in more physically active work compared to sedentary jobs also had a lower risk of coronary heart disease (Morris, JN et al. 1953).

Energy balance studies were conducted in obese (Curtis & Bradfield 1971) and non-obese individuals in an attempt to determine what contributes to obesity (Curtis & Bradfield 1971; Durnin, Blake & Brockway 1957). The EI of both groups was not different with the mean intake of the obese subjects of 8,500 kJ and non-obese 8,800 kJ. Expenditure in the obese was 11,300 kJ and non-obese 8,800 kJ. Expenditure was greater in the obese most likely because a greater body mass requires greater expenditure as the obese subjects spent 5% less time doing moderate activity than the non-obese and 5% more time sitting or in light activity (Curtis & Bradfield 1971; Durnin, Blake & Brockway 1957).

Later studies conducted early in the new century, have found that physical activity has not declined any further since the 1980s however dietary intake has increased and is one of the main determinants of increasing rates of overweight and obesity (Swinburn et al. 2009; Westerterp & Speakman 2008). Free-living men and women who are lean expend 8,000 – 15,000 kJ whereas obese men and women can expend from 10,000 to 18,500 kJ each day (Black et al. 1996).

1.1.7 Components of energy expenditure

Total daily EE is made up of three components: the energy required by the body at rest referred to as the basal metabolic rate (BMR, measured when fasted and after 8 hours sleep) or resting metabolic rate (RMR, measured at rest but under less strict conditions than BMR), the energy required for digestion, absorption and storage of food is referred to as the thermic effect of food (TEF) and the expenditure associated with activity (exercise and non-exercise activity thermogenesis or NEAT) (Levine 2005). The overall contribution of each component varies between individuals. For example, BMR is generally the largest component of TDEE in the general population and is largely influenced by lean body mass (70% of variability in BMR) that is directly related to sex and age (Cunningham 1980; Speakman & Selman 2003). The BMR of an athlete can be higher than a non-athletic person of a similar body mass due to the higher lean muscle mass and BMR can also be elevated while the body is recovering from training and competition (Almeras et al. 1991; Speakman & Selman 2003). The magnitude of the TEF is proportional to the energy and protein content of the diet and is also largely influenced by lean muscle mass (Donahoo, Levine & Melanson 2004), suggesting that athletes may have a greater contribution from the TEF.

Energy expenditure from purposeful exercise and NEAT will be the most fluid component of TDEE as they vary considerably between individuals (Westerterp 2008). Exercise refers to the expenditure from sports and fitness related activity while NEAT refers to non-exercise activities such as activities of daily living (ADL), fidgeting, sitting, standing and walking (Levine, Schleusner & Jensen 2000). The contribution of exercise and NEAT can vary from 15% in sedentary individuals with a low physical activity level (PAL) to 50% of TDEE in very active individuals with a high PAL. The PAL can be expressed as TDEE divided by RMR, with a PAL of 1.4 considered minimal or sedentary and 2.5 considered as a vigorously active lifestyle (National Health and Medical Research Council 2006). Values greater than this have been seen in extreme athletic conditions like that seen during the Tour De France (Westerterp 2003; Westerterp et al. 1986).

1.1.8 Energy expenditure of athletes

The TDEE of athletes depends on the sport, the training required for the sport, competition, time of season, body composition, sex and age of the athlete. Each component of TDEE including RMR, NEAT and exercise EE also varies. With the introduction of the DLW method, studies could be completed looking at the TDEE of athletes in the free-living environment. Female collegiate swimmers expended 10,900 kJ during a tapered training and 16,700 kJ for male swimmers (Jones & Leitch 1993). Cyclists in the Tour de France had a mean expenditure of 33,700 $kJ{\cdot}d^{-1}$ (Westerterp et al. 1986). Technologies such as heart rate measurement and accelerometers have enabled the estimation of EE in the field and although not considered ‘gold standard’ techniques, provide a reliable, accessible and cheaper option for measurement. Studies measuring TDEE are summarised in Table 1.

The contribution of exercise EE will generally be greater in elite and professional athletes and depends on training volume and competition (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013; Vogt, S et al. 2005). In early studies it was estimated that a 20 minute boat race over 4.5 miles required 2,500 kJ, a 2 hour marathon race 8,600 kJ and a five set tennis match 5,000 kJ (Leyton 1948). In male endurance athletes, there was a 18% difference in TDEE between a high and low volume training day. This was due to a 50% reduction in EE from training (Drenowatz, Eisenmann, Pivarnik, Pfeiffe, et al. 2013). In male elite cyclists during training camp, TDEE was 45% lower on a rest day (Vogt, S et al. 2005) when no training was completed.

Although research has been conducted on TDEE of athletes and the expenditure associated with training or competition has been studied, little research has been done on NEAT. Something as simple as fidgeting can noticeably increase EE when compared to a motionless state. Fidgeting-like activities while seated, increased EE by 2.6 ± 1.5 kJ.min^{-1} compared to sitting motionless and 4.2 ± 1.9 kJ·min^{-1} standing motionless (Levine, Schleusner & Jensen 2000). In endurance athletes, the proportional contribution of NEAT to total TDEE was 31% on a low volume training day and 26% on a high volume day however there was no difference in absolute NEAT values between the days (Drenowatz, Eisenmann, Pivarnik, Pfeiffe, et al. 2013). Time spent in sedentary activity increased by 4% on low volume days which was mainly offset by a 50% reduction in vigorous activity (Drenowatz, Eisenmann, Pivarnik, Pfeiffe, et al. 2013). In another study of endurance athletes, NEAT contributed 38% to TDEE however this value was greater as it included RMR during waking hours (Motonaga et al. 2006). It is thought that athletes may engage in active lifestyles outside of training (Westerterp 2008) which may be supported by the inverse relationship between NEAT and sedentary time in endurance athletes (Drenowatz, Eisenmann, Pivarnik, Pfeiffe, et al. 2013). Another study in cross country skiers reported that trained subjects did not compensate with reduced EE outside of training and non-exercise EE was not different between the trained and untrained subjects (Almeras et al. 1991). In opposition, another suggestion could be that NEAT may decrease outside of training due to fatigue from training at higher intensities or if the individual is in negative energy balance (Levine 2004). It could also just be that NEAT may be reduced due to a lack of time outside of training time for other activities.

The RMR is influenced largely by lean body mass, accounting for 70% of the variability and any change in this tissue will impact RMR (Cunningham 1980). Lean body mass is a function of age and sex and therefore these factors could be considered factors that influence RMR while other factors including energy balance, previous exercise, genetics and hormones may also play a role (Bogardus et al. 1986; Cunningham 1980; Sparti et al. 1997). A nine-week training study that elicited a 1.9 kg gain in lean muscle mass also had a 3% increase in RMR (Byrne & Wilmore 2001). Elite athletes tend to be high lean body mass and lower fat mass than the non-athletic or exercising population and therefore have a greater RMR. Males have a higher RMR as they tend to have greater amounts of lean mass than females however sex also contributes to this increased RMR, mainly due to the influence of hormones (Buchholz, Rafii & Pencharz 2001; Ferraro & Ravussin 1992). After controlling for lean mass and age, females still have a lower RMR than males by approximately 420 kJ (Ferraro & Ravussin 1992). In females, the phase of the menstrual cycle will determine RMR with the lowest rate at the beginning of the cycle and highest at the end with a difference ranging from 400 - 1,200 $kJ{\cdot}d^{-1}$ (Bisdee, James & Shaw 1989). Genetic variation explains 11% of the variability in RMR and with age there is a 1 - 2% decline from the second through to the seventh decade of life (Bogardus et al. 1986). An energy deficit can also reduce metabolic rate. A substantial energy deficit over a period of weeks can result in a 15 - 30% reduction in metabolic rate (Mole 1990). Sports that require low body and fat mass tend to cycle EI to meet body mass restrictions, which impacts RMR. Wrestlers who cycle mass loss to meet body mass category requirements have reduced RMR compared to those who do not cycle mass loss (Steen, Oppliger & Brownell 1988). Those who are in energy deficit tend to have lower RMR than those who are energy replete (Leibel, Rosenbaum & Hirsch 1995).

Exercise has a temporary indirect impact on RMR. Exercise that results in muscle tissue damage such as high intensity strenuous exercise or resistance training requires muscle repair and rebuilding which increases metabolic rate (Burt et al. 2014). This is known as post exercise oxygen consumption (EPOC). After resistance training RMR can remain elevated for up to 72 hours (Dolezal et al. 2000) as repair of muscle and protein resynthesis requires a high energy cost, possibly up to 20% of RMR (Welle & Nair 1990).

The TEF is the energy expended above the RMR associated with the digestion, storage, absorption and transport of food within the body. Typically, the TEF is about 6-10% of TDEE however this can vary depending on the energy content of the meal, nutrient composition of the foods consumed and types of foods. The 6-10% of EE for the TEF is for a mixed meal however the individual macronutrients vary with glucose around 5-10%, fat 3-5% and protein 20-30% (Flatt 1992). Consumption of food post endurance and resistance training increases the TEF. After a bout of swimming in collegiate males, EE measured by indirect calorimetry showed a 19.3 $kJ \cdot hr^{-1}$ greater expenditure when food was consumed compared to when it was not (Nichols, Ross & Patterson 1988). Although negligible, this may become substantial over time (Nichols, Ross & Patterson 1988). Similar results were evident after a bout of resistance training and provision of an 80% carbohydrate meal with 13% protein and 7% fat (Denzer & Young 2003). Both the control and intervention group consumed the meal however the control group did not complete the exercise. Both groups had increased $\dot{V}O_2$ above RMR however the exercise group was 14% greater than the control group (Denzer & Young 2003). Obesity is associated with a lower TEF, which is thought to be due to the degree of insulin resistance (de Jonge & Bray 1997).

The measurement of energy expenditure began just before the beginning of the 20th century and since this time the methods of measurement have evolved allowing for not only measurement of specific activities but measurement of total daily energy expenditure. Athletes expend a significant and varying amount of energy at different points in the season and throughout the training and competition week. Expenditure will fluctuate with training and competition loads while other components of total expenditure including RMR, TEF and NEAT will also be variable and impacted by body composition, training type, dietary composition activities of daily living. Measuring energy and dietary intake in conjunction with expenditure is necessary to ensure athletes are meeting requirements for health, performance and body composition goals.

Author	n	Age (yrs.)	Mass (kg)	Height (m)	Sport	Level	Method of Assessment	TEE (kJ)
Westerterp, 1986	4	-	69.2	-	Tour de France cyclists	Elite	DLW	33,700 ± 600
Almeras, 1991	7	-	-	-	Cross country skiers	National	Heart rate $\dot{V}O_2$	16,905
Jones et al, 1993	4	20.1 ± 1.7	74.1 ±9.3	1.86 ± 0.11	Swimmers	Collegiate	DLW	Tapering 16,700 ± 3,700
Sjodin, 1994	2F 2M	25 ± 2 26 ± 2	54.4 ± 5.1 75.1 ± 4.9	1.66 ± 0.02 1.86 ± 0.06	Nordic Skiers	National	DLW	15,100 – 20,200 25,400 – 34,900
Ebine, 2002	7	22.1 ± 1.9	69.8 ± 4.7	1.75 ± 0.05	Soccer	Professional	DLW	14,800 ± 1,700
Vogt, 2005	11	28.7 ± 4.2	71.0 ± 5.2	1.81.0 ± 4.2	Elite cyclists	Professional	RMR (Harris benedict equation), exercise EE (SRM power measurement system)	High Volume 20,874 Rest day 11,340
Motonaga, 2006	6	19-21	57.2 ± 3	1.71 ± 5.8	Runners	Sub-elite	Heart rate $\dot{V}O_2$	18,959 ± 3,103
Koehler, 2011	15	30.4 ± 6.2	80.8 ± 6.6	1.86 ± 7.8	Triathlon	Local	DLW Accelerometer (SenseWear™)	15,204 ± 3780 14,931 ± 1726
Drenowatz, 2012	15	23.6 ± 3.4	73.4 ± 9.7	1.82 ± 7.2	Endurance	Trained/local	RMR (ventilation hood), exercise EE (Heart rate $\dot{V}O_2$) and NEAT	High volume training week 20,260 ± 3,246 Low Volume training week 17,094 ± 2,675

							(accelerometer, SenseWear^{TM})	
Silva, 2013	7F	16.9 ± 0.7	64.0 ± 5.4	1.73 ± 3.3	Basketball	Elite junior	DLW	14,618 ± 1,012
	12M	17.0 ± 0.7	80.9 ± 7.7	1.93 ± 0.06				19,337 ± 2,851
Bradley, 2015	44	26.3 ± 3.3	92.1-110.1 ± 6.3	1.83 – 1.92 ±0.06	Rugby	Professional	Accelerometer (SenseWear^{TM})	Forwards 15,900 ± 530 Backs 14,800 ± 470

Table 1.1 Total daily energy expenditure of male athletes

TEE Total energy expenditure, kJ Kilojoules, DLW Doubly labelled water method, RMR Resting metabolic rate, EE Energy expenditure, NEAT Non-exercise activity thermogenesis.

1.2 Nutrition for athletes

The nutritional intake of athletes is critical for health, performance and recovery. Nutrition encompasses dietary EI, macronutrient and micronutrient intake, hydration and supplements (sports foods, ergogenic aids and vitamin and minerals), all which need to be prescribed with appropriate timing in and around training and competition (American College of Sports, American Dietetic & Dietitians of 2000). Historically, sports nutrition recommendations indicated "protein should not be too high, 50-80 g", "fat should not be consumed in amounts to burden the digestive organs" and carbohydrate is best obtained from rusks, chocolate, dried fruits, not sugar" (Vogel 1933). In 1936, it was recommended that caffeine be avoided in the training diet as it decreases muscular activity by as much as 23% (Voigt 1936). While in 1946 a light or heavy meal provided 2.5 - 3 hours before a 100 yard swim had no effect on performance (Haldi & Wynn 1946). In 1948, the recommendation "a good training diet must include, in addition to bread, meat, eggs and potatoes, a liberal supply of oranges, grape fruit, tomatoes, fresh beans, cabbage, carrot, greens, lettuce, cauliflower and spinach" was made. Fluid recommendations were "5 pints per day made up, as far as possible, of bland liquids" (Leyton 1948). Since this time, while recommendations have changed in some respects, a lot of the same general principles still apply.

1.2.1 Energy requirements and intakes

Adequate EI is required not only for performance but is essential for maintaining lean muscle mass, immunity and reproductive health (Loucks, A. B. 2004). Sub-optimal energy intake can result in fat and muscle being used as fuel, which may be the aim if mass-loss is required but if not, a loss of muscle will reduce strength and endurance performance (Burke et al. 2011; Rodriguez et al. 2009). Prolonged sub-optimal energy intake will result in insufficient nutrient intake, leading to nutrient deficiencies and further decrements in performance (Loucks, A. B. 2004). Energy intake may be planned to be in excess or decrement depending on the goals of the athlete.

Energy balance occurs when energy 'in' is equal to energy 'out'. Energy 'in' refers to the dietary energy consumed that is metabolised (Manore & Thompon 2007) or the EI after the energy lost in urine and faeces and is approximately 90-95% of intake (Jequier & Tappy 1999). Energy 'out' is the energy expended through the RMR, TEF, physical activity and growth during development. Put simply, if energy 'in' and 'out' are in balance, body mass is maintained, if energy 'in' exceeds 'out' body mass increases and if 'in' is less than 'out', body mass is lost. This is the primary determinant of body mass however macronutrient balance, genetics, physiology, environment and behaviour will also have an influence (Jequier & Tappy 1999). It should also be considered that body mass is not always a reliable indicator of energy balance as hydration, protein and glycogen stores can influence body mass, providing a false change that is not associated with fat or lean tissue loss. For example, mass gain can be from an increase in glycogen storage from a greater carbohydrate intake. Body mass provides little information about an athlete's nutritional or physiological status (Loucks, A. B. 2004).

Energy intake needs to be periodised according to the training program and time of season. During the general preparation phase of the season EI needs to be high to support training. As the training becomes more specific where volume is reduced but intensity increased, energy is slightly reduced but remains high. During the taper or competition phase, energy is reduced but enough energy is provided around competition to ensure sufficient stores. Energy intake is at its lowest when training volume and intensity is low, during the transition period (Stellingwerff, Maughan & Burke 2011).

To determine energy requirements, expenditure can be measured (discussed in section 1.1.3) or requirements can be estimated with predictive equations. There are a number of equations to predict RMR such as the Harris- Benedict and Cunningham equations that utilise height, body mass, age and lean body mass to estimate RMR (Cunningham 1980; Harris & Benedict 1918). The Cunningham equation includes a measure of lean body mass and is considered to be the most appropriate for athletes (Cunningham 1980). The result of this is then multiplied by an activity factor that can range from 1.2 for bed rest up to 2.2 for vigorous activity (Black et al. 1996; National Health and Medical Research Council 2006).

All methods both measured and estimated, need to be interpreted with caution as individual variability and other factors should be considered including whether body mass is being maintained, if nutrient stores are sufficient and reproductive health is normal (Loucks, A. B. 2004).

Matching EI with expenditure everyday may not be necessary and sometimes may not be possible. In some cases sub-optimal EI early in the week could be compensated for later in the week (Bradley et al. 2015). However failure to compensate for large energy deficits over the long term may result in fatigue and reduced performance (Broad 2008). High volume training days or competition days where athletes have a number of training sessions and little time to eat often result in an under consumption of energy. In some athletes, appetite can be suppressed from training especially when training is a high intensity that can induce feelings of nausea. In a study with male and female Ironman triathletes, energy balance was measured on race day (Kimber et al. 2002). The EI of females was 5,123 kJ below expenditure and 5,973 kJ below for males (Kimber et al. 2002). There would have been limited opportunity to consume enough energy to support expenditure.

It should also be considered that EI does not necessarily need to match EE. Relative energy deficiency (RED-s) is the balance between dietary EI and the EE required to support growth, health, ADL and exercise EE (Mountjoy et al. 2014). The leftover energy from dietary intake after exercise EE is required for metabolic processes is known as energy availability. Chronically low energy availability is associated with metabolic dysfunction and can result in compromised immunity, bone health, hormonal and metabolic abnormality and therefore performance (Loucks, A.B., Kiens & Wright 2011; Mountjoy et al. 2014). If after exercise, energy availability is above 126 $kJ \cdot kg^{-1}$ $FFM \cdot d^{-1}$, there is reduced risk of health and physiological problems (Loucks, A.B., Kiens & Wright 2011). Limited research is available in male athletes as RED has most often been associated with female athletes, however recently it has been acknowledged that RED-s can occur in males (Mountjoy et al. 2014). Risk is generally greatest in weight category and aesthetic sports however with increasing pressure to be within certain levels of body fat, there are increased risk in other elite and professional sports (Burke et al. 2011).

Often athletes are not under consuming energy but rather underreporting and this could be on purpose or unintentionally. In the general population there is an underreporting error of approximately 18% (Mertz et al. 1991) and 10-45% in athletes (Magkos & Yannakoulia 2003). Tour de France cyclists reported consuming 13 - 35% less energy than expenditure which was thought to be due to underreporting as they maintained body mass throughout the race (Westerterp et al. 1986). The EE and EI of male endurance athletes were monitored over high and low volume training weeks (Drenowatz et al. 2012) using a combination of fasted RMR measurement, individual heart rate oxygen consumption regression for exercise EE and the SenseWear Pro armband for NEAT for TDEE and the Block Food Frequency questionnaire for dietary intake. Energy intake was 11,180 ± 5,455 kJ (mean ± SD) in the high volume week and 10,445 ± 5,094 kJ in the low volume week, 45% and 39% lower than expenditure respectively (Drenowatz, Eisenmann, Pivarnik, Pfeiffe, et al. 2013). A similar result existed in nine female distance runners over seven days when intake was 8,759 ± 1,251 $kJ \cdot day^{-1}$, 32% less measured TDEE (Edwards et al. 1993). In both studies body mass and composition did not change and it was concluded that the athletes were underreporting intake rather than under eating (Drenowatz et al. 2012; Edwards et al. 1993). A greater TDEE is associated with a greater level of underreporting (Magkos & Yannakoulia 2003; Westerterp et al. 1986). Also, in some cases, athletes consume a large volume of food and have an increased number of eating occasions and find it hard to recall all food items (Burke 2001b). Athletes may also alter their dietary intake during reporting to make reporting easier or to reflect a ‘healthier’ intake for the professional assessing the diary (Black et al. 1991; Hill & Davies 2001; Mertz et al. 1991). Finally, there is also the possibility that EE was over estimated from an accumulation of error from the combination of methods of used to measure EE (Achten & Jeukendrup 2003; Zanetti et al. 2014).

Manipulation of EI and/or EE is required when changes in body composition are required. For body mass loss, EI needs to be approximately 2,000 $kJ \cdot d^{-1}$ less than expenditure which can come from either a reduction in intake or an increase in expenditure or a combination of both. For body mass gain in athletes, an excess of 2,000 $kJ \cdot d^{-1}$ is required over the short term (Rankin 2002). Other factors including macronutrient composition, meal pattern and nutrient timing also impact mass and composition change. Athletes in some sports will cycle their EI to meet mass requirements. Restricting EI over the long-term results in a reduction in metabolic rate (Mole 1990) but can also possibly lead to an increase in the storage of fat (Saltzman & Roberts 1995; Thompson, Manore & Skinner 1993). Those who are in energy deficit tend to have lower RMR than those who are energy replete, which could be influenced by mass loss from the energy deficit (Leibel, Rosenbaum & Hirsch 1995; Steen, Oppliger & Brownell 1988). Gymnasts and runners who were in energy deficit tended to have higher body fat levels. The greater the deficit, the higher the body fat levels tended to be (Deutz et al. 2000). The study also showed that the athletes who consumed a greater proportion of their daily energy requirements, tended to have lower body fat levels (Deutz et al. 2000).

Energy intake varies throughout the training and competition season and needs to be varied with expenditure, health and performance requirements and body composition goals. However, studies show that some athletes do not modify intake based on training volume (Drenowatz et al. 2012; Edwards et al. 1993). This may be for a number of reasons including lack of time to eat, lack of appetite or intentional energy restriction. Underreporting actual intake could also be responsible. While energy intake is important the macronutrient composition of the energy must also be considered and like energy, needs to be manipulated based on training and competition requirements.

1.2.2 Macronutrient requirements and intakes of athletes

The intensity and duration of exercise, the nutritional status of the athlete, sex of the athlete and the aim of the exercise session determine the macronutrient requirements of a sport (American College of Sports, American Dietetic & Dietitians of 2000). Fat and carbohydrate are the main substrates used to fuel aerobic synthesis of ATP in skeletal muscle and use varies depending on exercise intensity (van Loon et al. 2001). The diet prior to exercise, training status, substrate availability and environmental factors such as temperature will also determine the contribution of each substrate to overall fuel supply (van Loon et al. 2001).

At rest and during low intensity exercise, fat is the predominant fuel source providing approximately 55% of the energy (van Loon et al. 2001). When the intensity is at approximately 75% $\dot{V}O_{2max}$, fat oxidation decreases, providing only 25% of energy and carbohydrate provides 75% of the energy (van Loon et al. 2001). Carbohydrate is the predominant fuel at or close to $\dot{V}O_{2max}$ (van Loon et al. 2001). During anaerobic exercise, ATP together with the breakdown of intra-muscular phosphocreatine (PCr) and the breakdown of carbohydrate, mainly in the form of glycogen, are used for immediate energy (Gastin 2001). Glycogen and therefore carbohydrate, is required to rapidly generate ATP. During aerobic exercise, glycogen is also used for ATP production at a slower rate production (Gastin 2001). Substrate usage can be effected by environmental factors such as heat. During the last 30 min of exercise at 55% $\dot{V}O_{2max}$ in 35 °C, muscle glycogen utilisation increased by 25% and exogenous glucose oxidation decreased compared to exercising in a 16 °C environment (Jentjens, Wagenmakers & Jeukendrup 2002).

1.2.2.1 Carbohydrate requirements and intakes of athletes

Carbohydrate (CHO) stores are limited in the human body and need to be supplied through the diet. Carbohydrate requirements for athletes on some days are not too dissimilar to the general population and need to be periodised according to training volume and intensity, training goals or required outcomes and competition preparation (Stellingwerff, Maughan & Burke 2011). Daily carbohydrate requirements have been suggested as follows: 3 - 5 g·kg BM for low intensity or skills based activity, 5 - 7 $g{\cdot}kg^{-1}$ BM for a moderate exercise program, 6 - 10 $g{\cdot}kg^{-1}$ BM for an endurance program with 1-3 hrs of moderate to high intensity exercise and 8 - 12 $g{\cdot}kg^{-1}$ BM moderate to high intensity exercise greater than 4-5 hrs per day (Bangsbo, Norregaard & Thorsoe 1992; Burke et al.

2001; Burke et al. 2011; Cox et al. 2010; Thomas, Erdman & Burke 2016). For a summary of guidelines for carbohydrate intake for athletes refer to Burke et al (2011). Recommendations for carbohydrate need to be considered within the needs of the individual athlete, training requirements, energy needs and body composition goals. Interpreting these recommendations also needs to be done with care, and knowledge of the athlete and their sport. For example, a 110 kg AF player completing a 'moderate' training program with two sessions a day would require 770 grams of carbohydrate at 7 $g{\cdot}kg^{-1}$ BM. This could be difficult for the athlete to consume and tolerate based on their busy training schedule (Burke et al. 2011).

The dietary intake of athletes has been reviewed by Burke and colleagues and compiled into extensive tables detailing the energy and carbohydrate intake of athletes from before 1970, 1971 to 1989 and then from 1990 until publication (Burke et al. 2001). Prior to 1970, endurance and non-endurance athlete competing in the 1948 London Olympic games consumed approximately 6.0 $g{\cdot}kg^{-1}$ BM of carbohydrate (Berry, Beveridge & et al. 1949). Between 1971-1989 male endurance athletes reported an intake of 7.3 $g{\cdot}kg^{-1}$ BM and female athletes 5.4 $g{\cdot}kg^{-1}$ BM (Burke et al. 2001). Intake of male non-endurance athletes was 5.7 $g{\cdot}kg^{-1}$ BM and 4.9 $g{\cdot}kg^{-1}$ BM for females. After 1990, the intake of male endurance athletes was similar around 6.9 $g{\cdot}kg^{-1}$ BM and 5 $g{\cdot}kg^{-1}$ BM for females. Intake for male non-endurance athletes was 5.8 $g{\cdot}kg^{-1}$ BM and females, 4.5 $g{\cdot}kg^{-1}$ BM (Burke et al. 2001). It is likely that the intakes reported above are 10 - 20% higher when underreporting is taken into consideration (Burke et al. 2001).

It is very likely that athletes often do not reach carbohydrate recommendations because they are unable to consume enough or they are purposely avoiding carbohydrate (Burke et al. 2001). Large quantities of carbohydrate are difficult to consume and may cause gastrointestinal upset and create feelings of 'heaviness' in the gut (de Oliveira, Burini & Jeukendrup 2014). Strategies to combat this may mean relying on foods that are high in sugar or have been highly processed and can be easily digested, going against healthy eating recommendations. This may be suitable for competition days however less appealing for regular consumption.

In recent times carbohydrate has become the 'bad guy' of nutrients through promotion of fad diets (Rosenbloom 2014). Athletes are not immune to this information and will often avoid carbohydrate for body composition or health reasons (Burke et al. 2001). Other factors such as time restraints, nutrition knowledge and food availability can also play a role (Burke et al. 2001). Training with low carbohydrate availability can be useful in some instances however a long-term deficit can be detrimental to health and performance (low carbohydrate diets will be discussed in section 1.2.2.3). Training in an energy deficit with low carbohydrate intake in the long term can compromise immune function, training staleness and eventually burnout (Stellingwerff, Maughan & Burke 2011).

Acute fuelling strategies to promote optimal performance in key training sessions and competition are also provided to the athlete and will depend on the duration and intensity of the session and also whether energy stores need to be replaced rapidly between sessions.

Carbohydrate intake in the days and hours prior to competition and training, intake during performance and post-performance is necessary to maximise glycogen stores (Burke et al. 2011). The duration of the event or session guides carbohydrate requirements. For sessions or events less than 90 mins, an intake of 7 - 12 $g \cdot kg^{-1}$ BM in the 24 hrs prior or if the event is greater than 90 min, 10 - 12 $g \cdot kg^{-1}$ BM in the 36 - 48 hrs prior. Based on typical resting values of glycogen storage in the muscle of 100 - 120 $mmol \cdot kg^{-1}$ wet weight^{-1} (w.w) and glycogen synthesis is approximately 5 $mmol \cdot kg^{-1}$ $w.w^{-1} \cdot hr^{-1}$, it is suggested that 24 - 36 hrs are required to normalise glycogen stores prior to performance (Burke 2007). A study in endurance trained athletes showed that even greater muscle glycogen levels can be achieved. An intake of 10 $g \cdot kg^{-1}$ BM of carbohydrate increased baseline muscle glycogen from just under 100 $mmol \cdot kg^{-1}$ $w.w^{-1} \cdot hr^{-1}$ to 175 $mmol \cdot kg^{-1}$ $w.w^{-1} \cdot hr^{-1}$ within 24 hrs and were not different after 72 hrs (Bussau et al. 2002). Sports dietitians are able to tailor these recommendations to the individual athlete and will be dependent on their sport, session goals, body composition goals and personal preferences(Thomas, Erdman & Burke 2016).

In the hours prior to a session that is greater than 60 mins in duration, 1 - 4 $g \cdot kg^{-1}$ BM of carbohydrate can be provided in the form of easily digested carbohydrate that is low in fat, protein and fibre. A meal 4 hrs before exercise increases muscle and liver glycogen stores as well as providing additional glucose from storage in the gastrointestinal space (Coyle et al. 1985). However, this increases plasma insulin that suppresses fat utilisation and speeds up carbohydrate oxidation prior to exercise. Although this could be detrimental to performance, it does not seem to limit performance (Coyle et al. 1985). It has been suggested that the meal should provide enough carbohydrate that offsets the loss from increased oxidation with pre-exercise meals providing 200 - 300 g of carbohydrate demonstrated to prolong cycling endurance (Wright, Sherman & Dernbach 1991).

Carbohydrate intake during prolonged exercise (greater than 120 min) is necessary to prevent hypoglycaemia and maintain high carbohydrate oxidation rates thereby increasing endurance capacity (Jeukendrup, A.E. 2014). The amount of carbohydrate will depend on the type, intensity and duration of exercise but also the training status, preference and tolerance of the athlete. A dose response study found that ingestion of 60 - 80 $g \cdot hr^{-1}$ of carbohydrates improves time trial performance (Smith et al. 2010) however the gut needs to be trained to tolerate this carbohydrate load (Jeukendrup, A.E. 2010, 2014). In exercise greater than 2.5 hrs, a combination of multiple transportable carbohydrates (glucose and fructose) is beneficial as a combination of intestinal transporters can be used, enhancing carbohydrate uptake (Jeukendrup, A.E. 2010). Once the glucose transporters (SGLT1) are saturated, fructose can be absorbed by the fructose transporters (GLUT5) and a greater amount of carbohydrate can be consumed, up to 90 $g \cdot hr^{-1}$ (Jeukendrup, A.E. 2010). However in some athletes, fructose can increase the risk of gastrointestinal upset (de Oliveira, Burini & Jeukendrup 2014). In events lasting 30 to 60 min, carbohydrate mouth rinse can be effective and linked to improvement in performance however it is not clearly understood how these effects are mediated by the receptors in the oral cavity (Jeukendrup, A. E. & Chambers 2010).

Carbohydrate intake post exercise will depend on the necessity to restore glycogen stores for further exercise. The first hour after exercise has the highest rate of glycogen storage (Ivy et al. 1988) due to the activation of glycogen synthase by glycogen depletion (Wojtaszewski et al. 2001) however storage can be slowed by muscle damage caused during exercise (Costill et al. 1990). Glycogen stores can be normalised after 24 hrs through resynthesis and exogenous intake (Coyle et al. 1985). Some sports require stores to be replenished quickly as further training or competition is required soon after while there may be more time in other sports where the next session may not be for a number of days. When there is less than 8 hrs between fuel demanding sessions, an intake of 1.0 - 1.2 $g \cdot kg^{-1}$ $BM \cdot hr^{-1}$ for the first four hours is suggested and then resume daily needs (Burke et al. 2011; van Loon et al. 2000).

1.2.2.2 Protein requirements and intakes of athletes

Protein is required for structural and regulatory functions and is critical for survival. Protein is comprised of 20 amino acids, nine of which are essential and must be provided through the diet and from endogenous protein breakdown (National Health and Medical Research Council 2006). The amino acid Leucine has been identified as one of the most important in stimulating increased protein synthesis (Crozier et al. 2005). Protein acts as a substrate and trigger for adaptation after exercise, both resistance and aerobic. To maximise the adaptive response to training in athletes, net muscle protein balance needs to be maximised (Phillips & Van Loon 2011). To optimise muscle protein synthesis, the synergistic effect between exercise and protein intake is necessary (Moore et al. 2009). The maintenance of skeletal muscle mass is the balance between muscle protein synthesis and muscle protein breakdown (Phillips & Van Loon 2011). For hypertrophy to occur, periods of positive protein balance are required to allow for muscle protein accumulation (Phillips & Van Loon 2011). The majority of research has been conducted on protein intake and its effects on skeletal muscle post resistance exercise however newer research is also focusing on myofibrillar protein synthesis post endurance exercise. Myofibres are important in skeletal muscle contractile performance and therefore important in synthesis and turnover following endurance exercise (Konopka & Harber 2014).

The protein recommendations for the general population outlined for Australia, New Zealand and Canada suggest that 0.75 – 0.85 g·kg^{-1} BM·day^{-1} will be sufficient to meet the needs of 98% of the population and the United States suggest an intake of 46-56 g· day^{-1} (Health Canada 2016; National Health and Medical Research Council 2006; US Dept of Health and Human Services December 2015). Recommendations are based on nitrogen or protein balance where intake is equal to losses in a sedentary or minimally active population. The requirements for athletes are greater and recommendations from the American College of Sports Medicine, American Dietetic Association and the Dietitians of Canada suggest 1.2-1.4 g·kg^{-1} BM·day^{-1} for endurance athletes and 1.6-1.7 g·kg^{-1} BM·day^{-1} for strength trained athletes ('Position of Dietitians of Canada, the American Dietetic Association, and the American College of Sports Medicine: Nutrition and Athletic Performance' 2000; Phillips & Van Loon 2011). Determining requirements for athletes using the nitrogen balance method may not be suitable, rather requirements should be based on the optimal rate of replacement of proteins being broken down and to maximise adaptive processes (Phillips 2012).

Protein intakes above the recommendations for athletes have been reported as high as 3.5 g·kg^{-1} BM·day^{-1} (Phillips 2004). Previous thought was that higher protein intakes could affect renal function, however it has been shown that in people with normal renal function, an increased protein intake does not appear to compromise renal health (Phillips 2012). The National Health Medical Research Council of Australia states that a diet containing up to 2.8 g·kg^{-1} BM·day^{-1} of protein does not produce adverse effects on kidney metabolism in athletes (National Health and Medical Research Council 2006). A drawback of over consuming protein in the athlete’s diet is that it displaces other nutrients such as carbohydrate and fibre, which are required for performance and gastrointestinal health. Also, consumption in excess of the body’s requirements is oxidised as energy.

In addition to protein recommendations relative to body mass, the timing, spacing and quality of the protein source are also necessary factors to consider. Protein, containing essential amino acids are required post resistance exercise to aid recovery of muscle repair and building (Phillips et al. 1997; Tipton et al. 1999). The repair and building process continues for 48 hours post resistance exercise and protein intake should continue in this time to maximise recovery (Phillips et al. 1997). To determine the most appropriate dose of protein post resistance training for maximal muscle protein synthesis a dose response study using isolated egg protein was conducted (Moore et al. 2009). Protein doses from zero up to 40 grams were provided with muscle protein synthesis plateauing around 20 grams of protein intake. An intake of 40 grams provided no additional benefit over 20 grams (Moore et al. 2009). It has therefore been suggested that 20 - 25 grams protein post resistance training is required for optimal muscle protein synthesis (Moore et al. 2009; Phillips & Van Loon 2011) and to stimulate a high rate of myofibrillar protein fractional synthesis (Rowlands 2014) while a 40 gram dose of casein pre sleep stimulates muscle protein synthesis and improves net protein balance overnight (Res et al. 2012).

The quantity and timing of protein in the recovery period can influence muscle protein synthesis. After a resistance training session three protein feeding regimes were studied over a 12 hr period and included either 8 x 10 grams of whey protein in 125 ml every 1.5 hrs or 4 x 20 grams every 3 hrs or 2 x 40 grams in 500 ml every 6hrs (Areta et al. 2013). The intermediate feeding regime (4 x 20 grams) had the greatest effect on stimulating muscle protein synthesis in the 12 hr period (Areta et al. 2013). The myofibrillar fractional synthetic rate was similar in the first 1-4 hrs for all regimes however in the 4 - 6 and 6 - 12 hr periods, the intermediate regime had greater fractional synthetic rate than the other regimes feeding (Areta et al. 2013). Small doses of protein are insufficient to stimulate elevation of blood aminoacidemia which stimulates maximal rates of muscle protein synthesis, while bolus doses greater than 20 grams stimulate muscle protein synthesis however the excess protein is oxidised and therefore cannot be used again later (Areta et al. 2013). The combination of protein dose and timing between doses seems to provide the optimal feeding regime in this study group (Areta et al. 2013).

The type of protein provided is also important. High quality protein is available through animal proteins including milk, meat and eggs due to their digestibility and amino acid profile. To maximally stimulate muscle protein synthesis after exercise, approximately 8.5 grams of essential amino acids are required that is provided in 20 grams of protein from animal products (Moore et al. 2009). The intake of whey hydrolysate, micellar casein and soy protein isolate on muscle protein synthesis were compared at rest and after resistance exercise in young men (Tang et al. 2009). Consumption of whey resulted in 122% greater muscle protein synthesis compared to casein and 31% greater than soy protein and while soy protein had a 69% greater muscle protein synthesis than casein (Tang et al. 2009). It is thought the difference between the proteins is due to the amino acid content, specifically Leucine but also the speed of digestion (Phillips & Van Loon 2011; Tang et al. 2009). Whey and soy are considered to be digested ‘fast’ and casein ‘slow’ (Tang et al. 2009). For a detailed review on protein and adaptation in athletes see Philips and Van Loon (2011) and Phillips et al (2012).

Diets higher in protein (25 – 35% energy or 2.3 – 3.0 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$) are able to preserve and even increase lean mass while decreasing fat mass (Helms et al. 2014; Longland et al. 2016). An intake of 2.4 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ of protein compared to 1.2 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ during energy restriction and while also completing high intensity interval training showed the higher protein group gained 1.2 ± 1.0 kg of lean mass compared to the lower protein group with only 0.1 ± 1.0 kg ($p<0.05$) (Longland et al. 2016). Fat loss was also greater in the higher protein group with 4.8 ± 1.6 kg loss compared to a 3.5 ± 1.4 kg loss (Longland et al. 2016). It can also be more satiating, making the individual feel fuller for longer (Westerterp-Plantenga et al. 2009). Because of this, there tends to be a reduction in overall EI, which is the main determining factor for mass loss. An increased protein intake in athletes, although possibly beneficial for body composition, may compromise performance, as other nutrients, specifically carbohydrate may be displaced (Phillips 2014). If increasing protein intake to assist in body composition control, it should be strategically placed at appropriate times in the season where performance will not be impacted.

1.2.2.3 Fat requirements and intakes of athletes

Fat is a necessary part of the diet providing not only energy but also components of cell membranes and essential fat-soluble vitamins A, D E and K. Fat is required to aid absorption of the fat-soluble vitamins and also provide a substrate for hormone synthesis (Stellingwerff, Maughan & Burke 2011). During moderate intensity exercise, plasma free fatty acid (FFA) oxidation rates account for 50 - 70% of total fat oxidation while intramyocellular triacylglycerol (IMTG) could contribute up to 50% of fuel (Stellingwerff, Boon, et al. 2007; van Loon et al. 2001). Fat recommendations in an athlete's diet are generally based on the prioritisation of carbohydrate and protein within energy requirements. This results in an overall allocation of 20 – 25% of total energy (Broad 2008).

Lipid stores in skeletal muscle are an important fuel source during exercise and decline following prolonged exercise (Stellingwerff, Boon, et al. 2007). The lipid deposits are stored in sub-sarcolemma area of type 1 muscle fibres and are used more than other lipid deposits (Stellingwerff, Boon, et al. 2007). During three hours of exercise at 50% W_{max} approximately 12% of EE came from plasma FFA, 13% from other fat sources, 4% from plasma glucose and 25% from muscle glycogen (Stellingwerff, Boon, et al. 2007). Plasma FFA and glucose oxidation increased over time while muscle glycogen and other muscle derived triacylglycerol declined over time (Stellingwerff, Boon, et al. 2007). It has been proposed that high fat (>60% energy) low carbohydrate (<25% energy) diets may be beneficial in trained athletes by reducing the reliance on muscle glycogen through increased utilisation of muscle fat (Vogt, M et al. 2003). Increasing dietary fat to 60% for 7 days increased IMTG concentrations by 36%, which increased fat oxidation to 72% during 60 min of exercise at 50% of W_{max} (Zderic et al. 2004). The opposite also occurred with very low fat diets where a diet of 2% fat reduced fat oxidation during exercise by 27% compared to a diet of 22% fat (Zderic et al. 2004). Fat is clearly an important fuel source however a review comparing endurance performance between long-term high fat diets and high carbohydrates diets found no difference between diets and that at-best a high fat diet could only maintain endurance performance (Helge 2002). Therefore it was recommended against use of high fat diets and further research is needed into this area in particular the types of fat that are provided during dietary interventions as early research suggests that fat are oxidised differently (Krishnan & Cooper 2014).

Increased fat in the diet may be of some benefit where performance does not exceed a certain intensity (<65% $\dot{V}O_{2max}$) however even endurance based sports such as cycling and triathlons require surges of effort that require maximum intensity, relying on glycogen stores (Bentley et al. 2002; Fernandez-Garcia et al. 2000). In addition, high fat, low carbohydrate diets require an athlete to be very organised for their dietary intake while also having a limited selection of foods making the diet quite monotonous. More research is required to understand how low carbohydrate conditions can be used (Burke 2015).

1.2.3 Nutrition and body composition

Nutrition has a direct impact on body composition. An excess or deficiency of energy will result in fat and lean mass changes (Rankin 2002). An excess of energy without a strength-training program will most likely result in fat mass gain, while with a strength-training program, lean mass gain should occur. An additional 2,100 to 4,200 kJ per day is recommended for body mass gain while the opposite is true for body mass loss. However a reduction in EI may compromise performance and recovery and therefore if desired mass loss is required, the appropriate time in the training program should be targeted (American College of Sports, American Dietetic & Dietitians of 2000).

A loss in body mass requires an energy deficit. A gradual loss is recommended through moderate energy restriction that can be achieved by reducing EI, increasing EE or a combination of the two resulting in a loss of 0.5 - 1 kg each week (Fogelholm 1994). In athletes, maintaining lean muscle mass is desired in most cases however in some instances, a body mass loss is required for weight category sports, which needs to come from lean mass in individuals with already low body fat. Reducing fat intake is an easy way to reduce overall EI as fat is energy dense however modification of other macronutrients can also elicit change. First and foremost a reduction in EI needs to occur. Weight-loss rates (slow, 0.7% body mass loss per week and fast, 1.4% loss per week) were compared with two levels of energy restriction while completing strength training (Garthe et al. 2011). After EI of participants was assessed, their EI was reduced by either 19 ± 2% in the slow loss group and 30 ± 4% in the fast loss group (Garthe et al. 2011). Carbohydrate made up approximately 54% of energy intake and protein approximately 25% in both groups. Body mass declined in both groups by approximately 5.5 % where fat mass loss was 31± 3% in slow loss and 21 ± 4% in fast loss while lean mass increased by 2.1 ± 0.4% during the slow loss and remained in the same in the fast loss group (Garthe et al. 2011). Strength and performance was not compromised in either group with strength increases in both groups for some exercises (Garthe et al. 2011).

Macronutrient content of the diet can also be modified to elicit body composition change. Carbohydrate restricted high fat and higher protein diets can be effective for mass loss (Longland et al. 2016; Mettler, Mitchell & Tipton 2010; Volek et al. 2002). Normal weight men who were on a habitual diet of 48% carbohydrate were placed on a diet of 8% carbohydrate for 6 weeks (Volek et al. 2002). Energy intake was unchanged while fat was increased from 32% to 61% and protein from 17% to 30%. There was a small but significant change in body mass from 79.2 kg to 77.0 kg while the control group remained stable. There was a mean loss of approximately 3 kg in fat mass and gain of 1 kg lean mass in the high fat diet group with no change in composition for the control group. These changes were thought to be due to a reduction in circulating insulin concentrations (Volek et al. 2002). Another study observed preservation of lean mass when protein was greater in an energy-restricted diet (Mettler, Mitchell & Tipton 2010). A study in healthy males assessed the body mass loss and body composition changes from a short-term energy reduced diet containing either 2.3 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ or 1.0 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ of protein (Mettler, Mitchell & Tipton 2010). The energy from fat was increased in the lower protein group to match groups for energy. The lower protein group lost a greater amount of body mass (approximately 1.2 kg more) however this came from a much greater loss in lean mass (approximately 1.5 kg more). Fat mass loss was similar in both groups at approximately 1.2 kg (Mettler, Mitchell & Tipton 2010). Another study conducted during a high intensity exercise intervention placed subjects on an energy restricted diet containing either 2.4 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ of protein or 1.2 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$(Longland et al. 2016). The higher protein group gained 1.2 ± 1.0 kg of lean mass compared to the lower protein group with only 0.1 ± 1.0 kg ($p<0.05$) (Longland et al. 2016). Fat loss was also greater in the higher protein group with 4.8 ± 1.6 kg loss compared to a 3.5 ± 1.4 kg loss. Athletes requiring a loss in body mass might find a higher protein diet (2.3 $g \cdot kg^{-1} BM \cdot day^{-1}$) beneficial as it minimises lean mass loss however, if the composition of the mass loss is not an important focus, then the lower protein (1.0 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$) approach may be more beneficial. Part of the reason for the minimal loss of lean muscle with the higher protein diet could be due to a greater nitrogen balance during body mass loss and also the equal distribution of the protein across the day providing a steady supply of protein (Mettler, Mitchell & Tipton 2010).

Other strategies such as increasing the water content of meal can aid in reducing EI (Rolls, Bell & Thorwart 1999). One of three isoenergetic meals were provided as a pre-load to lunch to subjects; a casserole, a casserole with a water beverage or a chicken soup. Energy intake in the meal following was reduced by 26% if the soup meal was consumed. By increasing the water content of a meal the energy density of the meal is reduced (Rolls, Bell & Thorwart 1999). The feeling of fullness is increased, hunger is decreased and subsequent EI is reduced. Interestingly, if a beverage was provided with a meal, it did not have the same effect (Rolls, Bell & Thorwart 1999).

Approaches discussed above, tend to have one thing in common, a reduction in total EI. Although the approaches don’t directly prescribe a reduction in energy, they tend to result in less energy being consumed. Higher protein and higher fat diets are more satiating and therefore less energy is generally consumed (Westerterp-Plantenga et al. 2009). These types of diets are also limited in food groups and selection and can result in a reduced food intake due to monotony and possible difficulty in preparing or accessing foods.

1.3 Body composition and physique of athletes

Body composition and physique of an athlete refers to the tissue composition of the body and size, shape and proportions of the athlete. All sports have different requirements. Sports that require the body to be transported over distance such as marathon running, aesthetic sports such as gymnastics or light-weight category events require light, lean physiques, while sports that require strength and power such as Rugby, require large physiques. The measurement of these parameters can be used for identification of athletes for a particular sport or position within a sport, to monitor the growing athlete or those with body composition goals, to monitor training and to determine optimal body composition for weight class sports (Kerr, Ackland & Schreiner 1995).

1.3.1 The role of body composition in talent identification and selection

It has been said that successful athletes are those with the appropriate structure to perform their event (Carter in Clark DH 1985). This association exists in sports including rowing (Slater et al. 2005), football (Olds 2001), aesthetic sports (Claessens et al. 1999) and swimming (Siders, Lukaski & Bolonchuk 1993). Specific factors such as height, low body fat percentage, muscle mass and limb length can contribute in part to the success of an athlete however it is also possible to not have the optimal physique and still be successful in a sport (Hoare 2000). Success in team sports in particular requires skill, knowledge of match strategy, psychological factors and other physiological characteristics that determine success (Hoare 2000). There is also suggestion that "characteristic morphologies in different sports are diverging" and the "ideal athletic (body) type is being replaced by radically different, highly specialised and increasing divergent body types" (Norton & Olds 2001). In some sports, for example basketball the rate of increase in height is four times the secular trend of the population, suggesting that it is an advantage to be a larger athlete in these sports (Norton & Olds 2001), possibly impacting selection in high level teams.

Anthropometric traits are often used in junior team sports to select athletes especially in sports that require strength, height and body size for success such as football sports and handball (Malina 2004; Matthys et al. 2012; Pearson, Naughton & Torode 2006). These athletes tend to be early maturers and the advantage they have at the time of measurement may not continue into the later years when late maturing athletes catch up (Pearson, Naughton & Torode 2006).

Selection for positions within a sport can be influenced by physique, which is leading to specialisation for these positions. In junior basketball, both 15 year old male and female centre position players were placed in the 99th percentile for height compared to normative data of 15 year old Australians (Hoare 2000). Other measures including arm span and body mass can make a player more likely to be selected as the 'best' within a position. For example, the 'best' point guard male players had a 7.4 cm greater arm span than the 'rest' and the 'best' power forward players were 6.7 kg heavier than the 'rest' (Hoare 2000). In females, the centre position had proportionately longer legs (49.2% of total height) than the point guard position (48.2% of total height) however the point guard players identified as the 'best' had proportionally longer legs (48.2% of total height) than the 'rest' (47.4% of total height) in their group. The guard position requires stability and agility as they are ball carriers and lower centre of gravity is beneficial. This attribute also provides a biomechanical advantage in jumping and was reflected in a 10 cm greater vertical jump in the 'best' group compared to the 'rest' group (Hoare 2000). Other sports such as rowing incur a biomechanical advantage from anthropometric attributes. In addition to physiological measures, height and arm span measures were used to identify a group of 14-16 year old rowers who went on to be successful at national championships within six months of identification and selection in the Australian junior team (Hahn 1990). Also, a short sitting height with longer limb lengths are also characteristic of successful rowers (Hahn 1990).

1.3.2 Body composition in growth and development

Athletes are being identified for sports at early ages, during a critical time of growth and development. Rapid changes occur in height, mass, shape and tissue composition with puberty and this occurs at different ages for both sexes. Children of the same age will vary in biological maturity and those that mature early will generally be taller and heavier (Malina & Geithner 2011). In males this will be due to greater lean muscle mass while in females, greater fat mass. Body composition will vary throughout childhood through to young adulthood and is associated with age, sex and ethnicity (Malina 2005).

The adolescent period is associated with a rapid gain in muscle mass (Malina 2004). Boys gain a considerable amount of lean muscle mass during the adolescent growth spurt, which continues until about 20 years of age. In females, peak muscle mass values are reached at about 16 years of age and they will have approximately 1.5 times less lean muscle and 1.5 times more fat mass than males. The relative fatness of females gradually increases throughout adolescence whereas in males it declines from the adolescent growth spurt until it reaches its lowest point when they are 16-17 years of age when lean muscle is rapidly increasing.

It is possible that changes in body composition that occur with the growth spurt occur during the course of a competitive season (Malina & Geithner 2011) and therefore monitoring this change is important. In athletic adolescents it is hard to discern between changes in lean muscle mass from normal growth and development from maturation and from training. It is possible to assume that changes in lean mass are mostly attributable to maturation as recommendations suggest that any resistance training in younger athletes should predominantly be body mass based and therefore should not greatly stimulate additional muscle growth (Malina & Geithner 2011).

When measuring body composition and development in adolescence it is important to know when peak height velocity has occurred. Peak height velocity is the timing of maximal rate of growth in height during the adolescent growth spurt. A study in 1,172 junior Rugby League players found that peak height velocity occurred at around 13.6 years of age and there was no difference between players at the regional or national level (Till et al. 2011).

Fat free mass is closely related to height during growth and development while fat mass and percent fat mass is influenced by normal growth and maturation, nutrition and training (Malina & Geithner 2011). In sports such as wrestling where body mass and body composition are emphasised, recommendations have been made for young athletes to minimise the risk of compromising health and growth (Oppliger et al. 1996). It is suggested that young wrestlers should have their body composition measured prior to the season with a valid measure and for male wrestlers under the age of 16 with body fat less than 7% and wrestlers older than 16 and <5% body fat, medical clearance must be obtained (Oppliger et al. 1996). These recommendations are necessary for coaches and parents who may have little knowledge in this area to ensure growth and development is not compromised.

Compared to the general population, adolescent athletes who compete in sports will have greater Bone Mineral Content (BMC) and Bone Mineral Density (BMD) than the non-athletic population due to the weight-bearing activity and high impact activities that stimulate bone growth (Malina & Geithner 2011). A study of BMD and bone area in adolescent boys (16.8 ± 0.31 years) who competed in either badminton or ice hockey was completed and results compared to a control group (Nordstrom, Pettersson & Lorentzon 1998). When adjusted for body mass players from both sports had a greater BMD (Badminton 1.22 ± 0.06 $g \cdot cm^{-2}$, hockey 1.23 ± 0.07 $g \cdot cm^{-2}$) compared to the controls (BMD 1.18 ± 011 $g \cdot cm^{-2}$). The badminton players had greater BMD at many of the weight-bearing sites compared to ice hockey. A greater BMD is most likely due to the high-impact movements when jumping and strain from quick directional change associated with the game of badminton. Bone area was strongly related to muscle strength and height rather than the type of physical activity (Nordstrom, Pettersson & Lorentzon 1998). Another study compared the BMD of adolescent athletes in sports that include impact loading (gymnastics, basketball, athletics and tennis), to sports that do not (swimming and water polo) and a control group (Lima et al. 2001). Athletes in the impact loading group had a greater BMD than the other two groups and there was a positive correlation of BMD with weight and lean mass in all groups (Lima et al. 2001).

1.3.3 Monitoring body composition throughout training and competition

Training in sport is periodised and varies according to the sport (Gamble 2006). It is planned according to competition and involves peaking at certain times of the season. In swimming for example, there are a number of competitions for which the athlete is required to peak for, while in team sports, the athlete is required to compete at their best every week or multiple times per week (Gamble 2006). All sports will have a period of preparation or pre-season; competition phases of which there are can be numerous throughout a season and off-seasons or a time with reduced training loads. Each phase has specific goals: Preparation will focus on increasing the fitness, strength and skills required for the sport and often the best time to focus on body composition changes. It can also be a time of high volume training, requiring significant EE and EI. The competition period will often be associated with reduced training loads and tapering going into an event while the off-season or download period will again reduce training load with a focus on recovery and rehabilitation (Gamble 2006). Nutrition and body composition also need to be periodised in conjunction with the training program to ensure optimal nutrition for body composition goals, performance and recovery but to also ensure that optimal body composition is attained for the competition period of time within the season (Stellingwerff, Boit, et al. 2007). Competition and training phases have an impact on body composition, which needs to be carefully managed over a season. Numerous studies on seasonal body composition have been conducted in football sports and will be discussed later in this chapter (Bilsborough, JC et al. 2016; Burke, Gollan & Read 1986; Carling & Orhant 2010; Georgeson et al. 2012). Body composition changes occur in other sports particularly those where body mass cycling occurs in weight category sports.

In lightweight rowing, athletes are required to meet a specified body mass either as an individual or average across a crew. To meet these specifications, the rowers will typically lose body mass for the competitive season and regain the body mass in the off-season (Morris, FL & Payne 1996). Food restriction and intense exercise are used for long-term reduction and other techniques such as dehydration, are used for short-term reduction. Females lose an average of 3 kg from pre-season to early competition as a result of a 1,300-1,800 kJ energy deficit, a further 1 kg in competition and then body mass is regained in the off-season (Morris, FL & Payne 1996). Males are similar and lose 3 kg from pre-season until early competition, a further 2 kg into competition and back to baseline in the off-season (Morris, FL & Payne 1996). Body mass loss comes from a loss in fat mass while lean mass remains stable in both males and females (Morris, FL & Payne 1996).

1.3.4 Body composition requirements for sport

Each sport has its own body composition requirements which are required for performance. Aesthetic sports such as gymnastics and figure skating require low body fat levels, endurance sports such as long distance running that are body mass dependent require low body mass and body fat while less body mass dependent endurance power sports such as rowing and cycling require high power to weight ratios and moderate to low body fat levels. Endurance sports that require strength and speed such as team sports like Soccer and long sprint athletics are similar to above but tend to have a moderate body mass. Sports requiring strength, power and speed but not endurance such as athletics (sprints), baseball and basketball, have moderate body mass and moderate body fat levels and finally sports that require explosive strength such as throwers have high body mass and high body fat levels (Fleck 1983; Stellingwerff 2015).

The body composition of 528 male athletes participating in 26 Olympic events and 298 female athletes participating in 15 Olympic events had their body composition measured with hydrostatic weighing (Fleck 1983). Male athletes involved in weight class combat sports such as boxing were 6.9 ± 1.6% body fat and sports where body mass was supported such as swimming were 12.4% ± 3.7% body fat in males and 19.5 ± 2.8% in females. Sports that required athletes to cover large distances such as marathons, males had a low body fat of 6.4 ± 1.3% (Fleck 1983). A later study assessed the body composition of 889 athletes from 21 sports using anthropometric measures for the full group and DXA for half the group (Santos et al. 2014). Male wrestling and judo athletes had 12.2% (95 % CI 11.3-13.1) body fat, male swimmers 12.5% (95 % CI 11.3-13.7) and female swimmers 23.3% (95 % CI 22.1-24.4) and male triathletes 11.9% (95 % CI 11.2-

12.5). The level of competition in which the athletes competed was not defined and they were included in the study if they trained for more than 10 hours a week. Age also ranged from 16 - 45 years (Santos et al. 2014). Therefore, reported results may not be reflective of elite level athletes however provide a helpful tool to assist professionals working in sport in assessing and classifying body composition for their athletes.

Reference ranges are also necessary for weight category and aesthetic sports that are required to meet set body mass categories or conform to expected body shapes for their sport. Body composition plays an important part of their preparation and performance (Rankin 2006). To achieve body mass divisions and restrictions, practices are often undertaken that elicit rapid mass loss and there will be frequent body mass fluctuations between competitions. The assessment of body composition in these athletes is crucial to identify where changes can be made in relation to body fat and lean mass and whether the desired goals are realistic with changes being made of the long-term, preventing the need for drastic change close to competition. Also, reference ranges are necessary to ensure safe practice in young athletes, for example, male wrestlers under the age of 16 with body fat less than 7% and wrestlers older than 16 and <5% body fat, medical clearance must be obtained (Oppliger et al. 1996).

1.4 Field based team sports

1.4.1 Background of field based team sports

Field based team sports are intermittent in nature with repeated bouts of high intensity efforts interspersed with low intensity activity (Aughey 2011; Coutts, A.J et al. 2010; Wisbey et al. 2010). Depending on the sport, purposeful direct physical impacts will occur from tackles, scrums and collisions in addition to jumping and quick change of direction. For the purpose of this thesis, football codes will be the main focus of this section and include AF, Rugby League, Rugby Union and Soccer. Despite sharing some similarities, the codes also have some quite significant differences.

Australian Football is a physically demanding sport. In the professional league the pre-season conditioning period starts at the beginning of November and season proper begins around April with finals being played in September. Each team plays 22 matches plus three to four finals matches if they qualify. The off-season or download period is approximately six to eight weeks. The match has four 20 minute periods plus additional time for stoppages which can potentially result in up to 126 minutes of total match time. However, players are regularly rotated and do not play the full match with a mean match time of 98 ± 11.6 min (Varley, Gabbett & Aughey 2014). Rotations allow players to recover and maintain the intensity on the field (Wisbey et al. 2010). Players can be assigned to three positional groups: forwards, backs and mid-fielders however each position can be nomadic and players often travel further than the fixed positions. Ruck players tend to cover the least distance in a match, approximately 11.7 km while mid-field players cover the most at 12.8 km however this can be greater in some matches (Coutts, A.J. et al. 2015). High speed running (>14.4 $km \times hr^{-1}$) as measured by GPS accounts for up to 4 km of the total distance and up to 1.4 km of very high speed running (>19.9 $km \times hr^{-1}$) (Coutts, A.J. et al. 2015). There are approximately 82 high-velocity running efforts, 22 sprints and 82 accelerations (Wisbey et al. 2010). The activity profile of the match continues to change over the years with mean velocity increasing by 8.4%, increase in intensity by 14% and a 9% decrease in playing time (Wisbey et al. 2010).

Soccer, also intermittent in nature involves jumping, kicking and tackling while sustaining forceful contractions to maintain balance and control of the ball against defensive pressure (Stolen et al. 2005). The professional league in Australia is referred to as the A-League with 27 in-season matches plus finals beginning in October and culminating in May. The pre-season begins in July prior to season proper and the off-season is approximately six weeks, however some players will have international representation in this time. Other competitions around the world will differ in number of matches played and the time of year for the season. Regardless of the region the match is played, each 90-minute match is played over two, 45 minute periods, with players covering 10 - 12 km at the top level of competition (Stolen et al. 2005; Varley, Gabbett & Aughey 2014; Wehbe, Hartwig

& Duncan 2014). Low-intensity activity is approximately 90-95% of match time with 0.52 km of high velocity running (Varley, Gabbett & Aughey 2014; Wehbe, Hartwig & Duncan 2014). The majority of actions are performed without the ball while contesting possession and following players (Stolen et al. 2005).

Rugby League is a high impact collision sport played over two 40-minute halves and players cover approximately 6.2 km a match. Low intensity activity consists of about 5.9 km of activity and 0.33 km of high velocity running as measured by GPS. Players complete about 25 efforts of high-velocity running with approximately 19 collisions interspersed throughout (Varley, Gabbett & Aughey 2014). Players are separated into forwards and backs positions, with forwards tending to be larger players and backs tending to be leaner and faster to carry the ball. Rugby League is played professionally in Australia and across the world. The professional league in Australia consists of 15 domestic teams and one New Zealand team. The season begins in March and culminates after 25 matches plus finals in late September. Pre-season conditioning begins in November after a six to eight week off-season.

Rugby Union is similar to Rugby League in that it is a high impact collision sport played over two 40-minute halves. The professional competition in the Southern Hemisphere is referred to as Super Rugby and has recently expanded to include 18 teams from Australia, Argentina, Japan, New Zealand and South Africa. Each team plays 15 matches plus qualifiers and finals beginning in February and finishing in August. The pre-season conditioning phase begins in October approximately 16 weeks prior to the competition starting. The off-season is approximately six weeks however players may have international representation. In addition to repeated bouts of high intensity efforts, Rugby Union involves tackling, scrimmages, rucking and mauling. Players are classified into forwards and backs positions with forwards playing more of a defensive role and backs playing an offensive role requiring speed. Backs players cover approximately 7.2 km a match and forwards 6.7 km (Cunniffe et al. 2009). Backs spend approximately 77.8% of their time standing and walking, 0.9% high intensity running and 1.4% sprinting (Cunniffe et al. 2009). Forwards spend less time at low intensity at 66.5%, 1.1% completing high intensity running and 0.8% sprinting. Back experience 798 impacts and forwards 1,274 with forwards receiving 60% more high-level impacts than backs (Cunniffe et al. 2009).

1.4.2 Energy expenditure of football sports

The TDEE and EE of various sports has been measured (Drenowatz et al. 2012; Ebine et al. 2002; Westerterp et al. 1986). However, while the activity profiles of football sports are well established (Varley, Gabbett & Aughey 2014), the measurement of EE in these sports and/or under free-living conditions has not received much attention due to difficulty in measurement. Traditional methods of EE assessment require metabolic analysis that restricts typical movement and ADL (Levine 2005). Technologies such as heart rate monitoring, GPS and accelerometers are now being used to estimate EE (Coutts, A.J. et al. 2015; Coutts, A.J., Reaburn & Abt 2003; Cunniffe et al. 2009; Mara, Thompson & Pumpa 2015; Osgnach et al. 2010; Stolen et al. 2005).

Of the football sports, Soccer has been the most researched for on-field EE and TDEE (Briggs et al. 2015; Ebine et al. 2002; Mara, Thompson & Pumpa 2015; Rodriguez FA 1998; Stolen et al. 2005). The TDEE of professional male Soccer players was estimated using the gold standard DLW method as 14,800 ± 1,700 kJ (Ebine et al. 2002). Using accelerometry, TDEE was 10,679 ± 1,026 kJ in 15 year old academy Soccer players (Briggs et al. 2015) and 15,900 kJ ± 530 and 14,000 kJ ± 470 for Rugby Union forwards and backs respectively (Bradley et al. 2015). In Rugby League, TDEE was calculated with BMR, TEF and a physical activity level of 1.86 and was 19,643.4 ± 537.6 kJ (Tooley et al. 2015). Estimates of TDEE have not been made in AF. Consideration must be taken when comparing estimates in these studies as each method has its own limitations and estimates EE differently but also the populations used are also quite different varying in age, level of professionalism, physique and football code. These studies are able to provide a general idea of TDEE in these football codes.

The EE of a match can be significant, contributing approximately 30% of TDEE or 4,500 kJ (Rodriguez FA 1998). The EE of a match was measured during a simulated match using a Cosmed portable respirometer and compared this estimate to the heart rate-$\dot{V}O_2$ method (Rodriguez FA 1998). The EE estimated by oxygen uptake was approximately 62.75 kJ.kg^{-1} (50.2 ± 9.2 kJ·min^{-1}) for three professional players and 56.2 kJ.kg^{-1} (47.4 ± 4.7 kJ·min^{-1}) for six amateur players. The correlation of the heart rate method with Cosmed ranged from 0.74-0.98 with a mean overestimation of estimated $\dot{V}O_2$ of 10.3% when heart rate was used (Rodriguez FA 1998). It is also important to consider that anaerobic energy use cannot be interpreted by gas exchange calorimetry and is some cases where anaerobic contribution to EE is high such as during resistance training, a separate estimate should be considered (Scott 2005).

A new approach was proposed to assess the metabolic demands of Soccer players using a ‘Metabolic Power’ algorithm and found a similar result to above (di Prampero et al. 1986; Osgnach et al. 2010). The algorithm assumes sagittal plane acceleration and deceleration are primary drivers of energy cost (di Prampero et al. 1986; Osgnach et al. 2010). Two components of acceleration are considered; With inclined terrain and vertical orientation of an athlete, accelerated running is considered similar to travelling a constant speed up an ‘equivalent slope’; During sprinting an athlete exerts greater force than their body mass referred to as ‘equivalent mass’. This additional force is required to overcome acceleration (Osgnach et al. 2010). Therefore, energy cost is calculated as the function of the equivalent slope by the equivalent mass by a grass environment constant of 1.29 (di Prampero et al. 1986; Osgnach et al. 2010). For example, running at a constant speed of 14 km·hr^{-1} on grass equates to an approximate metabolic power of 20 W·kg^{-1} however a similar power can be achieved at 9 km·hr^{1} when acceleration is elevated.

Using the ‘metabolic power’ approach described above EE has been estimated in Soccer, Rugby League and AF (Coutts, A.J. et al. 2015; Kempton et al. 2015; Osgnach et al. 2010). In Soccer, data was collected from 56 matches of the Italian first division teams where 399 players from 20 teams were evaluated. Mean match distance was 10,950 ± 1044 m, match time 95 min 5 s ± 1 min 40 s and EE was 61.12 ± 6.57 kJ.kg^{-1} (estimate is the EE above that of resting metabolism).

Of the total distance covered, 26% was considered high power (>20 W.kg^{-1}), which corresponded to approximately 42% of the total EE. The same method was used in Rugby League and estimated EE ranged from 25.7 – 43.5 kJ.kg^{-1} (Kempton et al. 2015) with 25% high power running. In AF, estimated EE was 57 kJ.kg^{-1} in tall forwards to 65.6 kJ.kg^{-1} in midfielders with high power running ranging from 21.4 – 31% (Coutts, A.J. et al. 2015). The estimate in Rugby League seems low when compared to Soccer and AF however this may be due to the decreased playing time and running demands of the match (Coutts, A.J. et al. 2015; Kempton et al. 2015; Osgnach et al. 2010). When compared to measures taken in an exercise protocol designed to replicate a half of Rugby Union, EE is comparable with 23.1 kJ·kg^{-1} and 23.0 kJ·kg^{-1} for indirect calorimetry and accelerometry respectively (Zanetti et al. 2014). These estimates are much lower compared to others using the heart rate method showing the EE of Rugby League to be 87.6 kJ·kg^{-1} (Coutts, A.J. et al. 2015) and Rugby Union backs 66.0 kJ·kg^{-1} and forwards 78.7 kJ·kg^{-1} (Cunniffe et al. 2009). The metabolic power model likely underestimates EE as it does not account for EE of limb movement and the high metabolic costs of activities such as tackles (di Prampero et al. 1986; Osgnach et al. 2010) while the heart-rate method can overestimate by 15 - 20% as heart-rate remains elevated during the low intensity intervals in high intensity intermittent activity (Rodriguez FA 1998).

1.4.3 Energy and nutrient intake in football sports

As seen above, football athletes can expend a significant amount of energy on the field and throughout the day and therefore the assessment of EI is important to determine if they are meeting their energy requirements to support training, competition and body goals. In a recent assessment of EI and EE in professional Rugby Union players EI changed across the week with a mean intake (± SD) of 16,000 kJ ± 1,250 and 14,200 kJ ± 1,200 for forwards and backs respectively (Bradley et al. 2015). Intake and expenditure tended to balance each other over the week where early in the week, EE tended to be higher than intake while later in the week, EI was greater than EE leading into the match (Bradley et al. 2015). Total daily energy intake in Rugby League ranges from 15,670 kJ (Tooley et al. 2015) to 18,307 kJ (Lundy et al. 2006). Energy intake in Soccer was less than in the Rugby codes at 13,000 kJ (Ebine et al. 2002; Reeves & Collins 2003) and was less than the mean TDEE across a week (Ebine et al. 2002). A similar intake occurred in AF both in pre-season and during the competitive season ranging from 12,266 kJ in inexperienced players to 12,755 kJ in experienced players (Bilsborough, JC et al. 2016) and in county and club level Gaelic footballers of 12,533 ± 989 kJ and 12,164 ± 1,350 kJ respectively (Reeves & Collins 2003). Intake in AF has not really changed over time from when it was first measured in 1988 when it was 14,200 kJ however the macronutrient composition of the energy has changed with a reduction in fat intake and an increase in protein (Bilsborough, JC et al. 2016; Burke & Read 1988).

While EI is important it is also necessary to understand the energy substrates used during football matches. Even though a large portion of matches are spent at a low intensity allowing for the release and use of free fatty acids, high intensity activity relies predominately on muscle glycogen (van Loon et al. 2001). Carbohydrate intake needs to be periodised across the week depending on training and competition. Rugby Union players consume 3 - 4 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ early in the week for training sessions regardless of volume or intensity and increase intake to approximately 5 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ in the one to two days prior to the match (Bradley et al. 2015). A higher intake existed in Rugby League players, where they consumed 7 ± 1.6 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ leading into competition and 6.8 ± 2.3 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ on match day however this was significantly reduced post-match to 4.5 ± 1.5 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ (Lundy et al. 2006). Professional Soccer players had a mean intake of 5.9 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ (Reeves & Collins 2003) whereas AF players had a lower intake of 4.1- 4.2 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ in experienced and inexperienced players across pre-season and competition (Bilsborough, JC et al. 2016). Interestingly, intake of carbohydrate has not changed over time in AF players from when it was measured in 1988 at 4.4 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ (Burke & Read 1988) and intake is greater in county and club Gaelic football with intake of 4.5 - 5.2 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ where the level of competition and time dedicated to training is not considered as high (Reeves & Collins 2003). A lower intake of carbohydrate around 3 - 4 $g{\cdot}kg^{-1}$ $BM{\cdot}day^{-1}$ would be sufficient for skills based training however it seems that in the majority of cases, carbohydrate recommendations of 6 - 10 g·kg^{-1} BM·day^{-1} for athletes partaking in moderate to high intensity exercise lasting 1 - 3 hours (Burke et al. 2011), are not being met for match preparation. High-intensity exercise can separate top-class football players from those of a lower standard (Bangsbo, Mohr & Krustrup 2006) and therefore, sufficient glycogen stores are required and need to be maximised with adequate carbohydrate intake. Carbohydrate intake of 8 g·kg^{-1} BM·day^{-1} was compared with 4 g·kg^{-1} BM·day^{-1} on the glycogen stores of football players (Balsom et al. 1999) going into a 90 min small sided match. The higher carbohydrate group had approximately 27% greater glycogen stores than the lower intake group and performed approximately 33% more high intensity exercise during the match (Balsom et al. 1999).

Football codes in Australia typically play one match a week with five to nine days between matches and sometimes the A-league Soccer teams may have two matches a week if competing in international competitions. A recovery day or day off is usually scheduled in most football codes so rapid replenishment of glycogen with high intakes of carbohydrate may not be necessary. The focus of recovery should ensure repair of muscle damage in addition to replenishing glycogen stores with foods containing both carbohydrate and protein and replacing lost fluids (Holway & Spriet 2011). It has been suggested the combination of protein and carbohydrate can increase the rate of glycogen resynthesis however a recent study in competitive Soccer showed that a diet high in carbohydrate (70% of total energy intake) and protein (21% of total energy) versus a normal carbohydrate (55% of total energy) and protein (18% of total energy) diet made no difference in muscle glycogen storage (Gunnarsson et al. 2013). Rather than influencing glycogen uptake, the combination of protein and carbohydrate can accelerate protein synthesis (Howarth et al. 2009). The ingestion of 1.2 g·kg^{-1} BM·day^{-1} of carbohydrate is thought to be sufficient to begin glycogen replenishment with at least 20 grams of high quality protein for muscle protein synthesis (Howarth et al. 2009; Phillips & Van Loon 2011).

Protein quality and timing of ingestion is crucial for all athletes (Moore et al. 2009; Phillips & Van Loon 2011). For team sport athletes this is no different and should be evenly distributed throughout the day and immediately post training and competition for adaptation (Phillips & Van Loon 2011). The protein recommendation for football, power sports is 1.4 - 1.7 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ (Tarnopolsky 2006) which falls within recommendations for endurance (1.2 – 1.4 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$) and strength trained athletes (1.6 – 1.7 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$) ('Position of Dietitians of Canada, the American Dietetic Association, and the American College of Sports Medicine: Nutrition and Athletic Performance' 2000). Reported intake in team sport athletes tend to fall within or above recommendations. In 1988 the protein intake of AF players was 1.5 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ while in newer studies intake of professional Rugby Union, Rugby League and AF players is approximately 2.3 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ (Bilsborough, JC et al. 2016; Bradley et al. 2015; Lundy et al. 2006; Tooley et al. 2015). Intake in professional Soccer is 1.6 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$, county Gaelic football, 1.5 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ and club Gaelic football 1.3 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ (Reeves & Collins 2003). On match day in Rugby League, protein intake is reduced to 1.7 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ to make room for an increase in carbohydrate while intake is similar post match at 1.8 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ when carbohydrate decreases and fat and alcohol intake increases (Lundy et al. 2006). In AF, intake varies across the season where intake ranges from 1.9 - 2.2 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ in pre-season where training volume are high and recovery is crucial, to 1.4 - 1.5 $g \cdot kg^{-1}$ $BM \cdot day^{-1}$ at the end of season when fat and alcohol intake increases and dietary practices are relaxed (Bilsborough, JC et al. 2016). The greater intake of protein in AF and the rugby codes could partly be from a larger overall EI compared to Soccer players but it should also be considered that this high intake may be displacing carbohydrate which has been shown above to be sub optimal.

Fat recommendations for athletes of 20 – 30% of total energy are mainly based on the prioritisation of carbohydrate and protein in the diet (Broad 2008) and in football codes fat intakes mostly fall within this range (Bilsborough, JC et al. 2016; Lundy et al. 2006; Reeves & Collins 2003; Tooley et al. 2015) with the exception of Rugby Union at 33% (Bradley et al. 2015). Over time, fat intake has decreased with greater education and emphasis on body composition. In AF players fat intake in 1988 was 37% of total energy (Burke & Read 1988) and now fluctuates between 19 and 33% depending on time of season and experience level of the player (Bilsborough, JC et al. 2016). Fat intake is lowest during the competitive season (19.3 - 21%) and highest in pre-season (25.5 - 33%) when EE would be at its greatest when training volumes are high (Bilsborough, JC et al. 2016). Around competition, fat intake was 26.4 ± 5.7% leading into a Rugby Union match, 20.0 ± 7.1% on match day and significantly increased post- match to 28.8 ± 8.5%. Virtually no alcohol was consumed prior to the match however contributed 8.4 ± 11.6 % and 7.7 ± 13.5% on match day and post- match day respectively (Lundy et al. 2006). At the end of the competitive season, this is typically associated with relaxed nutrition intake when players have time off for recovery until the next season (Bilsborough, JC et al. 2016). In AF the energy from protein and fat was replaced with energy from alcohol that increased from zero intake to 12.3 ± 20.0% and 11.9 ± 16.9% for experienced and inexperienced players respectively. For a detailed review on nutrition intake in male and female team sports athletes, refer to Holway and Spriet (2011).

1.4.4 Body composition of football athletes

In field-based team sports, physique and body composition measures may not be as important for identification of talent as other factors such as skill, decision making, speed and fitness however they could be used to determine the appropriateness of an athlete for certain positions (Fuller et al. 2013). With increasing professionalism of the sports and its athletes, physique and body composition have evolved to meet the demands of the sports (Olds 2001) and once recruited to higher levels of competition, it is often manipulated with training and nutrition to meet program demands (personal observation). Football codes require a high proportion of lean muscle mass with lower fat mass, for speed, strength and power which is important for the numerous accelerations, jumps and tackles performed however athletes across and within the codes have vastly different physiques and body compositions (Gabbett, TJ 2006; McIntyre 2005; Pyne et al. 2006).

Physique and body composition will be dependent on football code, position within the code and their role. Soccer players tend to be the lightest and shortest of all the athletes in the football codes with the exception of the goal keeper and central defender (Reilly, Bangsbo & Franks 2000). Midfielders are the smallest players ranging height from 1.69 – 1.79 m and body mass of 65-74 kg, defenders and attackers are 1.77-1.8 m and 74 – 78 kg and goal keeps 1.85 – 1.8 m and 81 - 87 kg (Reilly, Bangsbo & Franks 2000; Sporis et al. 2009). Midfielders are the leanest with 8% body fat, attackers 10%, defenders 12% and goal keepers 14% (Sporis et al. 2009). Players are lean as they are covering large distances on the field for 90 min (Reilly, Bangsbo & Franks 2000). At the elite level of Soccer along with components of fitness and skill, physique and body composition are important aspects of performance and need to be adequate to suit the demands of the position (Sporis et al. 2009).

Australian Football player physiques are in-between Soccer and Rugby Union as they cover large distances but also endure physical contacts from tackles and collisions. A study conducted 28 years ago looked at the anthropometric profiles of AF players in the professional league (the Victorian Football League). The mean height and body mass of players was 1.81 m and 80.2 kg respectively. Body fat was estimated with skinfolds and prediction equations and found to be approximately 13.0% (Burke, Gollan & Read 1986). Since this time the anthropometric measures and body compositions have evolved with the changing nature of the match from when players trained on average of 7.3 ± 3.5 hrs per week (Burke, Gollan & Read 1986) in 1985 and had employment outside of football, while professional players are now full time athletes. Professional players are now on average, taller, heavier and leaner (Bilsborough, JC et al. 2015; Young et al. 2005). The height and mass of defenders, forwards and mid fielders are 1.87 ± 0.05 m, 1.86 ± 0.1 m, 1.88 ± 0.04 m and 87.7 ±7.5 kg, 87.0 10.1 kg, 86.8 ± 8.9 kg respectively (Young et al. 2005). Skinfolds for the same positions are 53.3 ± 12.1 mm, 59.7 ± 16.5 mm and 47.0 ± 7.8 mm respectively (Young et al. 2005) and DXA measured body fat is around 7.8% (Bilsborough, JC et al. 2015). Physique and body composition are highly variable within these positions with player heights and body masses upward of 2.0 m and 100 kg (Pyne et al. 2006). Within these positions there are also variations which is why the standard deviation for each position is large. There are taller heavier players including the ruckman, tall forwards and tall defenders, medium forwards, defenders and mid field players and smaller mid field players who play a roving role and cover large distances during the match (Pyne et al. 2006).

In Rugby Union and Rugby League the development of lean mass is desirable and required for strength, power and speed and necessary for competitive success (Duthie, G, Pyne & Hooper 2003; Olds 2001; Sedeaud et al. 2012). It was previously thought that Rugby Union players would benefit from high levels of body fat, as it would aid in protection during collisions (Brewer & Davis 1995). However, carrying excess fat can have a detrimental effect on performance as it reduces power to weight ratio, aerobic capacity (Gabbett, TJ 2005b) and is associated with poorer sprint times and repeated-sprint ability (Higham et al. 2013). Professional Rugby Union players, both forwards and backs, have had an increase in body mass from 87.8 kg between 1905 – 1974 to 95.1 kg between 1975 – 1999 (Olds 2001). Between 1987 and 2007 the mass of forwards has increased from 102.4 kg to 109.5 kg and backs from 83.0 kg to 89.6 kg while height did not change in forwards and only increased in backs by 1.5 cm (Sedeaud et al. 2012). The increase in size would predominantly be from selection of larger players as competitive success in Rugby Union is associated with a larger body size (Olds 2001). Trends were assessed over 10 seasons in Premiership Rugby Union in England and found that fly-half and prop positions increased in stature while body mass increased in the fly half and back row positions (Fuller et al. 2013). The changes over this time were attributed to the physical parameters that coaches required of their players rather than a consequence of broader population change (Fuller et al. 2013). Forward positions are taller and heavier to fend off players and gain possession of the ball while backs players are smaller to cover more ground and create scoring opportunities. Professional Rugby League forwards are 1.82 $\pm$0.06 m tall, weigh 98.4 $\pm$ 7.7 kg and have skinfolds of 69.7 $\pm$ 15.2 mm while backs are 177.9 $\pm$ 5.6 m, 85.5 $\pm$ 6.7 kg and 56.9 $\pm$ 12.8 mm respectively (Lundy et al. 2006). Rugby Union players are taller and heavier than Rugby League payers (Zemski, Slater & Broad 2015).

Forwards are 1.91 m (1.88 - 1.94 m), 111.7 kg (108.1 - 115.2 kg), have skinfolds of 73.1 mm (67.7 - 78.4 mm) and body fat percent of 14.2% (13.4-15.0%). Backs are 1.82 m (1.8 - 1.85 m), 91.7 kg (89.1 - 94.3 kg), have skinfolds of 49 mm (45.4 - 52.5 mm) and body fat of 10.2% (10.0 - 11.4%) (Zemski, Slater & Broad 2015). There was no overall difference between Caucasian and Polynesian players (Zemski, Slater & Broad 2015). Rugby Union players are most likely bigger than Rugby League as scrummages play a more significant role in Rugby Union and scrummaging force and thus success is highly correlated with a larger body size (Quarrie & Wilson 2000) (Olds 2001). The regional distribution of mass is of interest as it can impact on performance in each code. It is known that a strong trunk and legs are essential for performance in Rugby Union and a higher proportion of lean mass would be beneficial for the ability to produce force and power (Higham et al. 2014). Senior elite Rugby Union players in the forwards position have greater absolute lean muscle mass in the trunk (40.22 ± 3.61 kg v 34.22 ± 2.29 kg) , legs (30.54 ± 2.78 kg v 24.53 ± 2.64 kg) and arms (12.95 ± 1.26 kg v 10.69 ± 0.73 kg) compared to backs players which aligns with the positional requirements of the forward position using strength, power and force to obtain possession of the ball (Pumpa et al. 2012).

1.4.4.1 Seasonal body composition in football sports

Body composition measures can change considerably throughout the year and will depend on the training period. Preseason training in team sports generally has greater training volumes with a focus on building cardiovascular fitness and strength, and optimising body composition (Gamble 2006). For example, in AF training load as measured by session RPE (training duration multiplied by the mean training intensity defined by the RPE) is up around 3,500 au in pre-season and closer to 2,000 during the competitive season while resistance training load is about 50% less during the competitive season (Bilsborough, JC et al. 2016). The focus shifts during the competitive season with less of an emphasis on conditioning and a greater emphasis on skills based training (Meir 1994) and recovery from matches. The offseason is considered a download period where training volume is reduced while still trying to maintain some form of physical conditioning (Gamble 2006).

The seasonal body composition of AF players was first studied in 1986 (Burke, Gollan & Read 1986). Data was collected from 89 players across three levels of competition; professional league, lower level professional association and A-grade amateur association players. Body mass increased across a season from 79.64 ± 1.08 kg to 80.54 ± 0.06 kg as a result of a small change in estimated fat-free mass (69.36 ± 0.85 kg to 70.27 ± 0.86 kg) with very little change in body fat. Circumference measures (mid arm, chest) did not change. The lower level team had similar changes while the amateur players experienced greater reductions in body fat and an increase in lean mass resulting in an unchanged body mass. Amateur level teams experienced greater change across the season as they begin the season more deconditioned and therefore with increased activity through matches and training, their body composition improves (Burke, Gollan & Read 1986). A more recent study in AF examined changes across the pre-season and competitive season in experienced (≥4 years contracted to an AF club) and inexperienced (≤4 contracted to an AF club) players with DXA (Bilsborough, JC et al. 2016). Body mass did not change in experienced players while fat mass decreased in pre-season with a small non-significant increase in lean mass (Bilsborough, JC et al. 2016). Body mass increased throughout the season in inexperienced players with a reduction in fat mass and increase in lean mass (Bilsborough, JC et al. 2016). The greatest changes occurred in pre-season in both groups with a tapering off throughout the competitive season (Bilsborough, JC et al. 2016).

International Rugby Sevens (Union) players showed only a small reduction in skinfolds from the beginning of pre-season to the end of the competitive season (total 40 weeks) and change mainly occurred in backs players with a 5% reduction in skinfolds (Mitchell et al. 2016). Another study in 33 elite Rugby Super 14 (Union) players (Argus et al. 2010) found a greater reduction in skinfolds of 11.5% and estimated fat-free mass increased by 2.0 ± 0.6 kg in just a four week period (Argus et al. 2010). The Rugby Seven player's starting skinfolds are 54.5 ± 11.0 mm for sum of seven and the Super 14 players, 93.4 ± 26.7 mm for sum of eight. These results are impossible to compare due to the difference in the number of measurement sites however the high starting skinfolds in the Super 14 players may help to explain why they had a greater loss than the Sevens team (Argus et al. 2010; Mitchell et al. 2016). A study using DXA has not been published in Rugby Union and would be of benefit to gain detailed body composition information on seasonal changes however has been conducted in Rugby League (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011). Body composition was measured at three phases in the competitive season; end of the preseason, mid-season and immediately post competitive season (Harley, Hind & O'Hara J 2011). Fat mass significantly increased across the season from 13.59 ± 3.66 kg in pre-season to 14.49 ± 4.05 kg post-season while lean mass decreased from 77.38 ± 9.36 kg to 76.21 ± 9.44 kg. Similar results were seen in a study conducted in Australian professional Rugby League players (Georgeson et al. 2012). Both studies discuss similar reasons for the atrophy in lean muscle. During the competitive season the focus of training shifts to recovery between matches, reducing training volume including a reduction in the number of resistance training sessions from 2 - 4 to 0 - 2 (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011). The gain in fat mass was mainly attributed to muscle atrophy although it was also noted that dietary intake could play a role (Harley, Hind & O'Hara J 2011). Athletes tend to maintain dietary EI regardless of variations in training volume (Drenowatz et al. 2012). If EI exceeds that of EE when training volumes are reduced during the season, an increase in body fat can result. Both studies began their measurement period at the end of the pre-season period when players would have been at their fittest. Understanding the changes that occur from the beginning of the preseason period to the beginning of the competitive season are also beneficial. BMC increased from preseason (4,292 ± 595 g) to midseason (4,338 ± 613 g) and dropped again to postseason (4,326 ± 594 g) however not to preseason levels (Georgeson et al. 2012). Bone mineral composition is thought to increase across this time as training includes a hypertrophy phase, placing load on the bone, resulting in a high rate of bone accrual. The growth can plateau off or decline later in season as the focus of training shifts to maintaining fitness, placing less load through the bone (Georgeson et al. 2012).

Professional French league Soccer players showed some similar trends to above however body fat percent and fat-free mass were estimated using skinfolds and regression equations (Carling & Orhant 2010). Body fat decreased across their 2-month preseason and continued to decrease until their midseason break (Carling & Orhant 2010). After this time body fat began to return to pre-season values (Carling & Orhant 2010). Fat-free mass increased from preseason to the mid-season break and began to drop-off after this time (Carling & Orhant 2010). Similar results were seen in a study using professional 1st National League players from eastern Europe (Ostojic 2003). Interestingly, when the data was divided into playing positions, midfield players had the greatest gain and then loss in fat-free mass while fat-free mass in defenders continued to increase across the season, peaking at season's end (Carling & Orhant 2010). Players had the greatest gain in the off-season with a gain in fat and loss in fat-free mass (Carling & Orhant 2010). Greater changes in body composition existed during the competitive season rather than the conditioning (preseason) period as the intensive training and competition schedules of the European league resulting in greater metabolic loads and therefore improved body composition (Ostojic 2003).

1.4.4.2 Growth and development of young athletes in football sports

As mentioned earlier in this chapter, adolescence is a time of crucial growth and development. In football, the difference between physical maturity during puberty is apparent and can make football competition quite challenging as size differences can be considerable, creating potentially dangerous situations (Fuller et al. 2013). These differences are quite apparent between different ethnicities. The anthropometric characteristics of 116 junior elite Rugby League players (17 ± 1 yrs) from five clubs were measured and compared across ethnicity (Polynesian v non-Polynesian) (Cheng et al. 2014). Polynesian players were taller (181 ± 5.7 cm v 178.7 ± 6.2 cm) , heavier (90.6 ± 11.7 kg v 84.7 ± 11.1 kg), had greater arm girth (relaxed 36.1 ± 2.8 cm v 34.7 ± 2.5 cm) and bone breadth (humerus 7.8 ± 0.4 cm v 7.5 ± 0.4 cm) measures than non-Polynesian players (Cheng et al. 2014). The difference in physical maturity in young players has led some organisations to call for weight category teams in under 18 competitions.

The physical development of young players across a season can be considerable. A study conducted in 14 to 20-year-old academy Rugby League players measured anthropometric and fitness variables in three groups across the season (Till et al. 2014). Under 14 (55 ± 12.3 kg v 58.8 ± 11.9 kg), 16 (70.9 ± 11.1 kg v 74.3 ± 10.8 kg) and 18 (84.1 ± 10.8 kg v 86.0 ± 10.0 kg) year players had significant changes in body mass with only small reductions in skinfolds (Till et al. 2014). While under 20s did not have such large changes in body mass (90.3 ± 10. 6 kg v 91.3 ± 10.4 kg), they did have a significant reduction in skinfolds from 41.7 ± 12.1 mm to 36.6 ± 12.4 mm (Till et al. 2014). The greater changes in the younger players can be attributed to growth and development of these ages and although growth can still occur toward the age 20, changes are less dramatic and slow toward adulthood (Malina 2004). The reduction in body fat could be due the increased activity throughout the season compared to when the players are not playing in addition to increases in lean muscle mass and possible improvement in nutrition over this time.

Players are being identified early for selection and elevated to the professional leagues when they are 18 years of age. A study comparing the body composition of elite junior AF players and elite professional AF players (rookies 18-20 yrs and seniors 21 yrs +) was conducted to determine the physical readiness of younger players for professional football (Veale et al. 2010). There were no differences in height between age groups however body mass was 8 kg less in junior compared to senior players which came from a greater absolute lean muscle mainly in the legs and trunk region, fat and bone mass. Senior players also had a greater BMD than junior players which comes from a greater number of years exposed to weight-bearing exercise through sport participation (Veale et al. 2010). Similar trends were seen in Rugby Union from sub-academy (18.5 ± 0.5 yrs), academy (19.9 ± 1.1 yrs) and senior (26.5 ± 4.2 yrs) players (Pumpa et al. 2012). There was a 6 kg difference in lean muscle mass between sub-academy (79.84 ± 6.58 kg) and senior (86.09 ± 9.65 kg) players mainly coming from greater lean muscle in the trunk and arms of senior players (Pumpa et al. 2012). The difference between younger and senior players in body composition besides age, would be training load. The AF juniors trained approximately 8 hours a week while professional players train nearly 40 hours a week providing greater opportunity for muscular development (Veale et al. 2010). Suggestion was made that resistance training should be introduced at the junior level to build body mass (Veale et al. 2010). While this is a good idea, gains in mass and lean should be monitored closely as the junior athlete is still developing and rapid changes may not allow anatomical adaptation, increasing risk of injury (Naughton et al. 2000).

1.4.4.3 Impact of body composition on selection in football sports

Certain anthropometric and body composition attributes of football athletes will be more beneficial in each code and may impact selection at higher levels. Athletes will be recruited to a professional team based on skill, fitness and strength and in some sports, especially in young athletes, anthropometric and body composition factors (Hoare 2000). Body composition does not seem to impact on selection at the professional level (Pyne et al. 2005) however once recruited by a professional team there is increasing emphasis on the physical development of younger players (Pyne et al 2006) changes in body mass and body fat may be required over a relatively short period (personal observation). If these attributes are identified for each code, the athlete could develop these attributes early, possibly increasing their selection chances and minimizing the need for significant changes early in their career.

In younger players vying for selection in the national AF draft combine, height has substantially increased over a short period from 1999 to 2004 by 2.2 cm (average height 1.87m $\pm$ 0.66 m). This may be due to the targeted selection of taller players rather than morphological change in the population (Pyne 2006, Norton 2001). Body mass has not significantly changed over this time however the small change that has occurred may be due to increasing attention on nutrition and hypertrophy programs (Pyne et al. 2006).

In Australian Football, body composition variables do not seem to directly influence selection at the professional level (Pyne et al. 2005) however a study in younger athletes with an average age of 15.9 years found that 29 of 40 players who were selected for the under 18 AF team, had significantly greater height than those not selected (180.2 ± 7.2 cm vs 175.3 ± 5.3 cm) (Keogh 1999). Body mass also tended to be greater in selected versus no selected players, 74.6 ± 8.3 kg and 69.3 ± 5.8 kg respectively (Keogh 1999). In a later study, 485 male AF players aged between 16 and 18 years who played in the under 18 competition in Victoria participated in a study to determine whether pre-season anthropometric and fitness variables impacted selection and performance (Young & Pryor 2007). Selected players tended to be heavier (79.8 kg v 76.2 kg) and have a greater hand (23.1 cm v 22.6 cm) span than players not selected. The 3.6 kg difference in body mass may be due to greater physical maturity of the group which in this age group is a known predictor of selection in sports requiring bigger bodies for contact sports. In opposition to this finding, players with high possessions were shorter, lighter, had a shorter arm length and standing reach however these players had a greater $\dot{V}O_{2max}$, and faster 5 m and 20 m sprint times suggesting that being lighter and quicker are an advantage in gaining possession of the ball (Young & Pryor 2007). A similar study was conducted in 34 professional AF players from one team where anthropometric and fitness measures were used to determine if there was an impact on selection for the first match of the season (Young et al. 2005). Selected players were significantly older 24.0 ± 3.3 years and most likely had more match experience. Selected players, although not significant, tended to be shorter (1.86 ± 0.09 cm v 1.89 ± 0.06 cm) and heavier (88.9 ± 8.6 kg v 85.9 ± 9.9 kg) while sum of eight skinfolds were the same (52 ± 16 mm v 52 ± 8 mm). Fitness variables including speed and endurance (YoYo test) were better in those selected than not selected. Technical, psychological and tactical factors contribute to performance in AF however fitness variable are in most cases trainable and can impact selection (Young et al. 2005).

Regional and national level junior Rugby League players aged 13 - 16 years in the United Kingdom had anthropometric and performance variable assessed to determine if there was a difference between playing levels and whether these factors were able to predict likelihood of being selected at either level (Till et al. 2011). Peak height velocity had no association with level of representation, occurring at approximately 13.6 years of age. National players had a lower sum of skinfolds and outperformed regional players in vertical jump, medicine ball chest throw, sprints, agility and $\dot{V}O_{2max}$ (Till et al. 2011). A stepwise discriminant analysis predicted that seven variables would discriminate between national and regional players. In order, $\dot{V}O_{2max}$, chronological age, body mass, 20 m sprint, height, sum of four skinfolds and sitting height accounted for 28.7% of the overall variance and had an overall predictive accuracy of 63.3% (Till et al. 2011). Of these variables five are related to age and anthropometric characteristics, which demonstrates that in high level junior players, selection can be impacted by age and development (Till et al. 2011; Till et al. 2010).

1.5 Summary and Aims of thesis

1.5.1 Summary

The current review has identified gaps in the knowledge of energy expenditure dietary intake and body composition in team sport athletes and have been summarised below:

- Total daily EE is difficult to measure in any population, not just athletes, as methods are expensive, difficult to access, require trained technicians, do not allow for EE to be broken into components and restrict typical daily activity (Ainslie, Reilly & Westerterp 2003; Levine 2005). Reliable methods are required that are non-invasive, accessible and allow for the participant to move freely and participate in usual activity.
- Studies in athletes have shown that EE outside of training and competition from NEAT (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013; Motonaga et al. 2006), provides a significant contribution to TDEE and needs to be considered in nutrition programming for health, performance and in achieving body composition goals.
- The EE of team sport athletes is difficult to measure as methods restrict typical movement on the field and therefore would underestimate EE (Rodriguez FA 1998). New technologies such as accelerometers and GPS are becoming more accessible and providing a possible alternative for

measurement of EE on the field (Coutts, A.J. et al. 2015; Osgnach et al. 2010).

- Prior to the commencement of this project, EE studies in team sports measured either TDEE (Ebine et al. 2002) or match EE (Rodriguez FA 1998) and did not report the contribution of EE components.
- Few studies have been conducted in team sports that measure TDEE and match EE. Neither have been measured in AF.
- Prior to the commencement of this project, the dietary intake of AF players had not been measured since 1988 (Burke & Read 1988) and 2000 (Ebert 2000).
- As EE had not been measured in AF, it is unknown if players are meeting their energy requirements.
- Studies in team sports suggest that players are not meeting their carbohydrate recommendations required for performance (Lundy et al. 2006; Reeves & Collins 2003). As the dietary intake of AF players has not been recently assessed, it is important to determine the macronutrient composition of the diet so intake can be optimised for performance.
- The body composition of team sport athletes' changes throughout the season with modifications in training and competition loads (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011; Milanese et al. 2015).
- Prior to the commencement of this project the seasonal body composition of AF players had not been completed since 1986 (Burke, Gollan & Read 1986) and has not been completed in players competing in the professional Soccer league in Australia.
- Adolescence is a time of crucial growth and development and young athletes are being identified early to compete in their sports at a high level. Measuring body composition throughout this time is essential to monitor training loads and nutritional intake.
- The body composition of high level AF development athletes has not been measured longitudinally leading into the draft combine.
- Anthropometric characteristics have been examined in relation to selection by a professional team however only basic measures such as height, body

mass and skinfolds were used. Detailed measures of body fat, lean mass and BMC obtained via DXA have not been studied.

1.5.2 Thesis Aims

The aims of this thesis are:

1. To measure the total daily EE and match EE of AF players. This will be done by developing an EE algorithm utilising oxygen uptake and accelerometer data from the MiniMax 4.0 (Catapult Innovations, Scoresby Australia) to measure the EE of AF players during training and matches and against this, validate the MiniMax metabolic power calculation. In addition, the SenseWear^{TM} armband will be used to determine NEAT from ADL. This data would then be used to address the secondary aim of the study which is to quantify the TDEE of professional AF players.
2. To measure the energy and macronutrient intake of professional AF athletes and assess whether they meet their daily EE. In addition, the macronutrient intake of players with will be compared with current sports nutrition recommendations for team sport athletes.
3. To longitudinally measure changes in body composition across the season of professional Rugby Union, Soccer and AF players, identify where these changes occur in the body and how the changes compare across sports.
4. To longitudinally measure the anthropometric and body composition changes of national academy AF players over a two-year period in the lead up to the draft combine and whether body composition factors impact selection.

Chapter 2: General Methods

2.1 Estimation of energy expenditure

To determine the EE of AF players during training and matches it was identified that accelerometers are the most appropriate method to measure physical activity and therefore estimate EE. Laboratory based methods such as direct calorimetry and indirect calorimetry are not appropriate to measure the typical movement of team sport athletes or the free-living TDEE (Ainslie, Reilly & Westerterp 2003; Leonard 2012; Levine 2005; Seale & Rumpler 1997). Portable calorimetry would also restrict typical movement on the field especially as the match of AF involves contact (Levine 2005). The DLW method, considered 'gold standard' to measure free-living EE is an accurate and reliable measure for TDEE however it is expensive (approximately $1000 AUS for one adult), requires specialised expertise and measures average expenditure over 4 - 21 days, which does not allow for measurement of discrete tasks or periods of time (Bluck 2008; Westerterp 1999). The relationship between heart rate (HR) and EE at rest and during steady state exercise is considerable (Levine 2005) however to account for individual differences in fitness, measurement needs to be calibrated for each individual with $\dot{V}O_2$ during a variety of activities (Christensen et al. 1983). Even after this calibration, consideration must be taken as HR can be affected by other factors that are not associated with a change in $\dot{V}O_2$ such as illness, posture, emotional stress, ambient temperature etc. (Achten & Jeukendrup 2003).

Accelerometers are small, non-invasive devices that measure movement in three planes (tri-axial) and can determine the intensity, frequency and duration of physical activity (Bouten et al. 1994; Westerterp 2009) and allow for measurement of EE to be broken down into specific activities (Plasqui, Bonomi & Westerterp 2013). Varying results have been seen when comparing accelerometers to DLW in different populations however in most cases there is a moderate to strong correlation between methods (Plasqui, Bonomi & Westerterp 2013) with higher correlations generally seen with tri-axial devices (Butte, Ekelund & Westerterp 2012). The SenseWear™ armband has been validated for use in the measurement of ADL, at low to moderate intensity physical activity and at rest (Drenowatz & Eisenmann 2011; St-Onge et al. 2007) however is limited at high intensities (Drenowatz & Eisenmann 2011) or during intermittent exercise such as that experienced during teams sports such as Rugby Union (Zanetti et al. 2014). In the sporting context, Catapult Innovations (Scoresby Australia) have developed a device that acts as a GPS and accelerometer that has been validated to measure physical activity for use in sports (Boyd, Ball & Aughey 2011).

The following methods were used to estimate EE in chapter 3:

2.1.1 Maximal aerobic power ($\dot{V}O_2$)

In chapter 3, in the 4 weeks prior to the start of the competitive AF season, maximal aerobic power ($\dot{V}O_{2max}$) was determined in participants using an incremental exercise test completed on a motorised treadmill in a laboratory at 20.0 ± 1.0°C and humidity 51 ± 2.7 %. This test requires metabolic equipment that measures oxygen consumption and carbon dioxide production. Indirect calorimetry was used to this determine this output. The ratio of both oxygen consumption and carbon dioxide production ($\dot{V}CO_2/\dot{V}O_2$) is calculated and is referred to as the non-protein respiratory quotient (RQ). The RQ is the ratio between the oxidation of carbohydrate and lipid which can then be used to estimate EE based on the assumption that one litre of oxygen consumed is equal to approximately 4.81 kcal (McArdle, Katch & Katch 2001).

An open circuit system was used which is the most commonly used method in measuring basic daily activities and exercise (Ainslie, Reilly & Westerterp 2003; Leonard 2012). A metabolic measurement cart (S-3A/II and CD-3A analysers, Ametek, Pittsburgh, USA), calibrated before each test, measured oxygen uptake and estimated EE at each stage. After a 2 minute warm up at 10 km·h^{-1} the treadmill speed was increased by 1 km·h^{-1} every minute until volitional fatigue. Maximum $\dot{V}O_2$ was considered when the participant reached volitional exhaustion, when there was a plateau in oxygen uptake (maximal oxygen uptake) with increasing work rate and/or a respiratory exchange ratio ≥ 1.15 (McArdle, Katch & Katch 2001).

2.1.2 Measurement of physical activity

In chapter 3, for the duration of the maximal aerobic power test, the MiniMax 4.0 accelerometer (Catapult Innovations, Scoresby Australia) was worn in a vest and positioned between the shoulder blades. The device was worn in this position, as it cannot interfere with daily activity or in the case of contact sports, it cannot be positioned where it may hurt the athletes or the device can be easily damaged. It also needs to be placed in a position where whole body movement can be adequately captured. Placing the accelerometer between the shoulder blades keeps the unit out of the way particularly for contact sports and has been shown to be a reliable method to measure physical activity in team sports (Boyd, Ball & Aughey 2011).

Accelerometer data was used to calculate Playerload™ for each stage of the maximal test. Playerload™ is expressed as arbitrary units (au) and is a modified scaled vector magnitude and is a measure of total effort. The calculation is expressed as the square root of the sum of the squared instantaneous rate of change of acceleration in each of the three vectors divided by a scaling factor of 100 (Figure 2.1a) (Boyd, Ball & Aughey 2011). Playerload™ was plotted against the corresponding estimated EE for oxygen consumption for each minute of the $\dot{V}O_{2max}$ test. Correlation analysis was performed and individual regression equations were developed for each participant (Figure 2.1b). These equations were then used to estimate EE of training and matches.

$$\text{Player load} = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_{x1} - a_{x-1})^2 + (a_{z1} - a_{z-1})^2}{100}}$$

Where

a_y = Forward accelerometer

a_x = Sideways accelerometer

a_z = Vertical accelerometer

Figure 2. 1a: Player Load calculation

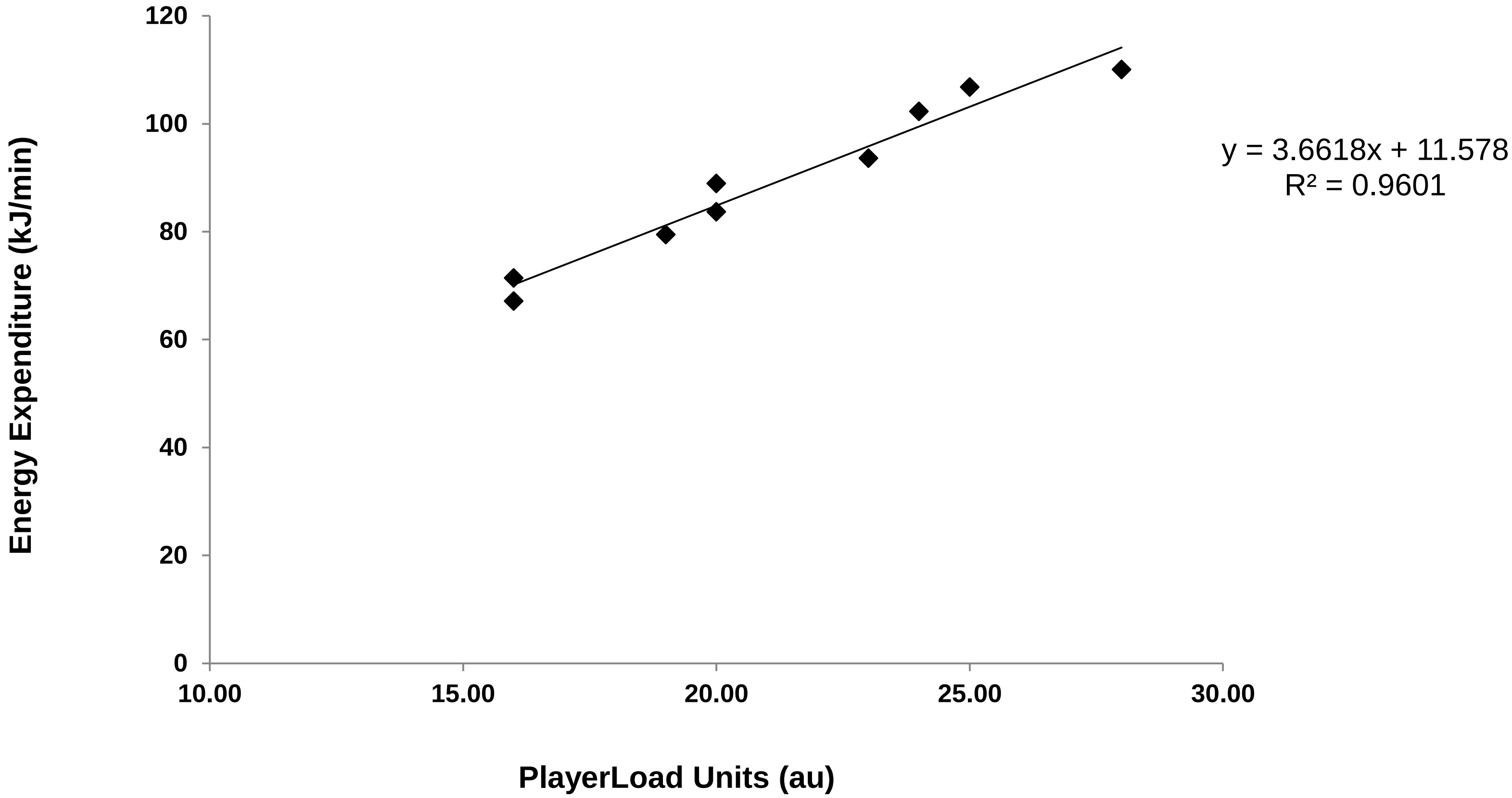

Figure 2. 2b: Example of PlayerLoad and energy expenditure correlation analysis for one participant.

To calculate EE for training and matches, Playerload^{TM} was measured in players who were available for matches and training. The accelerometer was worn in the main training session of the week prior to the match, the first six matches of the competitive season and an average taken of matches played. To ensure data was collected for only the time on field, each device was synchronized for starting times, time off the field of play and mandated breaks in play (Aughey 2010). The total Playerload^{TM} for the training session was inserted into the EE equation (*x*) to determine EE for each individual. The same was completed for match EE. A correction factor of 1.29 (Osgnach et al. 2010) was applied to calculate final EE. This was needed to correct for the additional energy cost of running on grass compared to a firm surface (Osgnach et al. 2010).

The Catapult software used in conjunction with the MiniMax 4.0 (Catapult Innovations, Scoresby Australia) utilises a ‘Metabolic Power’ algorithm that can estimate EE. In addition to the estimate from the above methods used in this study, ‘Metabolic Power’ was calculated for each individual player and correlated using pearson’s correlation with the study results. The ‘Metabolic Power’ algorithm assumes sagittal plane acceleration and deceleration are primary drivers of energy cost (di Prampero et al. 1986; Osgnach et al. 2010). Two components of acceleration are considered; With inclined terrain and vertical orientation of an athlete, accelerated running is considered similar to travelling a constant speed up an ‘equivalent slope’; During sprinting an athlete exerts greater force than their body mass referred to as ‘equivalent mass’. This additional force is required to overcome acceleration (di Prampero et al. 1986; Osgnach et al. 2010). Therefore, energy cost is calculated as the function of the equivalent slope by the equivalent mass by a grass environment constant of 1.29 (Osgnach et al. 2010).

2.1.3 Non-exercise activity thermogenesis and total daily energy expenditure

In chapter 3, to measure NEAT and TDEE, players wore the SenseWear^{TM} Armband (Model MF-SW, Bodymedia, Pittsburgh, PA) for seven days leading into a pre-season match.

The SenseWear^{TM} Armband (Software version 7, Model MF-SW, Bodymedia, Pittsburgh, PA) was used to determine the EE of daily tasks. The device is a tri-axial accelerometer and integrates a number of heat-related sensors including heat flux (the amount of heat dissipating from the body measured with a proprietary sensor), skin temperature (measured with a sensitive electronic thermometer) and galvanic skin response (electrical conductivity of the skin which changes in response to sweat and emotional stimuli) and demographic characteristics (gender, age, height, body mass). The armband is worn on the right upper arm over the triceps and participants were instructed to remove the armband while showering, swimming and during contact training sessions (field based training and matches) to avoid damaging the device and was kept on while sleeping. The SenseWear^{TM} software calculates RMR and EE based on the manufacturer's proprietary algorithm including subject height, body mass, age and sex in addition to accelerometer data and temperature measures.

To calculate TDEE for a training day, the calculated EE from training was summed with the EE calculated by the SenseWear^{TM} armband on that measurement day. The calculated EE from a match was summed with the EE measured on match day with the SenseWear^{TM} armband.

2.2 Nutrition

Dietary assessment of athletes is important to determine if their energy and nutrient requirements are being met for health, performance and recovery. There are few methods that can be used to determine intake however limitations must be considered when interpreting data.

The most precise measurement of dietary EI would be from a laboratory study where participants are provided with a known energy and nutrient composition however this method does not allow for the typical intake of that person and therefore does not provide an accurate reflection of intake (Rutishauser 2005). Retrospective methods including the food frequency questionnaire, a diet history or 24-hour recall rely heavily on the participant to recall the types and quantities of food and drink they consume. These methods provide a good idea of eating patterns and habits and take little time to complete however may not be representative of usual intake and need to be repeated a number of times for a more reliable reflection of intake at different times (Magkos & Yannakoulia 2003). Also, athletes tend to consume more food overall than the general population and remembering all food consumed can be difficult and increase error (Magkos & Yannakoulia 2003). The most practical and popular method of measurement is the weighed food diary or diet record (Magkos & Yannakoulia 2003). This method requires the participant to weigh and record their food and places a large burden on the participant however it is thought to be the most practical and accurate method (Magkos & Yannakoulia 2003). In athletes, it has been suggested that a 3-7day measurement period provides a good estimate of habitual energy and nutrient consumption (Black 2001; Deakin 2000; Magkos & Yannakoulia 2003).

It is also important to consider how the method of assessment performs on the group and individual level. For example, when collecting data on a group of participants to compare to another group, a 24 hour recall can be sufficient if there is a large enough group or a food diary collected over several days would also be suitable (Rutishauser 2005). To assess dietary intake at the individual level, a food diary collected over at least a week would be best. Duration of collection will also depend on the estimate trying to be obtained from the diet and the specified level of confidence (Schokman, Rutishauser & Wallace 1999). For example, as energy intake tend to be less variable, only a few days are required whereas specific micronutrients which are more variable, mat require a number of weeks.

2.2.1 Food diary and analysis

In Chapter 4, AF players completed a seven day weighed food diary leading into a pre-season match. Participants were provided with food scales, measuring cups, measuring spoons and were asked to keep record all food, drink and supplements. Written and verbal instructions were provided to participants and an example food diary for one day was provided to show the level of detail required when recording intake. Upon return of the food diaries at the end of the recording period, the diaries were checked by the dietitian and when necessary clarified data with the participant. The same dietitian analysed all diaries to reduce variability in data input and used the nutrition analysis software, Foodworks version 7 (Xyris, Queensland) which utilises the database of Australian foods (AUSNUT).

All food and fluid was included in the analysis including protein and carbohydrate powders and bar, sports drinks and carbohydrate gels. Vitamin and mineral supplements in pill, powder or tablet form were excluded.

If a product provided in a diary was not available in the database, nutrition information was obtained from the company website or label and added to the Foodworks software.

2.3 Body Composition and Physique

Measuring body composition is necessary to determine the optimal body composition of an athlete, to monitor this composition over time in both developing and developed athletes and to monitor training and nutrition (Kerr, Ackland & Schreiner 1995). Methods to determine body composition can be direct, e.g. cadaver analysis or indirect where a surrogate parameter is measured to estimate tissue or molecular composition, e.g. underwater weighing, multi-component models, DXA and 3D photonic scanning; doubly indirect where an indirect measure is used to predict another indirect measure, e.g. skinfolds and skinfold equations (Ackland et al. 2012). All methods have their advantages and limitations however in the elite sports environment the measurement of body composition need to be reliable, practical and accessible.

The methods selected for the studies in this thesis are body mass, stretch stature, skinfolds, DXA and 3D photonic scanning and will be expanded upon below.

2.3.1 Anthropometric and skinfolds measures

In chapters 3, 4, 5 and 6 height, body mass and sum of seven skinfolds were measured by an accredited anthropometrist (Level II ISAK) according to the methods of the International Society for the Advancement of Kinanthropometry (ISAK) and are summarised below.

Stretch stature was measured to the nearest 0.1cm using a digital stadiometer (Pro Scale, Accurate Technology Inc., NC, USA). The anthropometrist gently places their hands under the participant’s mandible and asks them to take a deep breath in and out. On exhalation, the anthropometrist gently lifts the head to measure the stretch stature. Body mass was measured on calibrated scales (Rite-weigh Scales P/L, Vic, Australia) to the nearest 0.1kg. The skinfold sites were defined using anatomical landmarks and a Lufkin tape measure. Calibrated Harpenden calipers (West Sussex, UK) were used to measure the triceps, subscapular, biceps, supraspinale, abdominal, thigh and medial calf skinfolds for a total of seven sites. Measures were completed twice and a third conducted if outside the TEM for that site. The mean was take and the sum of seven sites calculated (Marfell-Jones et al. 2006). The sum of 7 sites is most commonly used in team sports within Australia and was selected to keep consistent with current club practices (Gore, Tanner & Sport. 2013). The anthropometrist's between test technical error for the sum of seven skinfolds, body mass and stretch stature was 2.3%, 0.2% and 0.4% respectively.

2.3.2 Dual-energy X-ray Absorptiometry

Dual-energy X-Ray absorptiometry (DXA) is increasingly being used to measure body composition in athletes. Traditionally used as a diagnostic method for osteoporosis, filtered x-ray beams are passed through the participant, which are attenuated by the different materials in their path and classify the body into three compartments: fat mass, lean mass or fat free soft tissue and bone mineral composition (Nana et al. 2015). The participant is therefore exposed to a small amount of radiation (~0.5 μSv for a whole body scan), similar to that of a 7hr airplane flight, this dose however can vary depending on the equipment and setting used (Ackland et al. 2012). Due to this radiation dose, albeit small, it has been recommended that a maximum of four scans be conducted each year (Ackland et al. 2012).

The reliability of DXA can be influenced by technical and biological variations. Technical error can be caused by inherent machine error or natural 'drift', positioning of the subject on the scanning bed, analysis mode for regional composition, through experience of the technician and subject preparation (Nana et al. 2015). Whereas biological variations are day-to-day variations of the scanning participant and can be affected by consumption of food and fluid prior to the assessment and exercise (Nana et al. 2012a; Nana et al. 2011).

To minimise sources of error and improve reliability, 'best practice' guidelines should be adhered to (Nana et al. 2015). The accuracy and precision of DXA for assessing body composition in team sport athletes has been assessed. (Bilsborough, J, C. et al. 2014) Both the Lunar DPX pencil beam and Lunar prodigy fan beam machines were used in the assessment. Compared to a criterion whole body phantom both machines were high correlated (r = 0.9-1.0) and were accurate in measuring fat-free soft tissue (% CV 0.4 – 0.8) and BMC

(% CV 1.7 – 3.2). Results for fat mass were less accurate (% CV 13.4 – 25.6) (Bilsborough, J, C. et al. 2014). Both machines had excellent reliability for total fat-free soft tissue (pencil % CV 0.4-0.6; fan % CV 0.2-0.5) and BMC (pencil % CV 1.2-2.0; fan % CV 0.4-0.8) and acceptable reliability for fat mass (pencil % CV 4.7-7.8; fan % CV 1.9-3.6) and percent fat (pencil % CV 4.6-7.6; fan % CV 1.9-3.5).

DXA was used to determine lean mass, body fat and BMC of participants in chapters 3, 4, 5, 6. The same Hologic pencil beam machine (Discovery W, Hologic, MA, USA, Software; APEX 2.2) was used for all AF and Soccer scans and the same licensed DXA operator was used for every scan.

Quality control of the scans

Quality control (QC) was performed daily using the Hologic spine phantom. Once the scan was completed and the test passed, the plot was reviewed. The data points for BMC and on mineral density (BMD) from the QC scan should be within the two dotted lines. The CV for BMC should be at or below 0.80%. The CV for BMD should be at or below 0.60%. Although the step phantom only requires scanning once a week, the phantom was scanned prior to each scanning session for consistency. Once this was complete, the Radiographic Uniformity Test was completed automatically by the system.

Participant preparation and Set up

Participants reported to the laboratory between 0600 and 0830am prior to eating, drinking and training and prior to any testing participants were informed of the risks associated with radiation exposure during the scan.

A standard scanning protocol was used to ensure measurement reliability (Nana et al. 2012b, 2013; Nana et al. 2011). Firstly, participants are required to be hydrated which was tested by Urine specific gravity (USG). USG is a measure of the concentration of solutes in the urine and compares the density of urine to water density. The participant provides a urine sample in a specimen jar that is taken during the first void upon waking and is collected mid-stream. A drop of urine is placed on the refractometer (Atago URC-Ne, d1.000-1.050, Japan) and the measurement taken (Oppliger & Bartok 2002). Euhydration was considered when the USG result was <1.020 (Oppliger & Bartok 2002). All scans are completed in swimwear or running shorts and were kept consistent for repeat scans and all metal objects including jewellery, watches, zips etc were removed. Body mass and height which were measured previously, are entered into the software which then calculates the body mass index which is needed to determine if a high power whole body scan is required. A male with a BMI greater than 31 or a female greater than 32, will be selected for a high power option.

Participants are positioned on the bed according to The National Health and Nutrition Examination survey (NHANES) Body Composition Procedures Manual (Survey 2011-2012) (See Figure 2.2). Participants are positioned on their back in the supine position with hands pronated, placed slightly away from the hips. Legs are to be positioned slightly apart with femur rotated inwards and feet secured together with tape. Participants who fell outside of the bed parameters were positioned with their head outside of the measurement area (Nana et al. 2012b). The head was then measured and added back to the overall scan. A whole body scan is selected which takes approximately 7 min 30 sec. At the completion of the scan, the regions were defined by the technician. For repeat scans in longitudinal studies, the defined regions from the previous scan were used and only minimally modified if required.

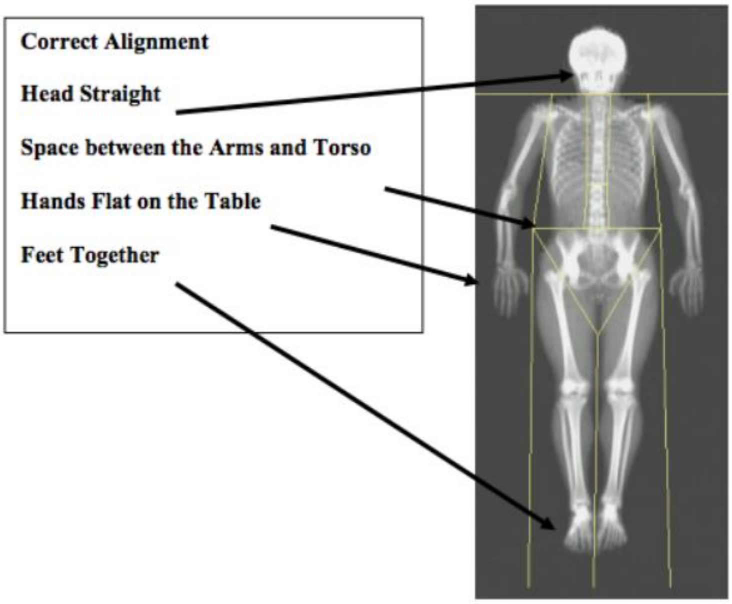

Figure 2. 3 NHANES Whole body scan positioning.

Taken from NHANES Body Composition Procedures Manual 2011-2012

2.3.3 3-Dimensional Scan Technology

Three dimensional photonic scan technology has traditionally been used in the clothing and apparel industry (Ryder 2012). White light scanners illuminate the body while a number of cameras capture the reflected light resulting in a 3D image produced by scanner software. Hundreds of measures are captured and total body volume can be estimated which is turn can estimate body density. From this, body fat can be estimated and is thought to be very precise when compared with measures taken by a trained anthropometrist (Garlie et al. 2010). The reliability of the TC^2 scanner has been conducted on 10 subjects where two scans were completed on each subject on the same day (Ryder 2012). A correlation of 0.922 ($p<0.001$) with a mean difference of 0.0899 was found (Garlie et al. 2010). The body fat estimate from the 3D scanner using the Department of Defence (DoD) prediction was compared to DXA. A correlation of 0.629 ($p<0.01$) was found between the 3D scanner and DXA and underestimated body fat by 2.77% (Ryder 2012).

In chapters 5 and 6, 3D scan technology was used to assess surface anthropometry and estimate body fat percent based on the DoD circumference equation included in the scanner software (Garlie et al. 2010). The scanner (Textile/Clothing Technology Corp (TC^2), Cary, NC, USA) was calibrated prior to each scanning session using the provided scanning balls and cylinder. A trained technician completed all scans in the same session as the DXA scan and skinfold measures. Participants were asked to wear light coloured (white, grey) form-fitting swimwear or underwear and a swimming cap for the scan. Participants were familiarised with the scanning process and were placed in the standard scanning position in the scanning booth. Feet were placed approximately shoulder width apart on the predetermined foot outlines and held the scanner handles which were positioned beside the body with hands facing inwards toward the thighs. The right handle had the scanner activation button in the thumb position. Once in position, participants were instructed to take a deep breath and then exhale when the technician indicated. This was to ensure the chest measure was taken when the participant had exhaled, rather than inhaled which would result in a greater chest circumference. This position was held for 10 sec until the completion of the scan. Results were based on the TC^2 pre-determined body fitness model assessment (Garlie et al. 2010).

2.4 Statistics

Statistical analysis throughout the thesis was performed using SPSS V.19.0 (IBM, Chicago, Illinois, USA). Results were considered statistically significant at $p<0.05$.

2.4.1 Regression analysis

The following is a brief description of the regression analysis utilised throughout the thesis:

Study 1

- Playerload™ was plotted against the corresponding estimated EE for oxygen consumption for each minute of the $\dot{V}O_{2max}$ test.
- Correlation analysis was performed and individual regression equations were developed for each participant.

Study 4

- Linear regression was used to determine if factors of body composition impacted selection in the draft.

2.4.2 Correlation analysis

The following is a brief description of the correlation analysis utilised throughout the thesis:

Study 1

- Estimates of EE as estimated by the regression equations developed in this study and estimates from the 'Metabolic Power' calculation utilised by the Catapult software.

Study 2

- To assess the relationship between EI and EE.

Study 3

- Measurement methods of body composition (DXA and skinfolds, DXA and 3D scan technology)

Study 4

- To determine correlation between skinfolds measurements and DXA measures of absolute and relative body fat.
- The magnitude of correlations was determined by: $r<0.1$, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; >0.9, nearly perfect; and 1, perfect.

2.4.3 Paired sample T-tests

The following is a brief description of the T-test analysis utilised throughout the thesis:

Study 2

- To assess the difference between measured intake of macronutrients and published recommendations.
- To assess the difference between EI and EE for each day of the week

2.4.4 Repeated measures analysis of variance

The following is a brief description of the ANOVA analysis utilised throughout the thesis:

Study 3

- Repeated measures ANOVA was used to determine change in body composition variables over the season in AF, Soccer and Rugby Union.
- A Bonferroni post-hoc analysis was used to determine at what stage of the season change occurred.

Study 4

- Repeated measures ANOVA was used to determine change in body composition variables over three measurement periods in AF development athletes.
- A Bonferroni post-hoc analysis was used to determine at what stage of the season change occurred.

If Mauchly's test of sphericity was significant, the null hypothesis was rejected and the Greenhouse-Geisser test of within subject effects was used. If the Mauchly's test of sphericity was not significant the null hypothesis was accepted and sphericity assumed.

Chapter 3. Study 1: Inertial Sensors to estimate the energy expenditure of team-sport athletes

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Only formatting has been altered to allow for layout compliance of the thesis.

3.1 Introduction

Quantifying the TDEE of an athlete allows individualised nutrition programming for sufficient energy supply. Whilst the activity profile of team-sport athletes is well established (Aughey 2011; Osgnach et al. 2010; Varley, Gabbett & Aughey 2014) few studies have measured the TDEE of these athletes (Ebine et al. 2002) or quantified the energy expended during training and matches (Coutts, A.J. et al. 2015; Coutts, A.J., Reaburn & Abt 2003; Stolen et al. 2005).

The measurement of EE in team-sport and/or under free-living conditions has not received much attention due to difficulty in measurement. Traditional methods of EE assessment require metabolic analysis that restricts typical movement and ADL (Levine 2005). The DLW method is considered 'gold standard'(Bluck 2008) for measuring TDEE, and estimated TDEE at ~14,000 kJ in professional Soccer players (Ebine et al. 2002). However, the DLW method does not differentiate between tasks and their relative contribution to TDEE, thus not allowing quantification of discrete tasks such as training or competition (Levine 2005). Heart-rate monitoring has also estimated the EE of professional Soccer, and Rugby Union players during matches as being between 5,700-7,100 kJ (Coutts, A.J., Reaburn & Abt 2003; Cunniffe et al. 2009; Stolen et al. 2005) but likely overestimates EE by 15-20% (Achten & Jeukendrup 2003; Novas, Rowbottom & Jenkins 2003). Thus, little is known of the EE in training and matches, nor the relative contribution of these to TDEE in team-sport athletes.

Global Positioning Systems (GPS) and inertial sensors may provide the practical solution to measuring physical activity of team-sport athletes (Barrett, Midgley & Lovell 2014; Boyd, Ball & Aughey 2011). Researchers have used GPS and metabolic power calculations in professional Soccer and AF to estimate EE of activities involving accelerations and decelerations during intermittent activity (Coutts, A.J. et al. 2015; Osgnach et al. 2010). In Soccer EE was ~61 $kJ \times kg^{-1}$ and AF ranged from 57-67 $kJ \times kg^{-1}$, or ~4,200 kJ to 5,200 kJ in absolute terms. This method has not been validated and does not take into account the direct impacts associated with contact sports such as AF.

Tri-axial accelerometers measure acceleration in three dimensions, and therefore all physical activity can be captured (Bouten et al. 1994). Sport-specific accelerometers are a reliable tool for measuring PA in team-sport athletes (Boyd, Ball & Aughey 2011) while other devices such as the SenseWear™ Armband (Model MF-SW, Bodymedia, Pittsburgh, PA) have been used to measure PA at low to moderate intensities (St-Onge et al. 2007) common in ADL. Energy prediction equations can be developed from the linear relationship between accelerometer data, $\dot{V}O_2$ (Barrett, Midgley & Lovell 2014) and estimated EE during a treadmill test (Bouten et al. 1994) which show reasonable concordance with DLW and calorimetry methods (Crouter, Clowers & Bassett 2006; Plasqui & Westerterp 2007; St-Onge et al. 2007). It is possible that two or more accelerometers with established reliability for different intensity tasks could be used synergistically to measure specific EE of tasks but also TDEE.

The activity profile of AF is greater than other team-sports with an average 12.6 km, 82 bouts of high velocity running, and 150 accelerations (Aughey 2010; Varley, Gabbett & Aughey 2014), thus ensuring a large metabolic cost. It is, therefore, likely that AF players have a higher match EE, and potentially higher training EE and TDEE than other team-sport athletes, but this is yet to be quantified.

The aims of this study were, to develop an algorithm utilising oxygen uptake and accelerometer data from the MiniMax 4.0 (Catapult Innovations, Scoresby Australia) to measure the EE of AF players during training and matches and against this, validate the MiniMax metabolic power calculation. In addition, the SenseWear™ armband will be used to determine NEAT from ADL. This data would then be used to address the secondary aim of the study which was to quantify the TDEE of professional AF players.

3.2 Methods

Eighteen professional AF players (22 ± 3 years, body mass 89.2 ± 6.2 kg, height 1.89 ± 0.07 m and body fat 9.9 ± 2.7%, Mean ± SD) gave written informed consent to participate in this study. The study was approved by the University Human Research Ethics committee; and conformed to the Declaration of Helsinki. Body composition was assessed by Duel Energy X-ray Absorptiometry (DXA, Hologic QDR).

Maximal aerobic power ($\dot{V}O_{2max}$) was determined in participants using an incremental exercise test completed on a motorised treadmill in a laboratory at 20.0 ± 1.0 ºC and humidity 51 ± 2.7%. Testing was conducted in week 14 and 15 of the pre-season, 3 to 4 weeks prior to the start of the competitive AF season when players would be considered at or close to peak match fitness. A metabolic measurement cart (S-3A/II and CD-3A analysers, Ametek, Pittsburgh, USA), calibrated before each test, measured oxygen uptake and estimated EE at each stage. After a 2 minute warm up at 10 $km \cdot hr^{-1}$ the treadmill speed was increased by 1 $km \cdot hr^{-1}$ every minute until volitional fatigue. Maximum $\dot{V}O_2$ was considered when the participant reached volitional exhaustion and maximum oxygen consumption was reached with increasing work rate. For the duration of the test, the MiniMax was worn in a vest and positioned between the shoulder blades as worn during matches and training. Accelerometer data were used to calculate Playerload™ (Catapult Innovations, Scoresby Australia) for each stage of the maximal test. Playerload™, expressed as arbitrary units (au) is a modified scaled vector magnitude and is a measure of total effort, expressed as the square root of the sum of the squared instantaneous rate of change in each of the three vectors divided by 100 (Boyd, Ball & Aughey 2011). Playerload™ was plotted against the corresponding estimated EE for $\dot{V}O_2$ for each minute of the test. Correlation analysis was performed and individual regression equations were developed for each participant. These equations were then used to estimate EE of training and matches.

To calculate the EE of training and matches, Playerload^{TM} was collected in players for the first six matches of the competitive season and in the main training session of the week. Each device was synchronized for starting time, time off the field of play and mandated breaks in play (Aughey 2010). The resulting EE regression equation was then applied to Playerload^{TM} for each session and a correction factor of 1.29 applied to calculate final EE. This was needed to correct for the additional energy cost of running on grass compared to a firm surface (Osgnach et al. 2010).

The EE calculated in this study was correlated with the metabolic power algorithm incorporated in the MiniMax software. The algorithm assumes sagittal plane acceleration and deceleration are primary drivers of energy cost (Osgnach et al. 2010). Two components of acceleration are considered. The ‘equivalent slope’ of an inclined terrain and the vertical orientation of the athlete is similar to that of accelerated running at a constant speed and the ‘equivalent mass’ where during a sprint an athlete exerts greater force than their body mass. Additional force is required to overcome acceleration (Osgnach et al. 2010). Energy cost is calculated as the function of the equivalent slope by the equivalent mass by a grass environment constant of 1.29. Metabolic power is derived from the energy cost of acceleration and running speed (Osgnach et al. 2010).

The SenseWear^{TM} Armband was used to determine EE outside of field training and for ADL and will be reported as NEAT. The device is a tri-axial accelerometer and integrates sensors for heat flux, skin temperature and galvanic skin response. The SenseWear^{TM} software acceptably calculates RMR (Malavolti et al. 2007) and EE based on a proprietary algorithm including height, body mass, age, sex accelerometer and skin temperature. Participants wore the armband on the right upper arm for seven days leading into a match and were instructed to remove the armband while showering, swimming and during contact training sessions (field based training and matches) to avoid damaging the device.

Total daily EE, NEAT, match EE and training EE are presented as absolute values (mean ± SD) and relative to body mass ($kJ \cdot kg^{-1}$) and time ($kJ \cdot kg^{-1} \cdot min^{-1}$). Regression analysis was used in development of EE equations for individual participants and has been presented with the coefficient of determination (R^2) and typical error (TE) with 90% confidence intervals (CI). Pearson's correlation was performed between EE methods and presented as change in the mean and 90% CI. Magnitude of correlations are reported as; 0.1 small, 0.3 moderate, 0.5 large, 0.7 very large and 0.9 extremely large.

3.3 Results

Descriptive results for participants are presented in Table 3.1. Injury, team selection and device malfunction resulted in only 12 full data sets from participants being collected for training and match data. Data collected from armband accelerometers to determine daily EE, resulted in 17 full data sets.

Regression equations were developed for each participant. Regression equations, correlations with TE and CV with 90% CI for each participant are in Table 3.1 and an example of a typical plot is presented in Figure 3.1. Overall, r =0.73 with 90% CI 10.7-13.6%.

The length of matches played was 121 ± 3.5 min with players participating in 64 -96% of the total playing time. The average PlayerLoad™ for this time was 1,235 ± 222 au resulting in an absolute corrected EE of 5,745 ± 1,468 kJ (range: 4,097 – 8621 kJ) or 64.7 ± 16.5 $kJ \cdot kg^{-1}$ or 0.66 ± 0.16 $kJ \cdot kg^{-1} \cdot min^{-1}$ per match. Variability between matches was 0.41 $kJ \cdot kg^{-1} \cdot min^{-1}$ (0.29-0.69). Using the metabolic power calculation, absolute EE was 5,118 ± 588 kJ for a match or 58.0 ± 5.8 $kJ \cdot kg^{-1}$ or 0.59 ± 0.06 $kJ \cdot kg^{-1} \cdot min^{-1}$. A large correlation between methods was observed (r=0.57; Mean difference mean = -9.4%, CI -19.0 – 1.4). Results for individual participants using each method are presented in Table 3.1.

The main training session of the week leading into the matches ranged from 66 - 83 min in duration. Average PlayerLoad™ of 565 ± 107 au resulted in an absolute corrected EE of 2,719 ± 666 kJ (range: 1,789 – 3,371 kJ), 30.4 ± 6.5 $kJ \cdot kg^{-1}$or 0.42 ± 0.08 $kJ \cdot kg^{-1} \cdot min^{-1}$ per training session.

Armbands were worn on average 90% of the time (151 hrs) across seven days of data collection, demonstrating good compliance. The MiniMax accounted for ~ 6 hrs of activity while 11 hrs were not captured by either device. These 11 hrs included time where participants were instructed to remove the armbands while showering and swimming. Average sleep was 7.0 ± 0.8 hrs per night, NEAT, including estimated RMR and resistance training sessions, and excluding on-field contact training, matches and pool sessions was estimated to be 15,544 ± 1,568 $kJ \cdot d^{-1}$. This equates to 174.2 ± 10.9 $kJ \cdot kg^{-1}$ or 0.14 ± 0.04 $kJ \cdot kg^{-1} \cdot min^{-1}$. Mean NEAT and armband compliance for each day are shown in Table 3.2. To estimate TDEE for a training day and match day, NEAT and training EE and NEAT and match EE were combined to give a TDEE for each day respectively and are reported in Table 3.2 and Figure 3.2.

Participant	Mass range (kg)	Height range (m)	Equation	R^2	TE (90% CI)	EE·kg^{-1} Study	EE·kg^{-1} MiniMax
1	85-90	1.80-1.85	2.934x + 18.988	0.827	0.31(0.22-0.51)	59.2	63.1
2	85-90	1.85-1.90	4.372x – 13.036	0.805	0.51(0.37-0.84)	99.1	69.2
3	85-90	1.85-1.90	4.300x – 6.184	0.926	0.25(0.18-0.43)	84.6	59.2
4	80-85	1.80-1.85	4.037x - 2.956	0.624	0.65(0.48-1.07)	75.4	57.4
5	95-100	2.00-2.05	7.794x – 70.796	0.716	0.80(0.57-1.44)	80.6	*
6	95-100	2.00-2.05	3.391x – 1.604	0.932	0.44(0.31-0.79)	46.7	40.54
7	90-95	1.90-1.95	3.440x + 0.259	0.987	0.15(0.11-0.26)	44.3	57.1
8	80-85	1.80-1.85	3.442x – 0.265	0.985	0.10(0.07-0.16)	56.5	42.0
9	85-90	1.80-1.85	3.487x – 1.480	0.934	0.56(0.39-1.01)	59.0	66.4
10	90-95	1.90-1.95	3.750x – 7.751	0.913	0.20(0.14-0.35)	59.6	60.2
11	80-85	1.85-1.90	2.710x + 19.31	0.855	0.26(0.18-0.44)	55.5	52.7
12	80-85	1.90-1.95	3.487x – 1.480	0.934	0.58(0.42-0.99)	55.5	52.9

Table 3. 1 Individual regression equations of participants, where x is PlayerLoad and y is energy expenditure.

n=12. Mass and height range reported to keep identity of participant un-identifiable. Typical error (TE) with 90% confidence intervals (CI) have been reported for regression equations. EE·kg^{-1} ‘study’ refers to data from equations developed in current study, EE·kg^{-1} MiniMax refers to data the metabolic power calculation (Catapult Innovations) for an average match. * Data not available

Day	NEATEE ± SD (kJ)	Time worn (%)	Exercise EE ± SD (kJ)	Training schedule
1	19,885 ± 2,422	97	-	T1
2	14,298 ± 2,040	91	-	T2
3	14,484 ± 1,522	93	-	DO
4	15,785 ± 2,006	85	2,719 ± 666	T3
5	16,068 ± 2,409	94	-	T1
6	13,414 ± 1,688	91	-	T4
7	13,324 ± 1,295	83	5,745 ± 1,468	MD

Table 3. 2 Approximate TDEE of AF players across 7 days leading in to match.

Energy expenditure of participants from NEAT including RMR, proportion of the day the SenseWear^{TM} accelerometer was worn, exercise EE measured by MiniMax and football training activities. NEAT as measured by SenseWear^{TM}, n = 17. Exercise EE as measured by MiniMax, n=12 only measured for the main training session and match.

T^1 = Swimming, light cross training (stationary bike and running), resistance training, core; T^2 = Light cross training (boxing), ball skills, resistance training; T^3 = Main training day with football specific drills and player contact; T^4 = Light training session with non-contact ball skills; DO = Player day off; MD = Match day (approx. 5.5 hr) – arrive at match venue 2 hr prior including light warm-ups + 2.5 hr match with mandated breaks in play + 1 hr recovery including ice baths, light cycle on stationary bike, massage treatment.

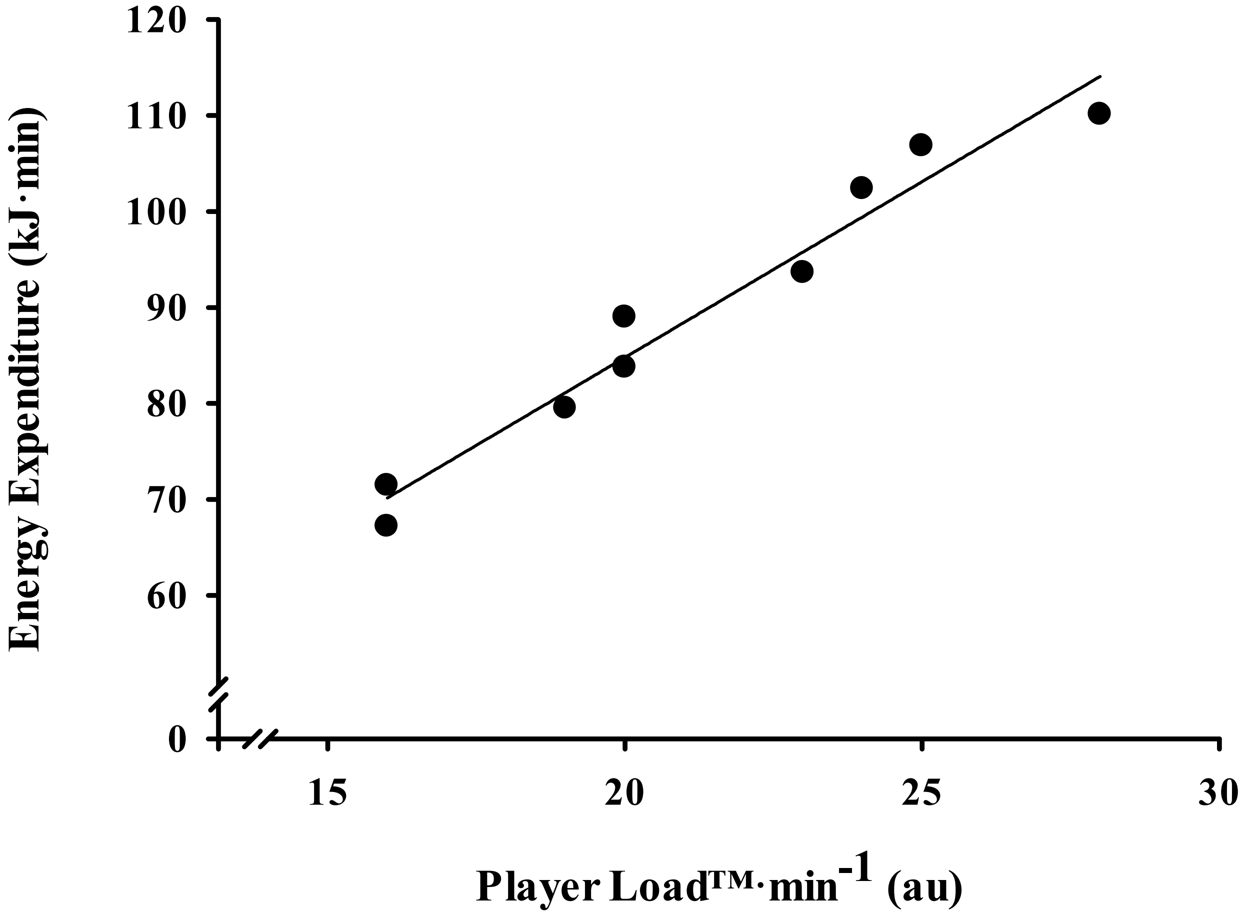

Figure 3. 1: A typical plot and regression equation between estimated energy expenditure and Playerload™ arbitrary units during each stage of a V.O2max test.

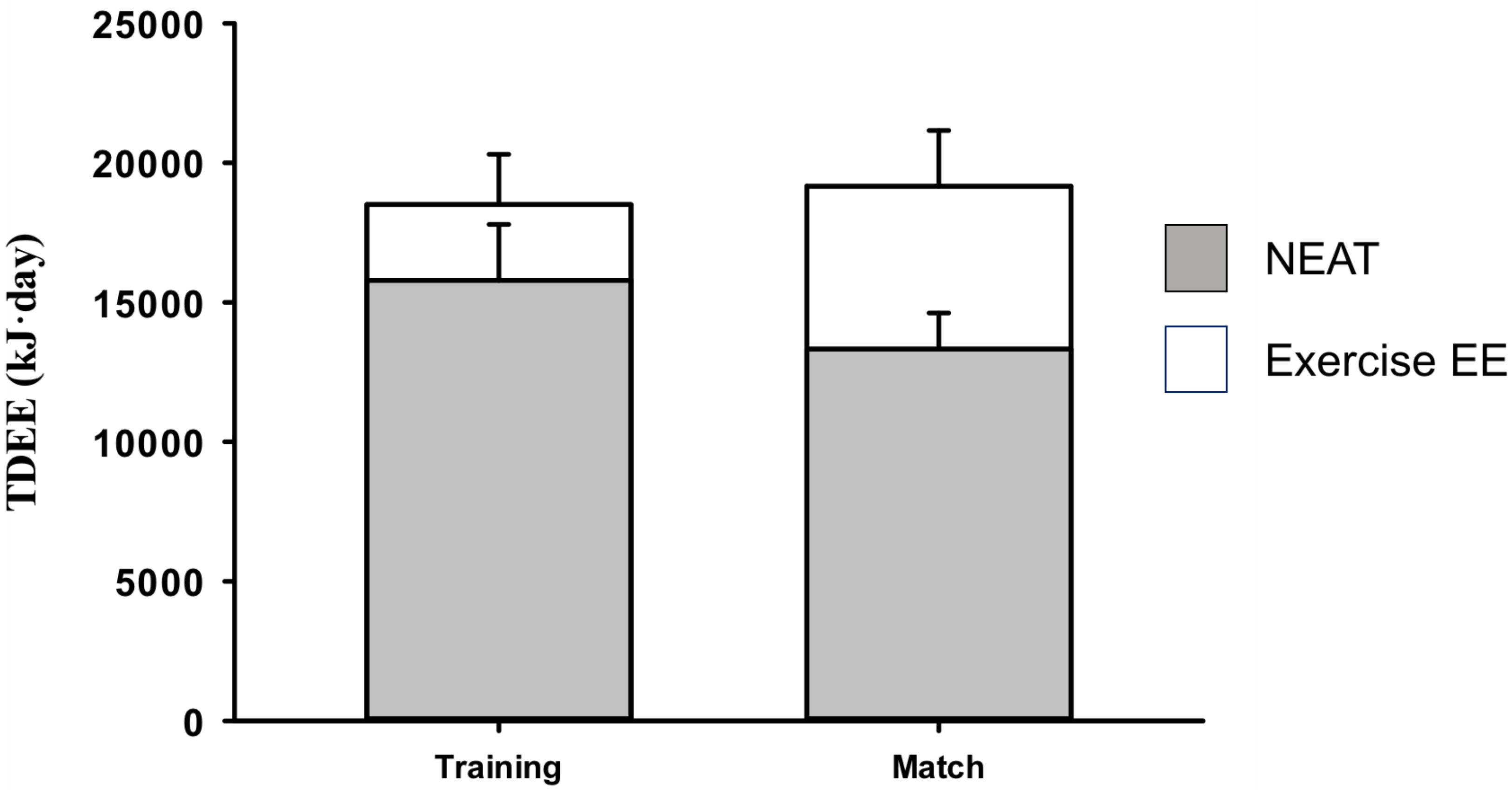

Figure 3. 2: TDEE (kJ•day) of participants and contribution of exercise EE and NEAT inclusive of RMR.

In season football specific training day TDEE: sum of mean NEAT and training, EE n = 12. Match day TDEE sum of NEAT and Match EE, n=12.

3.4 Discussion

This study determined the TDEE of AF players and the estimated EE contribution of matches and training. Tri-axial accelerometers provided a simple, non-intrusive and effective method of estimating EE across the day and during contact sport situations. The first major finding of this study is that PlayerLoad TM correlates well with $\dot{V}O_2$ and estimated EE during an incremental treadmill test. Within the confines of this, we were able to successfully estimate EE of AF players. Our results were comparable with metabolic power calculations (Coutts, A.J. et al. 2015; Osgnach et al. 2010) however, were considerably less than other football codes when compared to the heart rate / $\dot{V}O_2$ method (Coutts, A.J., Reaburn & Abt 2003; Cunniffe et al. 2009; Stolen et al. 2005).

Quantifying EE on the field for team-sports, is difficult due to lack of established, accurate and practical methods and those that have been used have limitations (Levine 2005). Estimated EE calculated in this study from the developed algorithm was ~64.7 kJ$\times$kg^{-1} (58.6 kJ$\times$min^{-1}). This is slightly higher than the EE measured by a portable ventilation system during a Soccer friendly of 62.75 kJ$\times$kg^{-1}(50.2 kJ·min^{-1}) (Rodriguez FA 1998). A lower EE would be expected in Soccer as the match does not involve deliberate physical contact, which would contribute to a higher EE in AF.

The heart rate/$\dot{V}O_2$ method also presents some critical limitations (Achten & Jeukendrup 2003). The EE of Soccer, Rugby League and Rugby Union was estimated to be 92.0 kJ kg^{-1} (71.9 kJ$\times$min^{-1})(Stolen et al. 2005), 87.6 kJ$\times$kg^{-1} (85.9 kJ$\times$min^{-1}) (Coutts, A.J., Reaburn & Abt 2003), 72.6 kJ$\times$kg^{-1} (94.4 kJ$\times$min^{-1}) (Cunniffe et al. 2009) respectively. Per minute of match time, this equates to 19, 32 and 38% greater estimated EE for each sport than the current study. This was not expected as the greater activity profile of AF (Aughey 2010; Varley, Gabbett & Aughey 2014) should result in a greater EE. This can most likely be attributed to the discrepancy of the heart rate/$\dot{V}O_2$ method during exercise that involves rapid and intermittent changes in activity (Achten & Jeukendrup 2003). During sub-maximal steady-state exercise, heart rate and $\dot{V}O_2$ have a linear relationship however during a Soccer match where EE was estimated simultaneously from both heart rate and a portable gas analyser (Rodriguez FA 1998), the heart rate method overestimated EE by approximately 15% (Rodriguez FA 1998)..

The algorithm developed in this study estimated EE of a match to be ~5,745 kJ (~64.7 $kJ \times kg^{-1}$) while the metabolic power calculation was ~5,118 kJ (58.0 $kJ \times kg^{-1}$). There was large correlation (r=0.57) between estimates however the metabolic power equation overestimated EE by ~9.4% with CI indicating large uncertainty. Our results are comparable to a separate study using metabolic power calculations in 39 AF players across a variety of positions for 19 matches where EE was calculated at 57-65.6 $kJ \times kg^{1}$ (Coutts, A.J. et al. 2015). The same method was used in 399 first division Soccer players for 56 matches with a mean EE of 61.12 $kJ \times kg^{-1}$ (Osgnach et al. 2010).

The method used to develop the EE algorithm with the MiniMax for this study, may be influenced by kinematic and anthropometrical variables associated with treadmill running, consequently underestimating EE for a given running velocity on grass as used for training and matches in AF. Running kinematics are modified on different surfaces (Hogberg 1952; Riley et al. 2008) as treadmill running reduces stride length, contact time, vertical and horizontal velocity and vertical displacement (Wank, Frick & Schmidtbleicher 1998). This leads to a reduction in energy cost compared to overground running. The energy cost of treadmill running ranges from 3.4 - 3.74 $J \cdot kg^{-1} \cdot m^{-1}$ (di Prampero et al. 1986) while running on grass is 13-36% higher. We therefore multiplied our EE algorithm by a published constant of 1.29 (Osgnach et al. 2010) to account for the difference between surfaces.

The accelerometer signal and subsequent data captured such as EE, will vary between individuals due to differences in running kinematics (Wixted et al. 2007) These variations may help to explain the relatively poor correlation and precision for participant 4 and 5 in the present study. In the first 4-5 stages (10-14 $km \cdot hr^{-1}$) of the treadmill test, PlayerLoad™ data plateaued while oxygen consumption continued to rise. A similar response was observed in two out of 10 AF players where accelerometer counts plateaued with increasing running speeds of 11-21 $km \cdot hr^{-1}$ (Wixted et al. 2007). These two individuals exhibited consistent vertical acceleration across all running speeds whereas the other participants had medio-lateral and anterior-posterior activity contributing additional counts (Wixted et al. 2007).

The metabolic power calculation takes into account the large metabolic cost of acceleration and decelerations (Osgnach et al. 2010) however the metabolic cost of tackles and jumps are not accounted for (Coutts, A.J. et al. 2015; Osgnach et al. 2010). There is also considerable error in measurement of accelerations and movements at high speeds using 10 Hz GPS (Buchheit et al. 2014), which was used in this study. The lack of a 'gold standard' method to compare against makes it hard to know what the 'true' EE of an individual athlete is. However, GPS/accelerometer data may provide the most practical, and accessible method to estimate a team-sport athlete's EE and dietary requirements.

The TDEE of AF players is similar to other team-sport athletes. Taking the activity profile of team-sports such as AF and Soccer into consideration, it was expected that the greater demands of AF (Aughey 2010, 2011) would result in a higher TDEE. The TDEE of AF players was estimated with a combination of the SenseWear™ and MiniMax accelerometers to capture a range of physical activity intensities to be ~ 18,500 kJ on a main on-field contact training day and 19, 100 kJ on match day. Compared to the gold standard, our estimate is 23-25% higher than professional Soccer players (TDEE; 14,800 kJ) (Ebine et al. 2002).

The contribution of NEAT to TDEE differs based on sport, training periodisation and training volume throughout a season (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013). High training load increases the percentage EE arising from exercise and therefore decreases the proportion from NEAT (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013). Despite increased exercise EE during high load periods, athletes still lead an active lifestyle with light to moderate activities and reduced time in sedentary activities (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013). This is demonstrated in the current study where NEAT (inclusive of RMR) contributes approximately 85% to TDEE on in-season main training days and 69% on match days in AF players. This is similar to male endurance athletes where the proportion of energy coming from NEAT and RMR ranged from 73-84% for high and low volume training days respectively (Drenowatz, Eisenmann, Pivarnik, Pfeiffer, et al. 2013). This indicates that although exercise EE significantly contributes to TDEE, other factors, particularly NEAT must be taken into account to ensure adequate energy is consumed to maintain energy balance in athletes.

Accelerometers are an accessible method for measuring PA and EE however limitations exist. Two accelerometer devices were selected for use in this study based on specific limitations and capabilities. The SenseWear™ armband is a reliable and valid method to measure EE during resistance training (Reeve, Pumpa & Ball 2013) and low to moderate intensity ADL (St-Onge et al. 2007) but is unable to reliably measure EE at higher intensities (Zanetti et al. 2014) whereas the MiniMax is valid and reliable for the high intensities required in intermittent team-sport athletes (Boyd, Ball & Aughey 2011). An accelerometer capturing all ranges of PA would be ideal for future research; however the use of two devices in this study provides a good overall indication of the energetic requirements of an AF player.

Total daily EE is likely to be higher than estimated in this study. Energy expenditure captured by the SenseWear™ armband, included resistance training but was only worn for an average of 90% across the seven day period (Table 3.2) due to either swimming, contact training sessions, showering or non-compliance. The MiniMax only measured the main on-field training session and the match, meaning other EE outside of these times were not measured. This equates to approximately 11 hours across the week where EE was not measured. The SenseWear™ armband can acceptably measure RMR of healthy individuals based on a proprietary algorithm (Malavolti et al. 2007) however athletes have greater lean muscle mass which is considered more metabolically active and therefore RMR may be underestimated. Finally, the armband has a large correlation (r=0.77) with indirect calorimetry measurement during resistance training however there are limitations in measuring these types of sessions as the armband only measures acceleration of the movement and not load. Therefore, a heavy weighted squat results in low accelerometer movement despite a high EE and would therefore be underestimated by the armband accelerometer.

3.5 Conclusion

The most pertinent finding of this study showed that AF players expend a considerable amount of energy over the day and a significant portion of this (~85%) comes from NEAT. Energy expended through daily tasks may be overlooked when tailoring programs for individual athletes and need to be considered along with training and match expenditures.

The calculated EE of individual players during a match using PlayerLoad™ correlated well with the MiniMax metabolic power calculation and found similar results to studies previously conducted in AF and Soccer. While all methods have their limitations, inertial sensors and GPS are practical methods that provide reasonable estimates of energy expended during contact team sports. Notwithstanding the potential limitations of this study, our results extend the body of knowledge in this area, and provide fundamental information for dietitians and conditioning coaches of field sport athletes.

3.6 Practical considerations

- Accelerometers provide an accessible, simple and effective way of measuring EE in the field.
- Estimations of training and match play EE are useful when tailoring dietary requirements for sports performance and recovery in individual athletes.
- Estimations of total daily EE are useful when tailoring dietary energy requirements for individual athletes who may need to make changes in body composition.
- The information obtained from accelerometers in estimating precise EE must be considered in the context of the limitations. Understanding the device limitations and operating within these is necessary.

Chapter 4. Study 2: Dietary intake of a team competing in the Australian Football League: Are they meeting requirements?

4.1 Introduction

Australian Football is an endurance based team sport with high-energy demands (Coutts, A.J. et al. 2015; Walker et al. 2016). Players can cover up to 13 km in approximately 98 min of on-field match time while enduring repeated contacts through collisions and tackles (Varley, Gabbett & Aughey 2014). The match is interspersed with repeated high velocity efforts with short recovery periods (Varley, Gabbett & Aughey 2014) and a large number of maximal accelerations (Aughey 2011; Varley, Gabbett & Aughey 2014) resulting in a high energy cost (Coutts, A.J. et al. 2015; Walker et al. 2016).

The EE of an AF match has been estimated to be between 57-67 $kJ \times kg^{-1}$ across playing positions (Coutts, A.J. et al. 2015; Walker et al. 2016) with an approximate absolute expenditure of 5,745 ± 1,468 (Walker et al. 2016). Energy is expended from a high volume of low-intensity activity (Varley, Gabbett & Aughey 2014) that requires limited energy turnover (Bangsbo, Mohr & Krustrup 2006). A high energy turnover is required for repeat intense actions (Bangsbo, Mohr & Krustrup 2006) such as tackling and collisions (Gastin et al. 2013) in addition to the higher velocity running and sprinting (Varley, Gabbett & Aughey 2014). The energy expended outside of training and competition from NEAT contributes a large portion of the TDEE (Drenowatz et al. 2012; Walker et al. 2016), the majority of which would be at a low intensity. Non exercise activity thermogenesis contributes approximately 85% to TDEE and 69% on match day for a TDEE of approximately 18,500 kJ and 19,200 kJ respectively (Walker et al. 2016). Matching EE with EI is known as energy balance and is thought to promote athletic performance (Rodriguez et al. 2009). Low dietary EI over the long-term may result in nutrient deficiency and in-turn compromise health (Rodriguez et al. 2009), however, there are times when EI will need to be in deficit or excess of expenditure, for example, when manipulating body composition (Burke, Loucks

& Broad 2006). Energy intake alone is not sufficient to assess dietary intake and the proportions of macronutrients must be considered.

Carbohydrate and fat are the predominant macronutrients required to fuel team sport athletes (Holway & Spriet 2011) while protein is crucial for recovery and repair (Phillips 2012). Only few studies have been conducted into the energy and nutrient intake of AF players, limiting the comparisons that can be made however the first study conducted over 25 years ago found an EI of 14,200 kJ made up of 44.0% carbohydrate, 15.0% protein and 37.5% fat reported (Burke & Read 1988). Ten years later, EI had reduced to 13,200 kJ however carbohydrate had increased to 51.7%, protein to 18.1% and fat intake reduced to 29.2% (Schokman, Rutishauser & Wallace 1999). Taking into consideration that different methods of measurement were used to record dietary intake, Nutrition advice in AF has ranged from following Australian population guidelines (Burke & Read 1988) and later encouraging a high carbohydrate across the entire week (Ebert 2000). Nutrition recommendations are now more specific for different activity levels and intensities ranging from 3 $g \times kg^{-1}$ $BM \times d^{-1}$ for a skills based session to 6-10 g $g \times kg^{-1}$ $BM \times d^{-1}$ for moderate to high intensity exercise of 1-3 hours (Burke et al. 2011). However, with greater access to nutrition professionals in clubs and more specific dietary guidelines for the athletic population, it is unknown if AF players have modified their dietary intake.

Over time, match style and intensity of AF has changed considerably (Norton, Craig & Olds 1999). The resources and focus on athletic training and recovery has also increased since this time, however whether dietary intake has altered and kept up with this change in intensity and if dietary intake is meeting recommendations for optimal performance is unclear (Burke & Read 1988; Schokman, Rutishauser & Wallace 1999). The aim of this study was thus to measure the energy and macronutrient intake of professional AF athletes and assess whether they meet their daily EE. In addition, this study also aimed to compare the macronutrient intake of players with current sports nutrition recommendations for team sport athletes.

4.2 Methods

Eighteen professional AF players (22.0 ± 3.0 years, body mass 89.2 ± 6.2 kg, height 1.9 ± 0.07 m and body fat 9.9 ± 2.7%, all data Mean ± SD) gave written informed consent to participate in this study. The study was approved by the Victoria University Human Research Ethics committee; and conformed to the Declaration of Helsinki.

In the seven days leading into a pre-season match AF players completed a weighed food diary. Players were provided with food scales and kitchen measures and instructed on how to the use equipment and record dietary intake. Players were instructed to record all food, fluid (including alcohol) and supplements taken in this time. Food diaries were analysed with the Foodworks nutrition software (Version 7, Foodworks, Xyris, Qld Australia) that utilises the AUSNUT database (Food Standards Australia New Zealand) for food and beverages. Vitamin and mineral supplements in tablet, capsule or powder form were excluded from the analysis due to their negligible energy and macronutrient content.

In conjunction with the collection of nutrition data, the measurement of TDEE including ADL, training EE and match EE were also collected and has been reported previously in chapter 3. In brief, the SenseWear^{TM} Armband (Model MF-SW, Bodymedia, Pittsburgh, PA) was worn for seven days leading into a pre-season match to measure ADL.

Training and match EE was measured with the MiniMax 4.0 (Catapult Innovations, Scoresby Australia), a sport specific accelerometer that has been validated for measuring exercise at a high intensity in teams sports (Boyd, Ball & Aughey 2011). MiniMax 4.0 data was correlated with oxygen consumption during an incremental $\dot{V}O_{2peak}$ test on a treadmill and individual regression equations were developed for each participant to estimate EE (chapter 3).

Daily EI and EE data is reported as the mean ± SD. Macronutrient intake is reported as mean ± SD, $g \times kg^{-1}$ $BM \times d^{-1}$ and percent of daily intake. One-way repeated measures ANOVA with Bonferroni post hoc analysis was used to determine variance over the week for EI, EE and macronutrients. Paired sample *t-tests* were used to assess the difference between measured intake of macronutrients and published recommendations. The difference between EI and EE for each day of the week was assessed with t-tests and Pearson's correlation used to assess the relationship between variables. SPSS (v 20,IBM New York USA) was used for analysis. Significance was set at 0.05 for all comparisons.

4.3 Results

Fifteen weighed food diaries were completed for the study period while only 12 complete EE data sets were collected due to injury, team selection and device malfunction. Mean daily EI was 14,719.0 ± 3,422.1 kJ and remained stable across the week with no difference between days ($F(6,60)=0.763$, $p<0.602$, Figure 4.1). When EI was compared to EE, only days 1 ($p<0.001$, CI: 2,828.5 – 7,602.1 kJ) and 4 ($p=0.017$, CI: 771.4 – 6764.8 kJ) were different (Figure 4.1). Of the seven days, EI and EE only correlated on day 7 ($r^2=0.795$, $p<0.018$). Overall, mean EI and EE over the 7 days did not correlate ($r^2=0.015$, $p<0.67$, CI: -0.44 – 0.61).

Dietary EI was predominantly made up of carbohydrate contributing 49.2 ± 1.7% of energy, with absolute carbohydrate intake being 456 ± 140 g per day or 5.1 ± 1.7 $g \times kg^{-1}$ $BM \times d^{-1}$ and did not differ across the week. Intake was sufficient to meet recommendations for low intensity skills based sessions (3-5 $g \times kg^{-1}$ $BM \times d^{-1}$) and the lower range of recommendations for moderate activity (5-7 $g \times kg^{-1}$ $BM \times d^{-1}$), however were considerably lower compared to the upper range of the moderate (5-7 $g \times kg^{-1}$ $BM \times d^{-1}$) and moderate to high intensity (6-10 $g \times kg^{-1}$ $BM \times d^{-1}$) days (Table 4.1).

Mean daily protein intake represented 21.5 ± 1.9% daily EI or 182.7 ± 44.1 g or 2.1 ± 0.5 $g \times kg^{-1}$ $BM \times d^{-1}$ and surpassed recommendations (Table 4.1). Intake did not differ across the week. Protein intake from protein powders and bars was highly variable ranging from 0 % intake on days with no training to 31% of total protein intake on days with training. This also differed between individual athletes depending on whether they chose to get their protein from foods or supplements with the mean intake on a main training day of 11.2 ± 10.4% of total protein. Mean fat intake was 98.0 ± 28.9 g per day or 1.1 ± 0.3 $g \times kg^{-1}$ $BM \times d^{-1}$ or 24.6 ± 7.6% of total energy and was within recommendations (Table 4.1). Fat intake did not change across the week. Energy and macronutrient intake results are presented in Table 4.2 alongside studies conducted previously to illustrate a possible change in intake over time however we are not concluding this is representative of all athletes and teams.

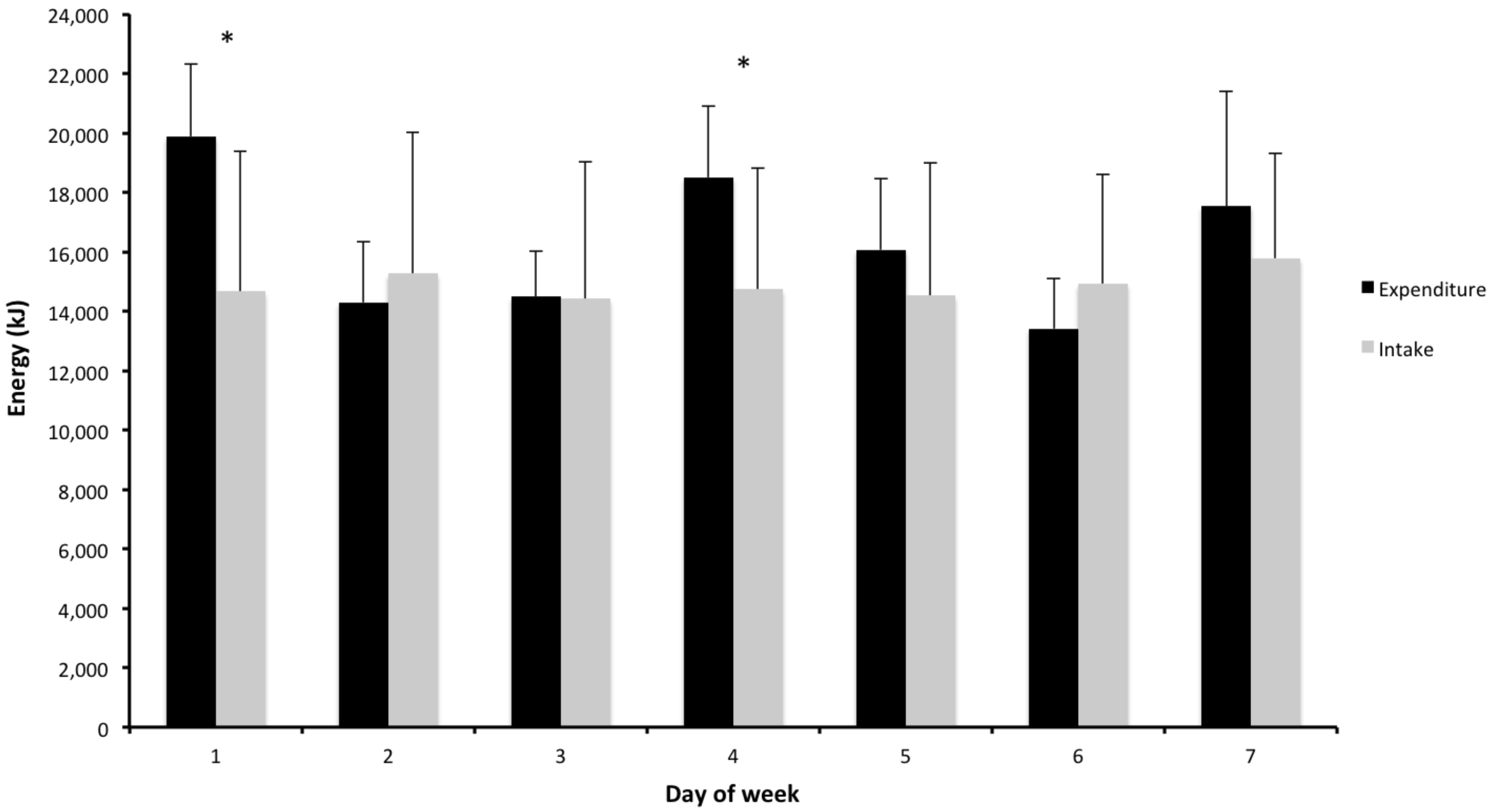

Figure 4. 1: Energy expenditure and intake of AF players during a regular training week. * EE and EI different (Day 1 p<0.001, Day 4 P=0.017). Day 1 = Swimming, light cross training (stationary bike and running), resistance training, core; Day 2 = Light cross training (boxing), ball skills, resistance training; Day 3 = Player day off; Day 4 = Main training day with football specific drills and player contact; Day 5 = Swimming, light cross training (stationary bike and running), resistance training, core; Day 6 = Light training session with non-contact ball skills; Day 7 = Match day (approx. 5.5 hr) –arrive at match venue 2 hr prior including light warm-ups + 2.5 hr match with mandated breaks in play + 1 hr recovery including ice baths, light cycle on stationary bike, massage treatments

	Recommendations g×kg^{-1}	Day of week	Mean Intake (95%CI)	*p-value* vs. lower end of recommendation	*p-value* vs. higher end of recommendation
CHO low intensity skills based activities (Burke et al. 2011)	3–5	1-2	5.1(4.4-5.8)	0.000	0.741
CHO Moderate intensity (~1 hr) (Burke et al. 2011)	5-7	4	5.2(4.1-6.3)	0.642	0.005
CHO Endurance exercise, moderate to high intensity (~1-3 hrs) (Burke et al. 2011)	6-10	5-6	5.3 (4.4-6.2)	0.125	0.000
CHO Pre event meal 1-4hrs prior to event (Burke et al. 2011)	1-4	7	2.2 (1.6-2.7)	0.003	0.000
Daily Protein (Phillips 2012; Rodriguez, Di Marco & Langley 2009; Rodriguez et al. 2009)	1.2 -1.7	1-7	2.1 (1.8-2.3)	0.000	0.018
Daily Fat % total energy (Rodriguez, Di Marco & Langley 2009; Rodriguez et al. 2009)	20-35	1-7	24.6 (21.7-27.5)	0.004	0.000

Table 4. 1: Macronutrient intake compared to recommendations. CHO carbohydrate

			Energy		Carbohydrates		Protein		Fat	
	n	Mean BM (kg)	kJ	kJ·kg^{-1}	g	g·kg^{-1}	g	g·kg^{-1}	g	%
Burke et al, 1988	56	82.3 ± 8.2	14,160 ± 3,000	170 ± 40	373 ± 94	4.5 ± 1.1	126 ± 27	1.5 ± 0.4	141 ± 33	37.5
Schokman et al, 1999*	40	86.2 ± 7.8 (SD)	13,200 ± 2466	153.8 ± 29	415.1 ± 111	4.8 ± 1.3	138.8 ± 28.5	1.6 ± 0.32	104.4 ± 35.7	29.2
Current study	15	89.4 ± 7.9	14,719 ± 3,422	165.7 ± 41	456 ± 140	5.1 ± 1.7	182.7 ± 44.1	2.1 ± 0.5	98.0 ± 28.9	24.6

Table 4. 2: Change in macronutrient intake over time in Australian Football. Data represented as Mean ± SD.

*Original data reported SEM. For comparison purposes, SEM has been converted to SD. BM, body mass; kJ, kilojoules; g , grams.

4.4 Discussion

Professional AF players in this study, despite expending a significant and varying amount of energy across the week, fail to meet energy and carbohydrate requirements to support sustained training, match performance and health. The players also appear to have a consistent EI across the week despite a variation in EE, which may impact on recovery and adaptive responses to training.

On high EE days, players were less likely to match expenditure with dietary EI. On days 1 and 4, EI intake was significantly less than expenditure by approximately 26% and 20% respectively. Both these days involved a busy training schedule (Figure 1) with numerous activities, ranging in exercise intensity. During high and low-volume training weeks, EI of endurance athletes was 45% and 39% lower than TDEE (Drenowatz et al. 2012). In a group of professional Soccer players, EE was measured with the 'gold-standard' DLW method and EI was 12% lower than TDEE (Ebine et al. 2002). In both studies, body mass did not change and it was therefore concluded that EI was under-reported rather than the athletes under-eating (Drenowatz et al. 2012; Ebine et al. 2002). The same conclusion may be drawn for the current study.

Under-reporting is a common limitation when measuring dietary intake (Burke 2001a; Cole et al. 2005; Drenowatz et al. 2012; Hill & Davies 2001; Magkos & Yannakoulia 2003). Athletes can under-report in dietary records by 10-45% (Magkos & Yannakoulia 2003). This can be intentional i.e. to improve perception of what they are eating or unintentionally, i.e. errors in measurement of food quantity (Burke 2001a). Under-reporting can also occur when there is an increased number of eating occasions due to high energy requirements or underreported more on days when intake was higher (Burke 2001a). On two days in this study (Days 1 and 4) when EI was significantly different from EE, the training schedule was busier than other days having a greater training volume and more training components and therefore less opportunity to eat. On the majority of other days, EI and EE were more closely aligned. It is difficult to determine if this is due to underreporting or if energy is actually being under consumed. Body mass and/or composition has been used to determine if EI is sufficient for EE (Drenowatz et al. 2012; Ebine et al. 2002) however over a short period of time a loss or gain in mass may be due to hydration status and/or glycogen stores that are associated with stored body water (Loucks, A. B. 2004).

It should also be considered that EI does not necessarily need to match EE. Relative energy deficiency (RED-s) is the balance between dietary EI and the EE required to support growth, health, ADL and exercise EE (Mountjoy et al. 2014). The leftover energy from dietary intake after exercise EE is required for metabolic processes and is known as energy availability. Chronically low energy availability is associated with metabolic dysfunction and can result in compromised immunity, bone health, hormonal and metabolic abnormality and therefore performance (Loucks, A.B., Kiens & Wright 2011; Mountjoy et al. 2014). If after exercise, energy availability is above 126 kJ·kg FFM·d^{-1}, there is reduced risk of health and physiological problems (Loucks, A.B., Kiens & Wright 2011). Taking this into consideration, basic analysis was completed on our match day intake and expenditure data showing a mean energy availability of 127 ± 13.5 kJ·kg FFM·d^{-1}. This is only data for one day and after taking methodological limitations into account, players in this group are most likely meeting their requirements. There may be more risk in pre-season due to large training volumes and busy schedules (Moreira et al. 2015). Limited research is available in male athletes as RED has most often been associated with female athletes, however recently it has been acknowledged that RED can occur in males (Mountjoy et al. 2014). Risk is generally greatest in weight category and aesthetic sports however with increasing pressure to be within certain levels of body fat, there are increased risk in other elite and professional sports (Burke et al. 2011). Further research in this area would be beneficial with the addition of physiological measures that were outside the scope of this study.

There are a number of other reasons why athletes may not meet energy requirements. There is a reduced desire to eat even though additional energy has been expended (Burke et al. 2003), that can be intensified by higher intensity exercise (Burke, Loucks & Broad 2006), and a busy training schedule may provide less opportunity to eat and replace energy used (Burke, Loucks & Broad

2006). In some cases athletes also eat less on competition days because of stress, fear of gastrointestinal discomfort and a match schedule that leads to altered eating patterns (Burke, Loucks & Broad 2006). There are also limitations to methods used to measure EI and EE. Seven-day food diaries are a reliable measure of dietary intake however place a high burden on participants which may lead to altered intake for ease of recording, generally resulting in an underestimation of energy consumption (Magkos & Yannakoulia 2003). Tri-axial accelerometers are a reliable method to measure TDEE when participant variables such as age, height and body composition measures are used in the proprietary algorithm and vary by 6-9% (Plasqui et al. 2005) however some activities such as cycling and resistance training may result in an underestimation of EE (Benito et al. 2012; Brazeau et al. 2011). There are limitations in measurement methods and unfortunately there is no gold standard method for measurement of dietary intake. Results should be interpreted with caution however they do provide a guide on dietary intake and expenditure data and can be used by dietitians in nutrition programming.

Mean EI in AF players has not changed since it was first measured in 1988 (Burke & Read 1988). Mean daily EI of the AF players in this study was 14,719 kJ (167 $kJ{\cdot}kg^{-1}$) while in 1988 it was 14,200 kJ (170 $kJ{\cdot}kg^{-1}$) and 13,200 kJ (153 $kJ{\cdot}kg^{-1}$) in 1999 (Schokman, Rutishauser & Wallace 1999) (Table 4.1). Absolute EI intake is similar to that of other high intensity team sports athletes over the past 30 years with a mean daily intake of approximately 15,300 kJ (Holway & Spriet 2011). While, relative to body mass, AF players consume more energy than Gaelic football players 151.0 $kJ{\cdot}kg^{-1}$ (Reeves & Collins 2003), and less than professional male Soccer players 173.4 – 186.3 $kJ{\cdot}kg^{-1}$(Ebine et al. 2002; Reeves & Collins 2003) and Rugby League players 192.5 $kJ{\cdot}kg^{-1}$ (Lundy et al. 2006). Interestingly, AF has a greater activity profile than each sport (Varley, Gabbett & Aughey 2014) yet players consume less energy. This difference may be due to reporting or possibly in the case of Rugby Union, EI may be greater to enhance body mass for the requirements of the sport. Energy intake is not the sole objective of dietary intake with the timing and amount of macronutrients also contributing to performance and health outcomes.

The macronutrient composition of the diet can have a significant impact on performance in team sport athletes (Mujika & Burke 2010) and has changed only slightly from 1988 (Burke & Read 1988), 1999 (Schokman, Rutishauser & Wallace 1999) and until now. Carbohydrate is an important fuel source for team sport athletes, and mean intake in this study was 5.1 $g \times kg^{-1}$ $BM \times d^{-1}$. Although we cannot categorically say this is representative of all teams and athletes due to our small sample size, our results are similar to those seen in other professional teams and codes. Gaelic football reported an intake of 5.2 $g \times kg^{-1}$ $BM \times d^{-1}$ (Reeves & Collins 2003) and 4.9 $g \times kg^{-1}$ $BM \times d^{-}1$ in a professional English Rugby League team ((Tooley et al. 2015) while intake was greater than seen in professional Rugby Union players with an intake of 3.4-3.5 $g \times kg^{-1}$ $BM \times d^{-1}$ (Bradley et al. 2015). Intake was less than in professional Soccer (5.9 $g \times kg^{-1}$ $BM \times d^{-1}$) (Reeves & Collins 2003) and professional Australian Rugby League players (6 $g \times kg^{-1}$ $BM \times d^{-1}$) (Lundy et al. 2006). Historically, intake has been 4.5 to 4.8 $g \times kg^{-1}$ $BM \times d^{-1}$ that is 13.5% and 7.7% less than the current study. Despite greater education on nutrition and periodising intake for different training types and competition, intake remained stable across the week. Recommendations suggest 3-5 $g \times kg^{-1}$ $BM \times d^{-1}$ for low intensity skills based training sessions, 5-7 $g \times kg^{-1}$ $BM \times d^{-1}$ for moderate intensity training and 6-10 $g \times kg^{-1}$ $BM \times d^{-1}$ for endurance exercise of moderate to high intensity for ~1-3 hours (Table 4.1) (Burke et al. 2011). While athletes are meeting carbohydrate requirements for skills and low to moderate intensity training days, of most concern is the shortfall in preparation for performance. A study conducted in professional Soccer players compared carbohydrate intake of 4.5 $g \times kg^{-1}$ $BM \times d^{-1}$ and 8 $g \times kg^{-1}$ $BM \times d^{-1}$ in the 48 hrs prior to a 90 min intermittent high intensity field and treadmill protocol (Bangsbo, Norregaard & Thorsoe 1992). The group consuming 8 $g \times kg^{-1}$ $BM \times d^{-1}$ carbohydrate were able to complete 1 km extra of intermittent running to fatigue than the group with a lower intake. In another study, 8 $g \times kg^{-1}$ $BM \times d^{-1}$ carbohydrate resulted in 38% more muscle glycogen and 33% more high intensity work than a 3 $g \times kg^{-1}$ $BM \times d^{-1}$ intake (Balsom et al. 1999). Although the amount of carbohydrate used in the above study does not meet the higher end of the 6-10 $g \times kg^{-1}$ $BM \times d^{-1}$ (Burke et al. 2011) it may be sufficient and more achievable in these groups of athletes.

Dietary protein is required for muscle protein synthesis (Phillips 2012), particularly important in sport for muscle hypertrophy, repair and recovery. Previous studies in AF reported protein intakes of 1.5 to 1.6 $g \times kg^{-1}$ $BM \times d^{-1}$ (Burke & Read 1988; Schokman, Rutishauser & Wallace 1999) however anecdotally athletes are now following higher protein diets to assist in controlling body fat (Phillips 2012) and a belief that more protein results in greater lean mass (Phillips & Van Loon 2011), leading to an over consumption of protein (Lundy et al. 2006). Mean protein intake in this study was 2.1 $g \times kg^{-1}$ $BM \times d^{-1}$, 28.6 and 23.8% greater than earlier studies in AF (Burke & Read 1988; Schokman, Rutishauser & Wallace 1999) and did not differ across the week. Similar intakes were reported in Rugby League players (Lundy et al. 2006) while Gaelic football and professional Soccer players had lower intakes (Reeves & Collins 2003). Recommendations for this group are 1.2-1.7 $g \times kg^{-1}$ $BM \times d^{-1}$ with participants surpassing the recommendation on most days. Protein intake from protein powders and bars ranged from 0 to 31% of total protein intake depending on the athlete and training day with a mean intake of 11.2 ± 10.4% on a main training day. In many of the players they were using protein powders mixed with foods such as bananas, berries, yoghurt and fruit made into smoothies, reducing the protein load from powders and increasing the contribution from food. As this is only a small group of players, this may not be representative of players from other teams as it will depend on the approach of the high performance team for example as food first approach or supplement based. Future research into the overall contribution of protein powders and bars is warranted in this group. Distribution of protein also seems to be back-ended later in the day coming from large serves of animal products at lunch and dinner. It seems AF players have adopted good post-session protein intake practices however additional education on protein distribution across the day is required (Phillips & Van Loon 2011). Protein intakes slightly above daily recommendations in healthy individuals are most likely not harmful to health (Phillips 2012) however the main concern is that other nutrients such as carbohydrate may be displaced, compromising performance (Phillips 2012).

Dietary fat recommendations for athletes are largely based on prioritizing carbohydrate and protein in daily energy requirements (Broad 2008). Recommendations of 20-35% of daily energy requirements (Rodriguez et al. 2009) are considered adequate and may be slightly lower to achieve a desired body composition. Dietary fat intake in this study was 24.6% falling within recommendations and is 37.5% (Burke & Read 1988) and 29.2% (Schokman, Rutishauser & Wallace 1999) lower than previous studies. The current intake is similar in professional Rugby League (25%) (Lundy et al. 2006), Gaelic football (25.9%) and is higher in professional Soccer players (27.5%) (Reeves & Collins 2003). Intakes may have declined over time due to increased awareness through education, emphasis on the impact of intake on body composition and possibly the increased availability of low fat food products available for purchase.

4.5 Conclusion

The main finding of this study shows that irrespective of improved professionalism, increases in training volumes and improved access to dietary education, the professional AF players in this study are not meeting carbohydrate recommendations to support performance and do not periodise intake based on training loads and match preparation. Despite all the performance and monitoring measures taken in the elite sports environment we still do not know enough about energy expended and dietary intake of our athletes.

4.6 Practical considerations

Taking methodological limitations into consideration, measurement of dietary intake and EE are important so athletes become more aware of their energy and nutrient requirements for different training loads. This will assist dietitians to individualise programs based on the player’s requirements and periodise according to training load and competition. As players are currently not meeting carbohydrate requirements for performance and in some cases not meet energy requirements, they may need to eat to discipline rather than satiety to ensure they meet their nutritional requirements thereby maximising performance and maintaining optimal health in the team sport environment. In addition, practical strategies to meet energy and macronutrient requirements for a busy schedule would benefit the player.

Chapter 5. Study 3: Body composition and physique of team sport athletes: a longitudinal study

5.1 Introduction

Football can be characterised by patterns of repeated high intensity play followed by periods of recovery at a lower intensity (Duthie, G, Pyne & Hooper 2003; Varley, Gabbett & Aughey 2014). In Australia, football can include AF, Rugby Union, Rugby League and Soccer and are all played at the professional level. Each code requires speed, skill, agility and endurance (Duthie, G, Pyne & Hooper 2003; Gray & Jenkins 2010), and with the exception of Soccer, players endure repeated purposeful high force contacts and collisions (Cunniffe et al. 2009; Varley, Gabbett & Aughey 2014). An obvious difference between codes at the elite level are the anthropometric traits and body composition requirements of players (Gabbett, TJ, Jenkins & Abernethy 2011; Sutton et al. 2009; Veale et al. 2010; Zemski, Slater & Broad 2015). These characteristics are important for performance (Gabbett, TJ, Jenkins & Abernethy 2011; Quarrie & Wilson 2000) and in some cases can impact a team's success (Olds 2001).

Rugby Union and Rugby League require strong and powerful physiques to compete in physical contests and collisions associated with the sport at the elite level (Gabbett, TJ, Jenkins & Abernethy 2011; Nicholas 1997), while Soccer attracts lighter, leaner players (Sutton et al. 2009) as they cover more than 10 km a match (Varley 2013), and purposeful contact is not required. AF athletes require a combination of strength and power for physical contacts while also requiring endurance to cover up to13 km a match (Varley, Gabbett & Aughey 2014). Within each code however, a range of physiques are required to meet positional requirements and at the professional level, athletes are identified for these positions based on their physical and anthropometric characteristics (Gabbett, TJ, Jenkins & Abernethy 2011; Nicholas 1997; Pyne et al. 2006; Reilly, Bangsbo & Franks 2000).

Forwards and backs players in the rugby codes have distinctive body types with forwards being taller and heavier as they need strength and power to gain possession of the ball (Gabbett, TJ, Jenkins & Abernethy 2011). There are also differences in parameters between positional groups in union and league. AF has various playing positions ranging from tall forwards, defenders and ruckman to medium forwards, defenders and mid-field players to small mobile mid-field players (Nicholas 1997; Pyne et al. 2006). Soccer has a more homogenous group (Reilly, Bangsbo & Franks 2000) with the majority of players a similar height and body mass while central defenders and goal keepers are taller and heavier (Reilly, Bangsbo & Franks 2000).

Measurement of body composition in the high performance environment is common practice (Ackland et al. 2012). The estimation of body fat has been the main focus in the past with the use of skinfold measurements however with the availability of newer technologies it is possible to quantify other tissues such as lean muscle mass and bone mineral composition. The knowledge of quantity and distribution of fat, muscle and bone and how these change over time provide greater insight into the effects of training and dietary programs (Ackland et al. 2012).

Within a season, body composition will vary with different training types and volumes but also with dietary intake (Bilsborough, JC et al. 2016; Duthie, GM et al. 2006). Previous studies have shown optimal body composition peaks at the end of the pre-season conditioning period (Bilsborough, JC et al. 2016) and as the competitive season progresses, lean mass can decline (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011) and fat mass can increase (Gabbett, TJ 2005a; Georgeson et al. 2012; Harley, Hind & O'Hara J 2011; Till et al. 2014). It is important to monitor these changes over time to ensure desired body composition goals are being met and maintained.

The aim of this study was to longitudinally measure changes in body composition across the season of professional Rugby Union, Soccer and AF players, identify where these changes occur in the body and how the changes compare across sports

5.2 Methods

Forty-six professional AF (age 23.8 ± 3.8 yrs) and 26 Soccer (age 22.7 ± 4.7 yrs) players who were contracted to play in the measurement year were recruited for this study. Team management and players in each respective team gave written informed consent to participate in this study. De-identified data for 33 Rugby Union players (age 28.1 ± 4.2 yrs) was provided by team management and written consent was provided for use of the data. The study was approved by the Victoria University Human Research Ethics committee.

A repeated measures longitudinal study was conducted. Data was collected on 3 occasions over a 12 month period at the beginning of pre-season (AF: November, Soccer: July) early in the competitive season (AF: April, Soccer: November) and at the end of the competitive season (AF: September, Soccer: May). The time of year for each measurement varied based on the specific football code’s season. Skinfold, DXA and 3D scanner data was collected in the body composition laboratory at Victoria University, Melbourne Australia for Soccer and AF. DXA data for was collected in Rugby Union participants at an external facility with an experienced technician and de-identified data provided. Data for Rugby Union was collected at the beginning of pre-season (October), end of pre-season/beginning of the competitive season (Late January to early February) and toward the end of the competitive season (Late May to early June).

DXA was used to determine lean muscle mass (LM), body fat (BF), bone mineral composition (BMC) and bone mineral density (BMD) of participants. The same licensed DXA operator was used for every AF and Soccer scan and analysis. A standard scanning protocol was used to ensure measurement reliability (Nana et al. 2015). Participants reported to the laboratory between 0600 and 0830 am prior to eating and training. A urine sample was provided to determine hydration status prior to the scan. The same Hologic pencil beam machine (Discovery W, Hologic, MA, USA, Software; APEX 2.2) was used for all AF and Soccer scans. Scans and analysis of Rugby Union players were conducted by the same DXA operator on a GM lunar pencil beam scanner (Lunar DPX-IQ, General Electric, Lunar Corp, USA; Software; enCore^{TM} 2009, V 13.20.033) and the same scanning protocol as above was used.

Height, body mass and sum of seven skinfolds was measured using ISAK (The International Society for the Advancement of Kinanthropometry) assessment standards. The between test technical error for the sum of seven skinfolds, body mass and stretch stature was 2.3%, 0.2% and 0.4% respectively. Height was measured to the nearest 0.1 cm using a digital stadiometer (Pro Scale, Accurate Technology Inc., NC, USA) and body mass was measured on calibrated scales (Rite-weigh Scales P/L, Vic, Australia) to the nearest 0.1 kg. Skinfold measures were taken with Harpenden calipers (West Sussex, UK). The skinfold sites measured include triceps, subscapular, biceps, supraspinale, abdominal, thigh and medial calf.

3D scan technology was used to assess surface anthropometry and estimate body fat percent based on the Department of Defense (DoD) circumference equation included in the scanner software (Textile/Clothing Technology Corp(TC^2), Cary, NC, USA). All scans were completed on the same morning as the DXA scan and completion of skinfold measures. The scanner was calibrated prior to each scanning session using the provided scanning balls and cylinder. Participants were asked to wear light coloured (white, grey) form-fitting swimwear or underwear and a swimming cap for the scan. Participants were placed in the standard scanning position in the scanning booth and were instructed to take as deep breath and then exhale when the technician indicated. This was to ensure the chest measure was taken when the participant had exhaled, rather than inhaled, resulting in a greater chest circumference.

Statistical analysis was performed using SPSS V.19.0 (IBM, Chicago, Illinois, USA). To determine change in body composition measures across the season for each code, a mixed-design analysis of variance (ANOVA) with Bonferroni post-hoc analysis was used. Pearson's correlation was used to determine the relationship between DXA body fat percent fat, skinfolds and 3D estimated body fat. The magnitude of correlations was determined by: $r<0.1$, trivial; 0.1-0.3, small;

0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; >0.9, nearly perfect; and 1, perfect. Results were considered statistically significant at $p<0.05$.

5.3 Results

Complete data sets were collected for 28 Rugby Union, 13 Soccer and 30 AF players with a mean age of 28.1 ± 4.17, 22.6 ± 4.8 and 23.6 ± 3.7 years respectively when the measurement period began. Reasons for incomplete data sets include injury, player transfer, International duties and player unavailability for testing.

Table 5.1 contains the anthropometric and total body composition results for Rugby Union, Soccer and AF at each time point across the season. Body mass did not change in AF or Soccer however both sports had a gain in lean mass of 0.9 kg ($p<0.01$) and 1.8 kg ($p<0.01$) respectively, from the start of pre-season to early in the competitive season. AF did not experience a change in DXA measured fat mass however skinfolds showed a loss of 5.4 mm (11% of pre-season measurement) across the season ($p<0.001$) which was outside the anthropometrist's technical error. Soccer participants lost 1.5 kg ($p<0.01$) in DXA measured fat mass from the start of pre-season to early in the competitive season (17.6% loss in fat mass), which was reflected by a 5.4 mm ($p<0.05$) loss in skinfold measures which equates to a 9.5% loss. BMD only changed in Soccer with a small reduction ($p<0.05$) from the start of pre-season to early in the competitive season. Rugby Union experienced the greatest changes with a significant reduction of body mass from the start of pre-season to the start of the competitive season ($p<0.05$) coming from an ~4 kg (3.5% body mass) loss in fat mass ($p<0.001$) and a 2.69 kg (4% body mass) gain in lean mass ($p<0.001$).

The results of regional analysis are presented in Table 5.2. AF showed minimal change in each region. In soccer, leg mass declined from pre to early in-season ($p<0.05$) from a small reduction in fat mass ($p<0.05$) while there was a 1 kg decrease in lean mass across the season ($p=0.01$). Trunk mass did not change however there was a significant reduction in fat mass of 1.95 kg from pre to early in-season ($p<0.01$) and a 1.3 kg gain in lean mass ($p<0.05$). There was a small increase in fat mass from early in-season to the end of season ($p<0.05$). Rugby Union had a similar trend to Soccer in the trunk region across the season as fat decreased by 1.95 kg ($p<0.05$) and lean mass increased 1.77 kg ($p<0.01$) from pre to early in-season. A small gain in fat occurred (0.7 kg, $p<0.01$) toward the end of season while lean mass declined (0.8 kg, $p<0.01$). Rugby Union leg mass decreased from pre to early in-season ($p<0.05$), which came from a 1.2 kg reduction in fat mass ($p<0.001$) while lean mass did not change with a decrease in BMC ($p<0.001$).

Circumference measures captured by the 3D scanner did not change across the season for AF or Soccer however estimated 3D scanner body fat percent was greater at the end of season when compared to beginning of pre-season ($p<0.05$, CI 0.07-4.0) in AF and was not different in Soccer (Table 5.3).

Skinfolds and DXA body fat percent were highly correlated in both AF and Soccer participants. The correlation of AF and Soccer combined for skinfolds was considered large, $r=0.742$ ($p<0.001$, CI 0.67 to 0.81) however the strength of the correlation varied across the season and between sports (Table 5.4 and Figure 5.1). Skinfold and DXA body fat percent had a very high correlation in Soccer at the end of the season ($r=0.87$, $p<0.001$) with a large but weaker correlation at the beginning of the season in AF ($r=0.70$, $p<0.001$). The 3D scanner estimation of body fat percent had a small correlation with DXA body fat percent in both AF and Soccer of $r=0.11$ ($p<0.16$, CI -0.05 to 0.26) (Table 5.4 and Figure 5.2).

	Pre-Season		**Early in season**		**End Season**		**F-value**	***p***	***n*²**
	Mean ± SD	95 % CI	Mean ± SD	95 % CI	Mean ± SD	95 % CI			
AF n=30									
BM (kg)	85.06 ± 8.64	81.7 – 88.4	85.93 ± 8.46	82.6 – 89.2	85.96 ± 8.21	82.8 – 89.2	3.647	0.046	0.119
SF (mm)	49.10 ± 9.32	45.3 – 52.9	45.19 ± 6.54*	42.5 – 47.9	43.71 ± 7.41[+*]	40.7 – 46.8	12.303	<0.001	0.339
FM (kg)	8.91 ± 1.91	8.2 – 9.7	8.73 ± 1.78	8.0 – 9.4	8.16 ± 1.63	7.5 – 8.8	4.368	0.021	0.139
% BM	10.79 ± 2.26	9.9 – 11.7	10.40 ± 2.07	9.6 – 11.1	9.85 ± 2.16[#]	9.0 – 10.7	5.276	0.009	0.163
LM (kg)	70.83 ± 7.26	68.0 – 73.6	71.73 ± 7.27*	68.9 – 74.5	72.51 ± 7.46*^	69.6 – 75.4	15.220	<0.001	0.360
% BM	83.17 ± 2.42	82.1 – 84.2	83.61 ± 2.38	82.6 – 84.6	84.38 ± 2.39[#]^	83.4 – 85.4	6.231	0.010	0.213
BMD (g/cm^2)	1.342 ± 0.089	1.308 – 1.376	1.348 ± 0.086	1.315 – 1.380	1.340 ± 0.087	1.307 – 1.373	0.943	0.373	0.033

Union n=28

BM (kg)	106.2 ± 13.3	101.1–111.3	104.4 ± 11.6#	99.9 – 108.9	104.5 ± 12.1*	99.8 – 109.2	7.781	0.003	0.224
SF (mm)	NA		NA		NA				
FM (kg)	21.14 ± 8.94	17.7 – 24.6	17.04 ± 7.07+	4.3 – 19.8	17.72 ± 7.47+	14.8 – 20.6	42.034	<0.001	0.609
% BM	19.25 ± 6.25	16.8 – 21.7	15.82 ± 5.15+	13.8 – 17.8	16.42 ± 5.41+	14.3 – 18.5	43.851	<0.001	0.619
LM (kg)	81.03 ± 7.94	8.0 – 84.1	83.72 ± 7.62+	80.8 – 86.7	82.71 ± 7.29#	79.9 – 85.5	18.194	<0.001	0.403
% BM	76.80 ± 6.47	74.3 – 79.3	80.59 ± 5.34+	78.5 – 82.7	79.61 ± 5.59+^	77.4 – 81.8	50.310	<0.001	0.651
BMD (g/cm^2)	NA		NA		NA				

Soccer n=13

BM (kg)	76.8 ± 7.44	72.3 – 81.3	76.95 ± 8.10	72.1 – 81.9	76.43 ± 8.17	71.5 – 81.4	0.597	0.514	0.047
SF (mm)	46.54 ± 7.64	42.1 – 51.0	41.16 ± 6.60#	37.4 – 45.0	42.11 ± 6.43#	38.4 – 45.8	7.567	0.005	0.368
BF (kg)	8.60 ± 2.61	7.0 – 10.2	7.09 ± 1.82*	6.0 – 8.2	7.72 ± 2.32^	6.3 – 9.1	10.025	0.004	0.455
% BM	11.62 ± 2.75	10.0 – 13.3	9.27 ± 1.66*	8.3 – 10.3	10.10 ± 2.04#&	8.9 – 11.3	16.251	0.001	0.575
LM (kg)	64.15 ± 5.86	60.6 – 67.7	65.95 ± 5.63*	62.5 – 69.4	64.72 ± 5.65&	61.3 – 68.1	12.715	0.001	0.514
% BM	84.11 ± 2.45	82.6 – 85.6	86.04 ± 1.64*	85.1 – 87.0	84.31 ± 1.99&	83.1 – 85.5	16.251	0.001	0.575
BMD (g/cm^2)	1.377 ± 0.076	1.331 – 1.423	1.334 ± 0.092#	1.279 – 1.391	1.342 ± 0.096	1.285 – 1.400	7.558	0.013	0.386

Table 5. 1: Seasonal change in body composition for AF, Soccer and Rugby Union. Data presented as Mean ± SD (95% CI)

* Different from pre-season (p<0.01) # Different from pre-season (p<0.05) & Different from Early in-season (p<0.01) ^ Different from Early in-season (p<0.05) + Different from pre-season (p<0.001). BM, body mass; SF, sum of 7 skinfolds; BF, body fat less head; LM, lean muscle mass less head; BMC, bone mineral composition less head; BMD, bone mineral density.

	Pre-Season		Early in season		End Season				
	Mean ± SD	95 % CI	Mean ± SD	95 % CI	Mean ± SD	95 % CI	F-value	*p*	n^2
AFL = 30									
Legs									
Mass (kg)	27.69 ± 3.0	26.5 - 28.8	27.77 ± 2.8	26.7 - 28.9	27.65 ± 2.8	26.6 - 28.7	0.186	0.787	0.007
FM (kg)	3.3 ± 0.94	2.9 - 3.6	3.1 ± 0.959	2.8 - 3.5	2.8 ± 0.86*&	2.5 - 3.1	10.99	<0.001	0.289
LM (kg)	23.1 ± 2.5	22.1 - 24.0	23.3 ± 2.3	22.3 - 24.2	23.1 ± 3.3	21.9 - 24.4	0.198	0.694	0.007
BMC (kg)	1.36 ± 0.16	1.30 - 1.42	1.35 ± 0.15	1.29 - 1.41	1.33 ± 0.16	1.27 - 1.39	2.31	0.12	0.081
Trunk									
Mass (kg)	38.07 ± 3.8	36.6 - 39.6	38.78 ± 4.1	37.2 - 40.4	39.47 ± 4.0+^	37.9 - 41.0	10.31	<0.001	0.276
FM (kg)	3.6 ± 0.91	3.2 - 4.0	3.5 ± 0.8	3.2 - 3.9	3.3 ± 0.98	2.9 - 3.7	1.55	0.22	0.054
LM (kg)	33.5 ± 3.6	3.2 - 3.5	33.9 ± 3.8	3.2 - 3.5	34.6 ± 4.6	3.3 - 3.6	2.57	0.086	0.087

BMC (kg)	0.95 ± 0.15	0.90 - 1.01	0.97 ± 0.16	0.91 - 1.03	0.99 ± 0.15*	0.93 - 1.04	7.568	0.001	0.219
Arms									
Mass (kg)	12.3 ± 1.8	11.6 - 13.0	12.4 ± 1.5	11.8 - 13.0	12.0 ± 1.4	11.5 - 12.6	2.198	0.121	0.075
FM (kg)	1.12 ± 0.28	1.01 - 1.23	1.2 ± 0.71	0.92 - 1.47	1.07 ± 0.41	0.91 - 1.23	0.576	0.526	0.021
LM (kg)	10.7 ± 1.7	10.0 - 11.3	10.8 ± 1.5	10.2 - 11.3	10.5 ± 1.4	9.9 - 11.0	1.614	0.209	0.056
BMC (kg)	0.54 ± 0.09	0.51 - 0.58	0.57 ± 0.13	0.52 - 0.63	0.58 ± 0.14	0.52 - 0.63	0.965	0.372	0.034
Rugby Union n = 28									
Legs									
Mass (kg)	36.08 ± 5.5	33.9 - 38.2	35.18 ± 4.7$^{\#}$	33.3 - 37.01	35.17 ± 4.8*	33.3 - 37.1	9.31	0.001	0.26
FM (kg)	6.67 ± 3.20	5.4 - 7.9	5.48 ± 2.5^{+}	4.5 - 6.5	5.50 ± 2.5^{+}	4.5 - 6.5	37.86	<0.001	0.584
LM (kg)	29.41± 3.45	28.1 - 30.75	29.70 ± 3.2	28.46 - 30.94	29.66 ± 3.21	28.46 - 30.87	1.530	0.226	0.054
BMC (kg)	1.88 ± 0.22	1.79 - 1.96	1.86 ± 0.21^{+}	1.77 - 1.94	1.87 ± 0.21$^{\wedge}$	1.79 - 1.95	7.471	0.003	0.217

Trunk									
Mass (kg)	48.26 ± 5.56	46.1 - 50.5	48.16 ± 5.1	46.2 - 50.2	48.1 ± 5.3	46.0 - 50.1	0.174	0.841	0.007
FM (kg)	11.1 ± 4.68	9.28 - 12.9	9.16 ± 4.06#	7.59 - 10.74	9.87 ± 4.42&	8.15 - 11.58	6.22	0.016	0.187
LM (kg)	37.36 ± 3.71	35.9 - 38.8	39.1 ± 3.78*	37.6 - 40.6	38.3 ± 3.67&	36.9 - 39.8	7.149	0.009	0.216
BMC (kg)	1.92 ± 0.035	1.79 - 2.06	1.83 ± 0.29	1.72 - 1.94	1.89 ± 0.29&	1.77 - 2.0	2.206	0.148	0.076
Arms									
Mass (kg)	12.51 ± 1.64	11.9 - 13.1	12.5 ± 1.39	12.0 - 13.1	12.3 ± 1.59	11.6 - 12.9	3.264	0.046	0.108
FM (kg)	1.42 ± 0.77	1.12 - 1.72	1.12 ± 0.59+	0.90 - 1.35	1.2 ± 0.65+	0.90 - 1.41	21.93	<0.001	0.448
LM (kg)	11.09 ± 1.27	10.60 - 11.58	11.4 ± 1.12*	10.95 - 11.82	11.10 ± 1.31	10.59 - 11.61	3.584	0.051	0.117
BMC (kg)	0.68 ± 0.09	0.65 - 0.72	0.68 ± 0.08	0.65 - 0.71	0.69 ± 0.09	0.65 - 0.72	0.320	0.728	0.012
Soccer n= 13									

Legs									
Mass (kg)	27.11 ± 3.3	24.9 - 29.4	25.9 ± 2.5$^{\#}$	24.3 - 27.6	25.7 ± 2.7*	23.9 - 27.5	13.73	<0.001	0.579
FM (kg)	2.92 ± 1.1	2.21 - 3.63	2.45 ± 0.84$^{\#}$	1.88 - 3.01	2.69 ± 1.1	1.97 - 3.41	6.087	0.009	0.378
LM (kg)	22.79 ± 2.40	21.8 - 24.4	22.2 ± 1.75	21.0 - 23.4	21.7 ± 1.75*$^{\wedge}$	20.6 - 22.9	6.087	0.009	0.378
BMC (kg)	1.42 ± 0.23	1.27 - 1.58	1.27 ± 0.19^{+}	1.15 - 1.40	1.28 ± 0.17^{+}	1.16 - 1.39	30.789	<0.001	0.755
Trunk									
Mass (kg)	34.94 ± 4.44	32.0 - 37.9	34.0 ± 4.1	31.2 - 36.8	34.0 ± 4.21	31.2 - 36.8	5.821	0.010	0.368
FM (kg)	4.62 ± 1.88	3.36 - 5.88	2.67 ± 0.84*	2.10 - 3.23	3.03 ± 1.01*$^{\wedge}$	2.30 - 3.76	24.519	<0.001	0.710
LM (kg)	29.16 ± 2.57	27.43 - 30.88	30.5 ± 3.33$^{\#}$	28.3 - 32.75	30.19 ± 3.21$^{\#}$	28.03 - 32.3	12.85	0.003	0.562
BMC (kg)	0.82 ± 0.01	0.73 - 0.92	0.82 ± 0.01	0.72 - 0.91	0.79 ± 0.01$^{\#}$	0.71 - 0.88	7.195	0.004	0.418
Arms									

Mass (kg)	10.19 ± 1.0	9.5 - 10.9	11.2 ± 1.40+	10.3 - 12.1	11.06 ± 1.48*	10.1 - 12.1	28.094	<0.001	0.737
FM (kg)	0.54 ± 0.02	0.42 - 0.67	0.92 ± 0.03*	0.74 - 1.01	1.04 ± 0.04*	0.76 - 1.32	15.430	0.001	0.607
LM (kg)	8.18 ± 0.97	7.53 - 8.83	9.76 ± 1.13+	9.01 - 10.52	9.54 ± 1.17*	8.75 - 10.3	30.567	<0.001	0.753
BMC (kg)	0.46 ± 0.09	0.40 - 0.52	0.47 ± 0.07	0.42 - 0.52	0.46 ± 0.08	0.40 - 0.51	0.745	0.487	0.069

Table 5. 2: Regional change in body composition across a season for AF, Soccer and Rugby Union. Data presented as Mean ± SD (95% CI) * Different from pre-season (p<0.01) # Different from pre-season (p<0.05) & Different from Early in-season (p<0.01) ^ Different from Early in-season (p<0.05) + Different from pre-season (p<0.001). FM, Fat mass; LM, lean mass; BMC, Bone Mineral composition

	Pre-season		Early in-season		End Season		F-value	*p*	*n²*
	Mean ± SD	**95 % CI**	**Mean ± SD**	**95 % CI**	**Mean ± SD**	**95 % CI**			
AFL n=30									
BF %	16.89 ± 3.74	15.65 – 18.14	17.48 ± 3.42	16.34 – 18.62	18.93 ± 4.67[#]	17.38 – 20.49	3.876	0.025	0.097
R Arm (cm)	35.66 ± 1.69	35.10 – 36.25	35.76 ± 1.70	35.20 – 36.35	35.71 ± 1.80	35.10 – 36.32	0.093	0.874	0.003
Chest (cm)	108.74 ± 4.00	107.41 – 110.08	109.12 ± 4.34	107.66 – 110.56	108.76 ± 3.87	107.48 – 110.06	0.930	0.393	0.025
Gluteal (cm)	101.02 ± 3.38	99.88 – 102.14	100.61 ± 3.71	99.36 – 101.84	100.71 ± 3.4	99.60 – 101.83	0.941	0.391	0.025
R Thigh (cm)	62.00 ± 5.32	60.24 – 63.78	61.90 ± 3.21	60.82 – 62.96	63.07 ± 3.53	61.89 – 64.25	1.478	0.237	0.039
R Calf (cm)	38.91 ± 1.91	36.06 – 41.76	39.27 ± 2.87	38.31 – 40.23	38.86 ± 1.8	38.25 – 39.45	0.080	0.803	0.002
Soccer n =13									
BF %	18.75 ± 2.88	16.92 – 20.58	18.34 ± 3.07	16.39 – 20.29	18.84 ± 2.90	16.99 – 20.68	1.752	0.209	0.137
R Arm (cm)	31.85 ± 1.63	30.76 – 32.95	32.00 ± 1.71	30.85 – 33.14	32.06 ± 1.60	30.99 – 33.13	0.407	0.550	0.039

Chest (cm)	101.14 ± 6.36	96.88 – 105.42	101.37 ± 6.47	97.01 – 105.71	101.45 ± 5.82	97.54 – 105.36	0.223	0.651	0.022
Gluteal (cm)	97.41 ± 4.42	94.44 – 100.38	97.59 ± 4.46	94.59 – 100.58	98.04 ± 5.47	94.36 – 101.71	0.717	0.419	0.067
R Thigh (cm)	57.84 ± 3.36	55.58 – 60.09	57.96 ± 3.47	55.63 – 60.29	58.32 ± 3.61	55.90 – 60.76	1.778	0.211	0.151
R Calf (cm)	37.44 ± 1.70	36.31 – 38.59	37.59 ± 1.75	36.42 – 38.77	37.49 ± 1.76	36.32 – 38.69	1.110	0.349	0.100

Table 5. 3: 3D scanner body fat estimation and circumference measures. Data presented as Mean ± SD (95% CI) * Different from pre-season (p<0.01) # Different from pre-season (p<0.05) & Different from Early in-season (p<0.01) ^ Different from Early in-season (p<0.05) + Different from pre-season (p<0.001). BF, Body Fat; R, Right.

	Pre-season		Early in-season		End of season	
	r	**P value**	**r**	**P value**	**r**	**P value**
Combined						
Skinfolds	0.647	<0.001	0.75	<0.001	0.82	<0.001
3D scan	0.29	0.054	0.1037	0.448	0.269	0.04
AFL						
Skinfolds	0.786	<0.001	0.698	<0.001	0.799	<0.001
3D scan	0.144	0.441	0.103	0.555	0.255	0.117
Soccer						
Skinfolds	0.769	0.009	0.761	<0.001	0.873	<0.001
3D scan	0.534	0.049	0.076	0.745	0.346	0.147

Table 5. 4: Correlation of DXA fat percent with skinfolds and body fat estimation from 3D scan technology.

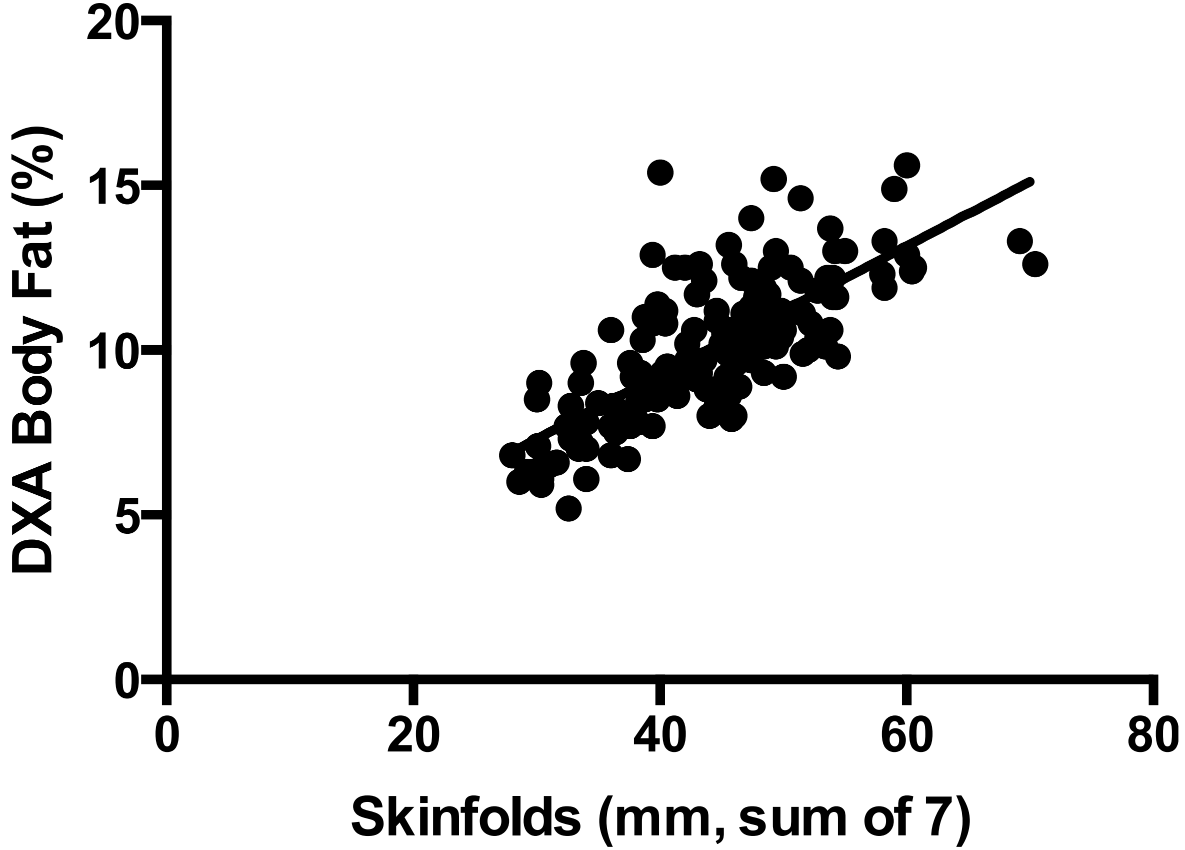

Figure 5. 1: Correlation of DXA percent body fat with sum of 7 skinfolds. r=0.74 (p<0.0001, 95% CI 0.66, 0.81).

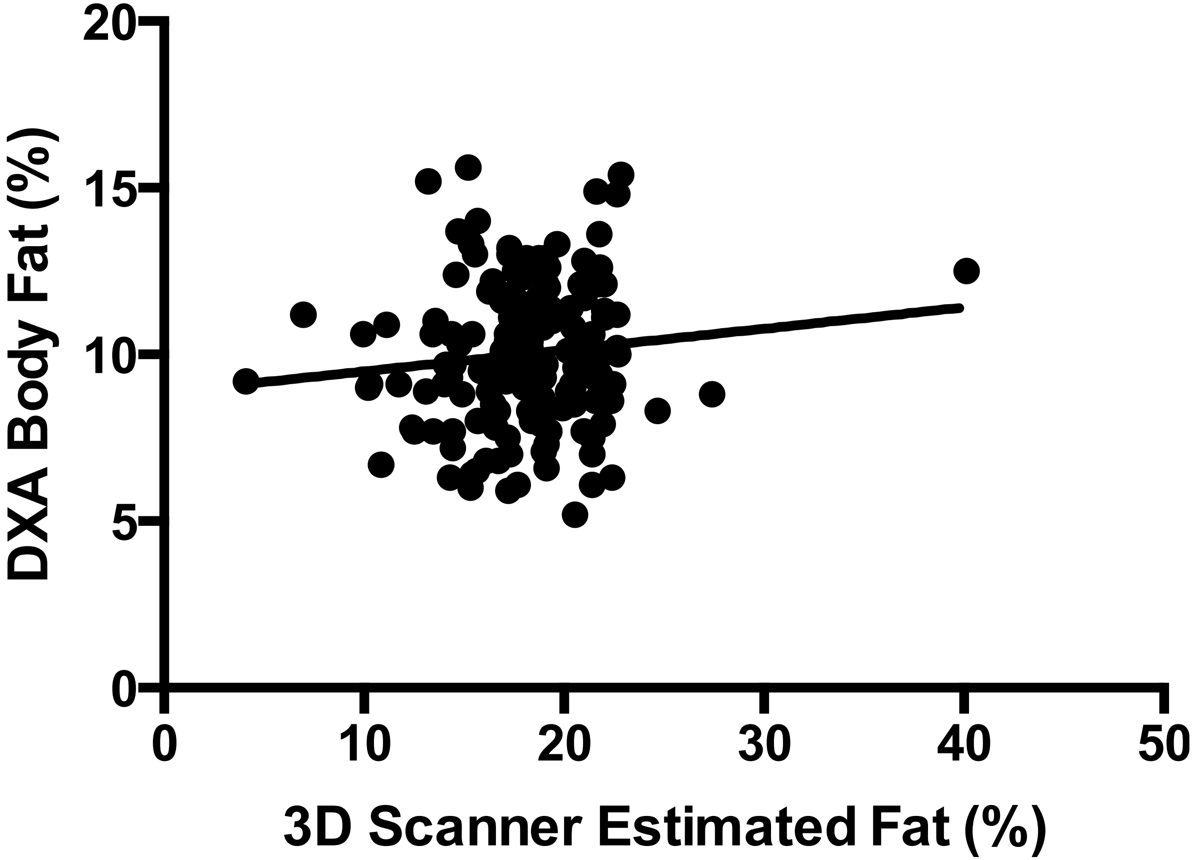

Figure 5. 2: **Correlation of DXA percent body fat with 3D scanner DoD percent body fat. r=0.11 (p<0.16, 95% CI -0.05, 0.27)**

5.4 Discussion

Determining seasonal variation in body composition is essential to monitor the effects of training and nutrition programs across a season. Elite sporting codes investigated in this study experienced significant changes in body composition across their respective seasons with Rugby Union experiencing the greatest overall change. The greatest changes in body composition for Rugby Union occurred from the beginning of pre-season to early in the competitive season where lean muscle mass increased while body fat decreased. Overall in this study, DXA and skinfold measures were able to detect change in body composition across the season while 3D scan technology could not. The sum of seven skinfolds had a moderate correlation with DXA measures of body fat while the 3D scan estimated body fat had poor correlation.

Rugby Union players require strength and size for tackling, scrums and collisions and therefore would require greater overall body size and lean muscle mass than AF and Soccer (Duthie, G, Pyne & Hooper 2003; Nicholas 1997; Reilly, Bangsbo & Franks 2000; Sporis et al. 2009). With a mean body mass of approximately 105 kg (range: 80.0 – 140.0 kg), Rugby Union participants were approximately 27 kg heavier than Soccer and 18 kg heavier than AF participants however this difference will be more or less depending on the position played with the difference being smaller between Rugby Union backs and greater with forwards. A portion of this comes from height however most notably from the amount of lean mass, almost 18 kg and 12 kg more than Soccer and AF respectively. These requirements may in part be responsible for the greater changes seen in this group compared to the other groups. The greatest changes occurred from the beginning of the pre-season to the beginning of the competitive season with a loss in body mass coming from a considerable loss in fat mass. Rugby Union participants lost nearly 20% of their initial fat mass or 3.5% of their body mass while gaining an additional 3.3% of absolute lean mass. These changes are typical of those seen in pre-season with a loss in fat as measured by skinfolds (Argus et al. 2010; Mitchell et al. 2016) and a gain in the proportion of lean mass as seen previously in a professional Rugby Union team (Duthie, GM et al. 2006).

During the competitive season there was only a small non-significant change in relative fat of 0.8%, only slightly less than the 1% seen in Rugby League (Harley, Hind & O'Hara J 2011) and a similar loss in lean mass of 1.3% and 1.5% respectively. The trunk area experienced the greatest gains in lean mass and loss in fat mass, which is consistent with the increased training load on this area due to the increased strength required for tackles and scrums (Bell et al. 2005).

The seasonal change in body composition of AF players was less pronounced than in Rugby Union with a small increase in total body absolute and relative lean mass and decrease in total body relative fat mass. Body mass did not change across the season and there was only a small non-significant change in body fat. As expected, lean muscle mass increased from pre- to in-season however of interest is the continued increase in lean muscle from in- to end of season that is contradictory to results seen elsewhere (Bilsborough, JC et al. 2016; Georgeson et al. 2012; Harley, Hind & O'Hara J 2011). The mean age of participants in the AF group in this study was 22.4 years, with 60% of participants younger than the mean age. The continued increase in lean mass may be due to the younger age of the group who are still developing (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011; Malina 2004; Malina, Bouchard & Bar-Or 2004) and possibly getting continued growth from resistance training and match exposure. Players contracted to another AF team who were considered inexperienced (played < 4 years) had a continued increase in lean mass from the pre-season until mid-competitive season that began to drop off toward the end of season (Bilsborough, JC et al. 2016). Whereas more experienced players (contracted to AF club for >4 years) had an initial gain in lean mass until mid pre-season which dropped off and was then maintained throughout the competitive season (Bilsborough, JC et al. 2016). The continued gain in the inexperienced group was attributed to the extra resistance training sessions completed by the group (Bilsborough, JC et al. 2016).

The seasonal body composition of Soccer participants followed a similar pattern and degree of change to that of AF participants. Body mass remained stable while the composition of the mass altered slightly. Body fat decreased from pre to in-season and slowly increased again throughout the competitive season. Lean muscle mass increased from pre to in-season and declined throughout the competitive season. Similar results using DXA were seen in Italian professional Soccer players measured over a three year period at three points throughout the season (Milanese et al. 2015). Similar to the Soccer group in the current study body mass did not change while body composition did. Fat decreased by 11.9% from pre to mid-season and increased by 4.1% from mid to end of season. Lean mass increased by 1.3% in pre-season but did not change from mid to end of season while BMD did not change. Although similar overall changes were seen, regional changes showed some inconsistencies. There was a significant loss in fat mass in the legs from pre to in-season however there was also a loss in lean mass. It is difficult to explain the loss in lean mass as collegiate (Silvestre et al. 2006) and Italian (Milanese et al. 2015) Soccer players experienced a gain in lean mass during this same period of the season. Consideration must be taken when comparing Soccer studies conducted in the European league players as the Australian professional league has a different seasonal structure. The Australian league has a 3-4 month pre-season and play around 30 matches in season while European leagues have a 1-2 month pre-season and can play around 40 matches a season.

Total body BMC did not change in AF or Soccer players and declined in Rugby Union players. Similar results were seen previously in AF and Soccer players while after an initial decrease of BMC was seen from pre to mid-season, there was an increase from mid to end of season (Bilsborough, JC et al. 2016; Milanese et al. 2015). The loss in BMC of Rugby Union players across pre-season may have been due to a significant loss in body mass from pre to in-season however as this is a period of high volume training including resistance training, it was thought that BMC would increase (Georgeson et al. 2012; Harley, Hind & O'Hara J 2011) The increase in the latter half of the season may be from match related load through the bones (Elloumi et al. 2009). BMC did increase in the trunk region for both AF and Rugby Union across the season. Forward players in Rugby Union have been found to have greater BMD than backs which is most likely due to the specific roles of forwards during the match including scrimmaging, supporting and jumping in line-outs that place mechanical and muscular loads on regional areas. Forwards have higher BMD and BMC in the whole spine (12-13%), pelvis (10-11%), and upper and lower limbs (9-18%) (Elloumi et al. 2009).

There are a number of reasons why body composition changes through the season, including amount and intensity of training, match time, dietary intake, illness, injury and travel (Duthie 2006). The football codes in this study experienced a loss in fat and gain in lean mass across their pre-seasons with the extent of loss different across each sport. Training load and nutrition were not measured in this study however the pre-season is associated with increased training loads (Argus et al. 2010; Bilsborough, JC et al. 2016), and often a time to target body composition goals (Argus et al. 2010). The extent of the change will vary between sports, athletes within the sport and the change that occurred during the off-season. Rugby Union participants seemed to experience greater changes than AF or Soccer. This is most likely due to the body composition requirements of the sport, with greater lean body mass required for performance at the elite level (Gabbett, TJ, Jenkins & Abernethy 2011). The AF and Soccer groups experienced less overall change with focus mainly on losing fat if gained in the off-season. The off-season is considered a time of recovery where training and competition loads are considerably less (Carling & Orhant 2010) and nutrition practices are often relaxed (Bilsborough, JC et al. 2016). Professional clubs now tend to provide personalised training and dietary programs to ensure players return in an adequate condition for preseason training (Carling & Orhant 2010). Body composition change throughout the competitive season is again reflective of the training and competition schedule. During the season when matches are played weekly, there is an increased emphasis on recovery and match preparation. This results in a reduced training volume especially the number of resistance training sessions (Harley, Hind & O'Hara J 2011). The atrophy in lean muscle mass reduces the BMR and due to players not modifying their dietary EI to match training volume, an increase in body fat occurs (Bilsborough, JC et al. 2016; Drenowatz et al. 2012).

The measurement of body composition in the high performance sports environment needs to be reliable, practical and easily accessible. Traditional methods such as skinfold measurement found change across the season in AF and Soccer and had a moderate to strong correlation with DXA measured body fat overall and at different points across the season. We observed poor correlation of the DoD 3D scanner body fat estimate with DXA body fat percent. The DoD body fat calculation used by the scanner uses circumference measures to estimate body fat, so a poor correlation was expected, as surface anthropometry does not account for the composition of the body under the skin. A separate study found a moderate correlation ($r=0.629$, $P<0.01$) with DXA measures however showed a significant underestimation of body fat (Ryder 2012). 3D scan technology has shown to be a reliable method for capturing limb circumferences measures (Ryder 2012). We were unable to detect changes in limb circumference measures in this study, most likely attributable to the small body composition changes which would have resulted in minimal circumference change. However we note that measuring changes in circumference due to growth and development of young athletes, injury and effects of targeted training for change in size, may be a more applicable use of this tool.

While the current study utilised a number of anthropometric tools completed across the full season of each of the codes, the study however had some limitations that should be acknowledged. The DXA scans for Rugby Union were completed on a separate scanner to those conducted on AF and Soccer which can compromise comparison across sports. Scan completed with the 3D scanner relied on the automatic measurement algorithms that identified landmarks on the body, which can result in measurement error (Garlie et al. 2010). Future studies may benefit from identifying specific landmarks with reflective markers to assist in identifying landmarks during analysis (Schranz et al. 2010). Finally, nutrition and training load have significant impact on body composition. These measures would be useful to correlate with the changes seen in the study and would be beneficial in future studies, however these measurements themselves have a number of limitations.

5.5 Conclusion

This study examined the change in body composition across the season of three football codes utilizing three measures of physique and body composition. The main findings show that body composition changes considerably in the pre-season period when training volumes are high and there is a greater number of resistance training sessions. Values begin to return to pre-season levels toward the end of the season. DXA measurement provides the most insight to body composition change occurring across the season while 3D technology was unable to identify change. DXA and skinfold measures are moderately correlated providing a good alternative to track changes in subcutaneous fat measures in this cohort of elite athletes, while 3D technology does not.

5.6 Practical considerations

Body composition needs to be monitored across the season using practical and reliable measures that suit the needs of the sport. DXA provides detailed information on body composition and can be used to monitor changes in lean muscle mass, fat mass and bone mass and can be used 3-4 times in a season to monitor longitudinal change particularly in those who may experience significant change in body composition such as young athletes, those with body composition goals or those who sustain longer term injury.

Chapter 6. Study 4: Body composition and physique change in of Australian Football development athletes aged 16-18 years

6.1 Introduction

National sporting organisations seek to identify young talented athletes with a high likelihood of success (Pearson, Naughton & Torode 2006). Identifying future talented athletes that will have success in team sports however is complex, with athletes requiring a combination of physiological, psychology and skills based characteristics (Burgess & Naughton 2010; Vaeyens et al. 2008). In addition, although adolescents have the required characteristics for a particular sport, these attributes may not continue into adulthood (Ackland & Bloomfield 1996). Anthropometric and body composition characteristics often influence selection into junior teams with early maturing players with greater physical development being selected over less mature and developed players of a similar age (Pearson, Naughton & Torode 2006). In skills based sports this can mean that late maturing adolescents are over-looked and the talent pool reduced (Burgess & Naughton 2010).

In AF the culmination of talent identification (ID) occurs at the national draft combine where 18-year-old players undergo a battery of fitness, psychological and skills based testing. This information is then provided to prospective clubs and players can be recruited through the draft selection. AF is a team sport requiring repeated high intensity efforts interspersed with low-intensity activity and repeated physical contacts and collisions (Varley, Gabbett & Aughey 2014). Players therefore require a balance of leanness with muscularity and mass that varies with positional requirements (Veale et al. 2010; Young et al. 2005). As with most team sports at the junior level, selected players are often taller and heavier than those not selected (Young et al. 2005) while these measures have little impact on draft selection at the higher level (Burgess, Naughton & Hopkins 2012; Pyne et al. 2005). Within months of being recruited by a team, the young athlete can be selected to play at the highest level against more physically developed players. Emphasis is placed on the physical development of young players with an increase in lean muscle mass and a reduction in body fat (Pyne et al. 2006), often required over a relatively short period thereby becoming the rationale for this study. Identifying body composition requirements earlier in the development pathway would prevent the need for rapid changes when selected at the elite level. Currently, the anthropometric and body composition data collected is limited and a more comprehensive body composition assessment would be of benefit.

The aim of this study was to longitudinally measure the anthropometric and body composition changes of national academy players over a two year period in the lead up to the draft combine and whether body composition factors impact selection.

6.2 Methods

Thirty, 16 year old AF players from a national academy team who were eligible for selection in the AFL draft combine when they were 18 years of age were recruited for this study. Team management, parents of players and players provided written informed consent for participation in the study. The study was approved by the Victoria University Human Research Ethics committee (HRETH 12/200).

A repeated measures longitudinal study was conducted. Data was collected on three occasions over a 2 year period when the players were 16, 17 and 18 years of age. Testing occurred at a similar time each year when the players came together for a training/testing camp in late September. Data was collected in the body composition laboratory at Victoria University, Melbourne Australia.

Anthropometric measures including height, mass and skinfolds were measured in accordance with International Standards for Anthropometric Assessment (Stewart et al. 2011) and collected as part of usual data collection for this group. Height was measured to the nearest 0.1 cm using a digital stadiometer (Pro Scale, Accurate Technology Inc., NC, USA) and body mass was measured on calibrated scales (Rite-weigh Scales P/L, Vic, Australia) to the nearest 0.1 kg. In line with the National Draft Combine procedures the sum of seven (triceps, subscapular, biceps, supraspinale, abdominal, front thigh, medial calf) skinfold thicknesses were measured. Calibrated Harpenden skinfold callipers (West Sussex, UK) were used and a qualified anthropometrist with a TEM of 1.3 mm conducted the testing.

Dual energy x-ray absorptiometry (DXA) was used to determine lean mass, body fat and BMC of participants and was included in data collection for this study. Prior to each scanning session the DXA machine (a pencil beam Hologic Discovery, QDR 4500) was calibrated according to manufacturer guidelines. The same machine and DXA technician completed all scans and analysis. Players presented to the lab in a fasted state prior to exercise (Nana et al. 2012b) and were asked to remove all metal objects and jewellery. Hydration was tested by Urine Specific Gravity (USG) test. Players wore swimwear or underwear for scans. Players were positioned on the DXA according to guidelines specified by the Australian and New Zealand Bone and Mineral Society, such that they were within the scanning area on their back with hands pronated flat on the scanning bed and legs were rotated inwards with big toes touching and secured together with a strap. For players outside the scanning parameters, procedures as specified by Nana (Nana et al. 2012b) were followed. This positioning was repeated for all scans.

Girth and circumference measures of the body were conducted using 3D body scans (Textile/Clothing Technology Corp. ([TC]^2, NC, USA). These scans were conducted on all participants directly before or after the DXA. Subjects removed jewellery and wore only skin coloured tight shorts and a swimming cap to cover the hair. Body scanners use light to illuminate the body, while a series of cameras capture reflected light in a short 5 second scan, resulting in a 3D image created by the software.

Statistical analysis was performed using SPSS V.19.0 (IBM, Chicago, Illinois, USA). Descriptive statistics (Table 6.1) are presented as the mean ± SD. Repeated measures analysis of variance (ANOVA) with Bonferroni post hoc analysis was used to assess change in body composition measures across the three time points with and without age as a co-factor. Test-retest reliability (coefficient of variation) on AF players with a pencil beam machine has previously been reported for total body fat mass (5.9%, CL 4.7-7.8), fat free soft tissue (0.5%, CL 0.4-0.6) and BMC (1.5%, CL 1.2-2.0) (Bilsborough, J, C. et al. 2014). Skinfolds and absolute fat mass was correlated using Pearson's r. Linear regression was used to determine if factors of body composition impacted selection in the draft. Results were considered statistically significant at $p < 0.05$.

6.3 Results

Group selection varied each year resulting in 16 complete data sets for three time points. Descriptive results are presented in Table 6.1. The mean age of the group at the time of the draft was 18.4 ± 0.3 years with 65% born in the first six months of the year. Compared to age matched boys in the general population, mean height was above the 90th percentile and above the 75th percentile for mass for each time point (Australian Paediatric Endocrine Group).

There was a significant time effect for height, absolute and relative fat, absolute lean mass and BMD (Table 6.1; $p<0.001$). Pairwise comparisons showed a significant change in height at all time points (Table 6.1; $p<0.001$), with a 1.1% increase from year 1 to 2 (95% CI; 0.73, 1.41), only a 0.64%, from year 2 to 3 (95% CI; 0.47, 0.81), resulting in an overall 1.72% increase from year 1 to 3 (95% CI; 1.29, 2.15). The greatest change in mass occurred from 16 to 17 years with 7.2%, (95% CI; 4.91, 9.42) while change from 17 to 18 years was smaller, 2.1%, (95% CI; 0.84, 3.34). There was 9.55% increase in mass across the entire measurement period (95% CI; 6.97, 12.13). Sum of seven skinfolds did not change however there was a significant decrease in absolute fat mass of 23.02%, (95% CI; -28.63, -17.4) between year 1 and 2 and only a small mean change of 3.5% (95% CI; -7.37, 14.4) from year 2 to 3, as some participants had an increase in fat mass while some had a decrease. There was a 19.57, decrease in fat mass from year 1 to 3 (95% CI; -29.63, -17.4). From years 1 to 2 there was a 7.62% increase (95% CI; 6.22, 9.03), 1.76% increase, (95% CI; 0.53, 2.98) between year 2 and 3 and a 9.01% increase between year 1 and 3 (95% CI (7.05, 10.97) in absolute lean muscle mass. BMD increased by 3.49% (95% CI; 2.50, 4.48) from year 1 to 2 but was not different from year 2 to 3.

From year 1 to 3, girth measures from 3D scans show the chest had a mean increase of 4.8%, 95% CI (2.52, 7.11), left bicep 7.7%, 95% CI (4.89, 10.5) increase, waist 3.2%, 95% CI (1.71, 4.72), hips 4.2%, 95% CI (3.16, 5.23), left thigh 5.2%, 95% CI (3.60, 6.71) and left calf 2.0%, 95% CI (1.27, 2.78). All measures excluding the left and right biceps were different between years 1 and 3 ($p<0.01$). Result are reported in Table 6.2.

Skinfolds and absolute fat mass had a strong correlation at each time point with an r-value of 0.951, 0.885 and 0.940 for each year respectively ($p<0.001$). Skinfolds and body fat percent also correlated well with r-values of 0.947, 0.834 and 0.821 each year respectively ($p<0.001$). However, skinfolds and fat mass did not reflect similar changes in composition. Skinfolds did not change over time while fat mass showed a significant reduction of 2.5 kg from 16 to 17 years of age ($p<0.01$). No relationship was found between BMD and body mass, BMD and lean mass or BMD and fat mass.

Of the 16 players with complete datasets, 12 were drafted to an AF team. For players who were drafted, body composition variables including height ($F(1,14) = 2.5$, $p<0.05$; $r^2=0.149$, $p=0.140$) total body mass ($F(1,14) = 4.1$, $p<0.05$; $r^2=0.227$, $p=0.062$), skinfolds ($F(1,14) = 1.3$, $p<0.05$; $r^2=0.086$, $p=0.271$), body fat % ($F(1,14) = 0.81$, $p<.05$; $r^2=0.055$; $p=0.384$) or lean mass % ($F(1,14) = 0.13$, $p<.05$; $r^2=0.009$; $p=0.720$) did not predict where a player was drafted.

	Year 1 (n=16)	Year 2 (n=16)	Year 3 (n=16)
Age (yrs)	16.4 (0.3)	17.4 (0.3)	18.4 (0.3)
Height (cm)	187.0 (7.1)	188.1 (7.0)*	188.7 (7.4)*#
Mass (kg)	77.7 (6.5)	81.0 (7.0)*	82.9 (7.6)*#
Skinfolds (sum 7)	54.2 (14.5)	54.7 (13.1)	54.6 (13.5)
Fat mass (kg)	10.8 (2.8)	8.3 (2.4)*	8.5 (2.2)*
Fat mass (%)	14.0 (2.5)	10.4 (2.5)*	10.4 (2.6)*
Lean mass (kg)	63.3 (4.6)	67.7 (5.2)*	69.3 (6.1)*
Lean mass (%)	83.1 (3.7)	83.9 (2.9)	83.7 (2.5)
BMC (g)	3032.9 (251.7)	3139.0 (263.4)*	3219.4 (315.7)*
BMD (g/cm^2)	1.257 (0.071)	1.290 (0.070)*	1.298 (0.069)*

Table 6. 1: Descriptive body composition statistics over 3 times points. Mean (SD) * Different from year 1 ($p<0.01$), # different from year 2 ($p<0.01$). BMC, Bone Mineral Composition; BMD, Bone mineral density.

	Year 1 (n=16)	Year 2 (n=16)	Year 3 (n=16)
Chest (cm)	96.42 (4.1)	98.85 (3.7)*	100.98 (3.5)*
Left Bicep (cm)	30.8 (1.9)	32.3 (1.7)^	33.3 (1.8)
Right Bicep (cm)	31.3 (2.3)	32.9 (1.9)*	33.2 (2.5)
Waist (cm)	79.4 (3.6)	80.6 (3.8)*	82.1 (3.5)*
Hips (cm)	98.6 (3.6)	101.3 (3.4)*	102.6 (4.2)*#
Left Thigh (cm)	50.6 (2.9)	51.8 (2.5)	53.1 (2.5)*#
Right Thigh (cm)	51.4 (2.6)	52.7 (2.8)	54.0 (2.4)*
Left Calf (cm)	37.3 (2.3)	37.9 (2.2)*	38.0 (2.3)*
Right Calf (cm)	37.3 (2.2)	37.8 (2.2)*	38.1 (1.9)*

Table 6. 2: Girth measures over time captured by 3D scan technology. Mean (SD) * Different from year 1 ($p<0.01$), ^ Different from year 1 ($p<0.05$), # different from year 2 ($p<0.05$)

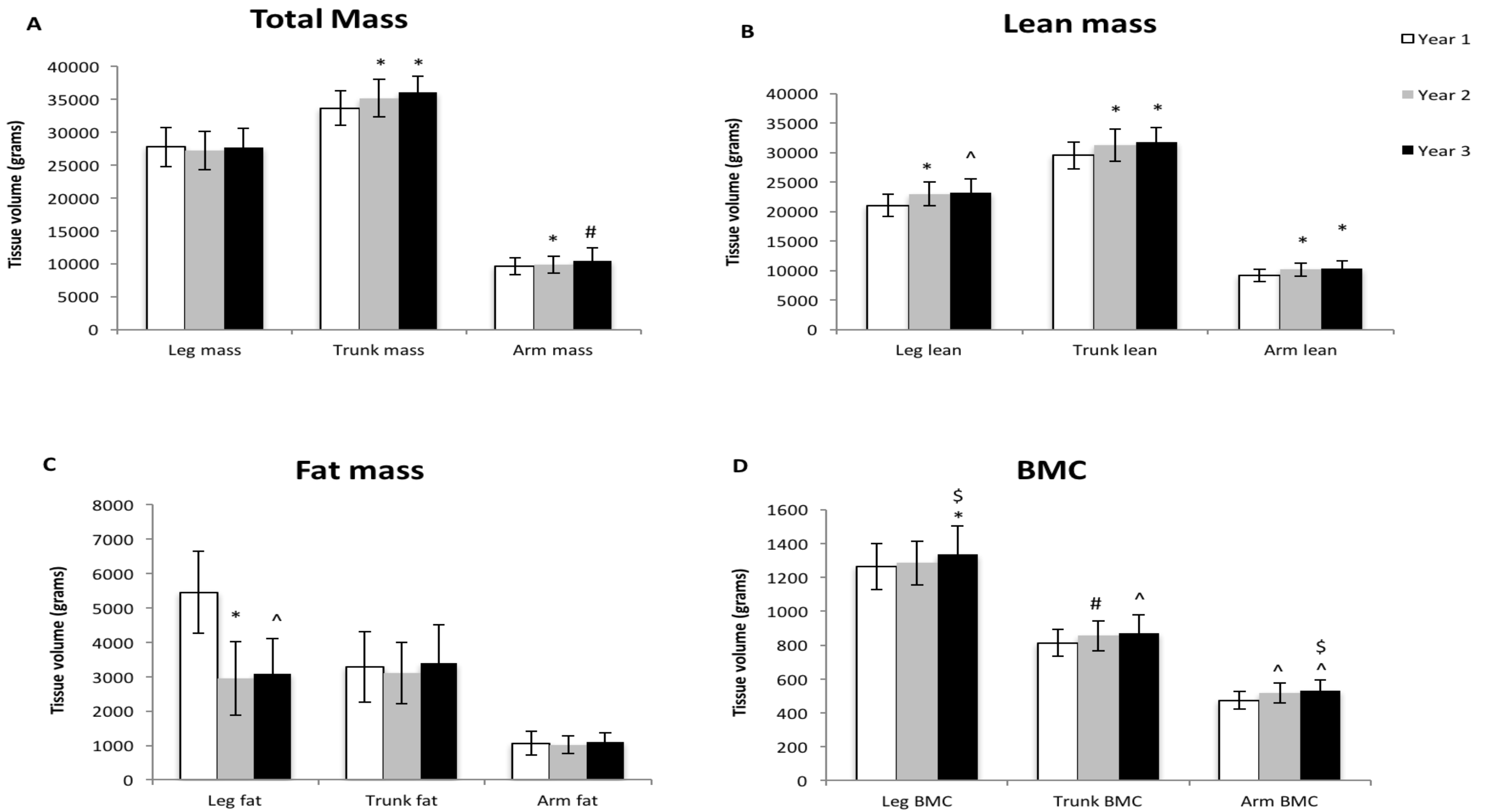

Figure 6. 1: **Regional changes in body composition in participants from 16 to 18 years.** A. Regional changes in total mass B. Regional changes in lean mass C. Regional changes in fat mass D. Regional changes in bone mineral composition. * Different from year 1 ($p<0.001$), ^ Different from year 1 ($p<0.01$), # Different from year 1 ($p<0.05$), $ Different from year 2 ($p<0.05$).

6.4 Discussion

This study describes the longitudinal anthropometric and body composition changes of a group of 16 to 18 year old AF players eligible for selection in the national draft and whether body composition had an impact on draft selection. The group participating in the study were considered the best players for their age group and were selected to take part in a development program leading into the draft. This is the first study to longitudinally assess body composition in this group using DXA and 3D scan technology. Results indicate there was a significant change in body composition over time in this group with the greatest change early in the study. Body composition variables did not have an impact on where a player was selected in the draft.

The greatest change in body composition occurred from 16 to 17 years of age in this study. There was an increase in body mass mainly from a gain in total lean muscle mass in the first year with a smaller gain in the second year. The adolescent period is associated with a rapid gain in muscle mass (Malina 2004) which could account for the large gain of mass in the first year of the study. However, the small gain in height over the two-year period suggests the adolescent growth spurt has most likely occurred (Malina 2004) prior to the study around 14 years of age. As height and mass follow a similar pattern of deceleration as height during this time (Rogol, Clark & Roemmich 2000), a large gain in mass would not be expected. Normal growth in combination with a resistance-training program can result in muscle gain (Malina 2004), however it is difficult to distinguish where these changes come from (Malina & Geithner 2011).

The reduction in body fat follows expected patterns during this period where relative fatness reaches its lowest point around 16-17 years of age and there is a concomitant, rapid increase in lean mass with slower gain in fat (Malina 2004). A large portion of fat loss came from a reduction in leg fat mass, again consistent with growth and maturation patterns in adolescence where bone and muscle increases with a simultaneous loss of fat from the extremities (Malina 2004). It should be noted that this group could have initially been selected because they were more physically developed than other players their age. With this in mind, their growth spurts may have occurred earlier and therefore their young adult values reached sooner than less mature players. These results may also not reflect the results of the broader group available for selection in the draft.

BMD and BMC increased from 16 to 17 years and 16 to 18 years of age in this study. Adolescents competing in sports that produce ground reaction forces such as running, gymnastic and tennis have greater BMD than non-impact sports (swimming and water polo) or healthy active controls (Lima et al. 2001). Results from this study at age 16 and 17 years (1.26 ± 0.07 – 1.29 ± 0.070 g/cm^2) show a greater BMD than ice hockey players (1.23 ± 0.07 g/cm^2), badminton players (1.22 ± 0.06 g/cm^2) (Nordstrom, Pettersson & Lorentzon 1998) and students of a similar age who participate in a range of physical activities (1.17 ± 0.09 g/cm^2) (Ginty et al. 2005). This is most likely due to a combination of greater total body mass and amount of lean muscle mass of the AF players (body mass: 77.7± 6.5 – 81.0 ± 7.0 kg, lean mass: 63.4 ± 4.6 – 67.7 ± 5.2 kg) than the ice hockey players (body mass: 71.8 ± 7.0 kg, lean mass: 57.1 ± 4.6 kg), badminton players (body mass: 67.3 ± 6.7 kg, lean mass: 53.4 ± 4.7 kg) and students (body mass: 71.2 ± 13.4 kg, lean mass: 54.9 ± 6.2 kg) that places a greater mechanical load on the bones, increasing BMD in addition to the physical demands of AF such as running, jumping, changing direction and collisions that have an osteogenic stimulus (Lima et al. 2001; Nordstrom, Pettersson & Lorentzon 1998). At age 17 years, BMD is slightly higher (1.29 ± 0.07 g/cm^2) than a similar group of elite junior AF football players of the same age (1.27± 0.06 g/cm^2) measured previously (Veale et al. 2010). Intermittent sports involving quick directional changes, physical contacts and jumps placing large strains on the skeleton tend to have greater BMD (Morel et al. 2001). Regional BMD is affected not only by ground impacts but the vibrations and strain from muscular contractions at their bony attachments (Morel et al. 2001) like those experienced during body contacts in tackling. Forwards in Rugby Union who are frequently involved in physical contact have a greater BMD and BMC than other positions (Elloumi et al. 2009). Some studies have shown correlation between BMD and body mass and BMD and lean muscle mass (Lima et al. 2001) however this was not found in our study.

A greater body mass is associated with increase ground reaction forces with downward movements while a greater lean muscle mass applied exertion forces to the bone increasing density (Lima et al. 2001).

As would be expected, the group in this study were taller and heavier than age-matched boys in the general population (Australian Paediatric Endocrine Group). Compared to similar aged players in other high intensity intermittent team sports, players in this study were taller and had a similar body composition of backs players in Rugby Union (Delahunt et al. 2013) while they were taller and leaner than backs players in Rugby League (Cheng et al. 2014). Participants were also considerably taller, heavier and had more fat mass than elite 16 year old Soccer players (Reilly et al. 2000). At the age of 16, study participants were considerably taller and heavier (187.0 ± 7.1 cm and 77.7 ± 6.5 kg) than players selected in a state level under 18 AF team (height: 180.2 ± 7.2 cm, Mass: 74.6 ± 8.3 kg) (Keogh 1999) however the mean age of under 18 AF team was 15.9 ± 0.8 years and the study was conducted over 15 years ago.

In a similar study conducted approximately five years later, selected players were 183.9 ± 6.9cm and 79.8 ± 8.3kg (Young et al. 2005). Throughout the adolescent years of participation, the height of selected players tends to be increasing. This was also observed in players eligible for selection in the AF draft (approximately 18 years of age) from 1999-2004 where the researchers stated there was a 2.2 cm increase in mean height over the 5 year period while body mass and skinfolds did not substantially change (Pyne et al. 2006). Our study indicates that height and skinfolds have remained stable since the study completed over 10 years ago (Pyne et al. 2006) while body mass has increased by approximately 2 kg. When compared to a study completed in elite junior (17.7 years of age) AF players in 2010 using DXA (Veale et al. 2010), participants in our study were of a similar height, mass and body composition at the same age. Compared to older (19.4 years of age) AF rookie players (Veale et al. 2010), the 18 year olds in our study were similar in height, body mass and fat mass and had less lean mass and BMD. They were also approximately 5 kg lighter in lean mass, 1 kg leaner in fat mass and had a lower BMD than senior players (Veale et al. 2010). Over the two-year study period, players were provided a periodised strength training program and nutritional guidance as part of their academy program which they were responsible for completing however this may or may have not been completed depending on their respective team requirements, school and access to equipment. Despite this guidance, there was no difference in body composition between the study group and the group studied in 2010 (Veale et al. 2010) It was thought that with provision of this additional guidance, the players in this study would be better prepared physically from a body composition perspective for elite level competition once drafted. Future studies would benefit from monitoring adherence to a resistance training program and to determine the extent of body composition changes that can occur with an appropriate program during growth and development.

Anthropometry and body composition did not have a direct impact on selection for the draft in this study however the limited power of this study should be acknowledged. This is consistent with other findings in under 18 year AF competition where other fitness variables better predicted selection and subsequent career success in AF (Burgess, Naughton & Hopkins 2012). Although anthropometry and body composition did not directly impact selection or career progression, they are associated with other fitness variables such as jumping ability and 20 m sprint performance (Burgess, Naughton & Hopkins 2012; Pyne et al. 2005). Once recruited to a team, over 50% of the young players make their debut (Pyne et al. 2005) and some are exposed to senior football within 4-5 months of being recruited (Veale et al. 2010). Although the player may be ready in terms of skill, they may not be physiologically ready, with senior level players having greater body mass and levels of lean mass (Veale et al. 2010). Knowing this, often, body composition becomes a focus and gains in lean mass are desired. Training programs eliciting rapids gains in lean mass prescribed during marked changes in growth and physical development may place these athletes at increased risk of injury as tendons and bony insertions are still weak and unable to manage the increased load placed on them (Naughton et al. 2000). Understanding an athlete's growth and development prior to being drafted may help determine their readiness for the training programs utilised at the elite level. In addition, if these requirements were identified prior to being drafted it would allow for change over a longer period, avoiding rapid changes when selected at the professional or elite level. Individualised age specific programs targeting these goals should be developed and closely monitored (Naughton et al. 2000). It should also be considered that when these players were selected into this group at the age of 16 years, body composition may have influenced selection. In elite junior AF, players who were heavier were more likely to be selected to play (Keogh 1999; Young et al. 2005). Match performance indicators, specifically hit-outs and marking, and team success were associated with a greater height and body mass (Young & Pryor 2007). This is also true in other sports. Elite Soccer players with a mean age of 16.4 years, were leaner and more muscular than their sub elite counterparts (Reilly et al. 2000). Elite junior starters and national players in Rugby League were taller and heavier than non-starters and regional players (Gabbett, T et al. 2009; Till et al. 2011). Although results from this study did not show a relationship of body composition and selection, this cannot be confirmed as there were only 16 complete datasets, reducing the power of the study.

Methods used to measure body composition need to be carefully selected for the intended purpose and results must be interpreted with caution (Ackland et al. 2012). This study has utilised a combination of methods measuring different physique and body composition components that also reflect different outcomes. Skinfolds remained stable while there was an increase in body mass. It could be assumed that a gain in mass came from an increase in muscle mass as skinfolds remained the same throughout the study. Results from the DXA scan however, show an increase in lean muscle mass in addition to a significant loss in body fat. Interestingly, skinfolds and body fat (percent and absolute) were highly correlated however skinfolds did not reflect the loss of fat mass. Therefore, using skinfolds and body mass measures may not provide a reliable picture of body composition over time in young male adolescent athletes and would be best used with measures such as body circumferences, lengths and bone breadths which provide additional information on growth during development.

This study utilised 3D scan technology to collect data on body circumference measures. Three dimensional scans provide a quick, non-invasive method to simply collect this data. It is not possible to compare circumference measures from 3D scans in this study to traditional anthropometric tape measurements as participants are positioned differently during measures and therefore consequently produce different results (Wang et al. 2006). Estimates of body fat are not accurate or reliable from the 3D scans as discussed in chapter 5 (Ryder 2012). However, within subject circumference measures are reliable and can be used to track changes in body size and shape (Wang et al. 2006). The majority of measures reflected the change seen in DXA measurements however circumference measures do not determine the tissue components of the regions measured (Brodie, Moscrip & Hutcheon 1998). For example, from year 1 to 2, there was no change in thigh circumference however there was a significant increase in lean mass and reduction in fat mass. Arm total mass and lean mass increased over both years however circumference measures only showed change from years 1 to 2. An increase in total and lean mass of the trunk area from years 1 to 2 and 1 to 3 are reflected in circumference measures of the chest, waist and hips. Used in combination with DXA, 3D scans will provide detailed anthropometric and body composition profiles over the development period (Ackland et al. 2012). Circumference measures used in conjunction with skinfolds and body mass measures may allow for interpretation of body composition changes.

All measurement methods have inherent limitations (Ackland et al. 2012). Circumference measures, limb lengths and bone breadths provide additional information on growth during development and can be useful as part of a talent identification model in some sports, however require a trained technician and can be time consuming. The time associated with these types of measures can be reduced with the use of 3D scan technology. While DXA has its own limitations, such as exposure to a radiation dose (albeit small) and it may also be more difficult and costly to access, it provides a detailed assessment of body composition, its segments and development over time. Small changes in composition should be interpreted with caution as reliability will vary with different scanning conditions (Nana et al. 2015). Repeated measures over a number of years should be conducted during adolescence so growth and maturation can be properly monitored.

6.5 Conclusion

The present study examined the changes in anthropometric and body composition measures of a group of AF development athletes approaching the national draft combine and whether these measures had an impact on selection. The most significant changes in body composition occurred from 16 to 17 years of age however due to limited power, we were unable to determine if body composition had an impact on selection. Results show that players are more physically developed than previous studies with close similarities to older rookie and senior players. If players are more physically prepared, rapid changes in body composition can be avoided when selected by a team and more physically ready to compete at the elite level. Addressing these requirements earlier in the development process prior to being selected in professional teams would be of benefit. Clear goals should be set for development stages, which are closely monitored, optimising physical development during a critical time of growth.

6.6 Practical considerations

- Use measurement methods or a combination of methods that provides sufficient information to monitor growth, development and response to programming. For example, DXA scans in combination with anthropometric measures would be ideal if access is available.
- Understand methodological limitations. Interpret body composition results from all methods with caution and use qualified technicians.
- Collection of physique and body composition data will allow coaches and fitness staff to understand the physiological factors associated with growth and maturation during adolescence to better plan training programs for this group.
- Physiological factors including anthropometric and body composition measures should be closely monitored during adolescence to ensure

optimal growth and development and so training programs can be individualised to the athlete's needs.

Chapter 7. General discussions, practical applications and conclusions

7.1 General Discussion

7.1.1 Introduction

The information presented in this thesis provides an insight into the EE and dietary intake of AF players. It also determines how the body composition of team sport athletes including AF, Soccer and Rugby Union, fluctuates throughout a season and how adolescent AF players physically develop over time. The first study measured the total daily EE and match EE of AF using accelerometry. The energy and nutrient intake was simultaneously measured over the same period for the second study. The third study measured and compared the body composition changes across a season in professional AF, Soccer and Rugby Union players using DXA, anthropometry and 3D scan technology. The fourth and final study assessed the body composition changes of 16-18-year-old AF development players leading into the draft. In this section, the major findings of each study will be presented and discussed.

7.1.2 Inertial Sensors to estimate the energy expenditure of team-sport athletes

Prior to this thesis the TDEE or match EE of AF had not been measured. The TDEE of Soccer players had been estimated with the gold standard DLW method (Ebine et al. 2002) and match EE in Soccer and Rugby League using the heart rate-$\dot{V}O_{2max}$ method (Coutts, A.J., Reaburn & Abt 2003). Therefore, the aim of this study was to estimate the TDEE and match expenditure of AF players from one team who compete in the professional league in Australia. It is difficult to measure EE in the field particularly in contact team sports but also in the free living environment as methods can restrict typical movement (Levine 2005). Accelerometry is a reliable and non-invasive method to measure PA and estimate EE and was therefore chosen to estimate TDEE for seven days and on the field during matches. The main finding of this study was that AF players expend a considerable amount of energy across the day and NEAT expenditure outside of training and matches contributes a substantial portion of daily expenditure. Also, during this thesis a study was published in AF using metabolic power to estimate EE of AF matches (Coutts, A.J. et al. 2015) however the method had not been validated against indirect calorimetry. Metabolic power calculations were therefore included into study analysis and correlated with estimates from PlayerLoad™ and calorimetry data. Results were moderately correlated and similar to the estimated from the Coutts study (2015).

A limitation for study one is that two types of accelerometers were used to measure EE. The SenseWear™ Armband accelerometer is reliable in measuring low to moderate intensity exercise (St-Onge et al. 2007) and is currently limited during high intensity activity like that seen in AF. A sport specific tri-axial accelerometer (Catapult MiniMax 4.0), validated to measure physical activity on the field in team sports (Boyd, Ball & Aughey 2011), was therefore used to measure high intensity activity and EE during training and matches. Ideally, one accelerometer unit would be worn for all activity to reduce measurement error. Ideally more than one team in the AF League would have been used however due to the need to protect the intellectual property of the team and athlete's performance data, collection was limited to this group.

The study identified some important considerations. There is a considerable individual variation in the contribution of EE from outside of training and matches due to commitments outside of being an athlete and this needs to be taken into consideration for nutrition programming. Also, accelerometers are an accessible and reliable method to measure EE however factors such as running kinematics may effect accelerometer output (Wixted et al. 2007). Results from this study contribute to the small body of knowledge in this area. On an individual level, results need to be interpreted with caution and in conjunction with other methods such as dietary intake when prescribing programs. Having knowledge of daily EE provides the practitioner and the athlete valuable information when tailoring dietary intake.

7.1.3 Dietary intake of a team competing in the Australian Football League: Are they meeting requirements?

The dietary intake of AF players was first measured in 1988 (Burke & Read 1988) and then again in 1999 (Schokman, Rutishauser & Wallace 1999) and since this time match style and intensity has evolved. The resources and focus on athletic training and recovery has also progressed since this time, however whether dietary intake has been modified and if dietary intake is meeting recommendations for optimal performance is unclear (Burke & Read 1988; Schokman, Rutishauser & Wallace 1999). In addition, the measurement of energy expenditure should be conducted in conjunction with the assessment of dietary intake and interpreted together rather than in isolation. Therefore, to supplement the EE measures from study one, dietary intake measures were assessed simultaneously in this period. Seven day weighed food diaries were used to measure the energy and macronutrient intake of professional AF athletes and compared to their daily EE and macronutrient recommendations.

The main findings of this study were that professional AF players, despite expending a significant and varying amount of energy across the week, did not appear to meet energy and carbohydrate requirements to support high volume training, match performance and health. However, these findings should consider that athletes may underestimate intake or methodological limitations may also underestimate intake (Magkos & Yannakoulia 2003). These results are comparable to a recent study published in another professional AF team where the mean carbohydrate intake was below recommendations and did not vary at different times throughout the season (Bilsborough, JC et al. 2016). Players were less likely to match EE and EI on high expenditure days with intake being considerably less on these days while expenditure and intake were more closely aligned on other days. The under consumption of energy on high expenditure days was not compensated for at other times unlike that seen in a study in professional Rugby Union were a low intake early in the week was compensated for later in the week with an over consumption of energy (Bradley et al. 2015).

Although this study only provides a snap shot of one point in the season for one team, the information contributes to a small body of knowledge that needs to be improved in AF. Dietary intake in athletes is influenced by a number of factors such as appetite, training schedule, body composition goals, food beliefs and intolerances and to improve intake in athletes a greater understanding of these factors is required so programming can be individualised to a greater extent. Further research is necessary to identify eating behaviours in athletes and the impact of nutrition on other factors such as biological measures, health, performance and recovery.

These studies show that in most cases athletes are failing to manipulate energy and nutrient intake according to their training load and energy expenditure. Using the methods in study one to identify fluctuations in daily expenditure, are required not only by the practitioner so intake can be programmed to meet expenditure but to also educate the player so they can identify when intake needs to be manipulated. Being aware of limitations both in the measurement of dietary intake such as underreporting and underestimating and the measurement of expenditure including device limitations are necessary so informed decisions can be made in conjunction with other data such as longitudinal body composition measures.

7.1.4 Body composition and physique of team sport athletes: a longitudinal study

Determining seasonal variation in body composition is essential to monitor the effects of training and nutrition programs across a season. The changes in body composition will depend on the sport, body composition requirements of the sport and individual body composition goals. This thesis compared the body composition changes of professional AF, Soccer and Rugby Union players from the beginning of pre-season to the end of the competitive season using a number of body composition measures. Each code experienced changes in body composition with Rugby Union experiencing the greatest overall change.

There are a number of reasons why body composition changes through the season, including amount, intensity and type of training, match time, dietary intake, illness, injury and travel (Duthie 2006). Rugby Union players require a greater overall body size than AF and Soccer due to the strength and size required for tackling, scrum and collisions (Duthie, G, Pyne & Hooper 2003; Nicholas 1997; Reilly, Bangsbo & Franks 2000) and this was shown in an 18 kg and 27 kg greater body mass than AF and Soccer respectively. Pre-season was associated with the greatest change in body composition where Rugby Union players lost 20% of their initial fat mass and gained an additional 3.3% of absolute lean muscle mass. AF and Soccer has smaller changes during this time. In a recently published study in another group of AF players, the group was split into experienced (played >4 years) and inexperienced players (played < 4 years). The inexperienced group had an increase in lean mass until the middle of the competitive season while the experienced group only had small increase in lean mass until middle of the pre-season. Our study also showed a small increase in lean mass across the season which is likely due to the relatively young age of the group. In addition to the seasonal body composition measures conducted by Bilsborough et al (2016), nutrition and strength measures were also taken. Energy and carbohydrate intake did not change across the season while changes in fat free soft tissue mass were correlated with changes in upper-body strength performance (Bilsborough, JC et al. 2016). A limitation of the study in this thesis was that other measures associated with body composition such as nutrition, strength, training load and injury were not conducted and future studies must include these.

Dietary intake will directly impact body composition change across the season. Chapter 4 identified that AF players were not consuming enough energy on high expenditure days leading into a match and did not compensate for this at another time. If players are not increasing energy intake during periods of high expenditure like that in pre-season (Bilsborough, JC et al. 2016), body composition change can be compromised. For example, repair and synthesis of muscle will be inhibited and lean muscle mass changes will be small. Unfortunately, the initial focus in pre-season is to lose fat mass that was gained in the off-season, thereby compromising gains in lean mass. Using methods such as DXA to assess body composition allows for the differentiation of tissues and focus can be shifted to preservation and gain of beneficial lean mass tissue rather than fat mass.

Body composition data in isolation only provides part of the story and needs to be considered in conjunction with other measures. Expanding the EE and intake data collected from chapters 3 and 4 to a number of points throughout the season in conjunction with other measures such as strength data will provide a clearer picture of why changes or lack thereof, are occurring in these athletes.

7.1.5 Body composition and physique change in Australian Football development athletes aged 16-18 years

National sporting organisations seek to identify talented athletes with a high likelihood of success (Pearson, Naughton & Torode 2006). The aim of this study was to longitudinally measure the anthropometric and body composition changes of national AF academy players over a two-year period using a number of measurement methods, in the lead up to the draft combine and whether body composition factors impacted selection.

The impact of anthropometric and body composition measures on selection in AF has been studied (Burgess, Naughton & Hopkins 2012; Robertson, Woods & Gastin 2015) before however the measurement methods used in this thesis, specifically DXA and 3D scan technology, provide a more detailed body composition analysis and it was thought this may highlight other body composition factors that may have an influence on selection. Results indicate that in this group and for this particular draft year, mass, height and body composition did not have a direct impact on selection, however it should be considered that in other selection years or with a larger cohort of players, this may not be the case. Match activity profiles in under 18 year AF competition such as a greater amount of time spent sprinting in games better predicted selection and subsequent career success in AF (Burgess, Naughton & Hopkins 2012) while height has been identified as one of three factors as the most important attributes in predicting draft success (Robertson, Woods & Gastin 2015). Although body composition did not impact selection in this study it should be considered that once recruited to a team, over 50% of the young players make their debut (Pyne et al. 2005) and some are exposed to senior football within 4-5 months of being recruited (Veale et al. 2010). Although the player may be ready in terms of skill, they may not be physiologically ready, with senior level players having greater body mass and levels of lean mass as illustrated in Table 7.1, which was generated using data from chapter 5 and 6. Knowing this, body composition often becomes a focus and gains in lean mass are desired. Training programs eliciting rapids gains in lean mass prescribed during marked changes in growth and physical development may place these athletes at increased risk of injury as tendons and bony insertions are still weak and unable to manage the increased load placed on them (Naughton et al. 2000).

Monitoring changes in body composition in young AF elite athletes is important while they are undergoing significant physical change in addition to completing high training and match loads (Henderson et al. 2015). The greatest change in body composition occurred from 16 to 17 years of age in this study. There was an increase in body mass mainly from a gain in total lean muscle mass in the first year with a smaller gain in the second year. The reduction in body fat followed expected patterns during this period where relative fatness reached its lowest point around 16-17 years of age and there was a concomitant, rapid increase in lean mass with a slower gain in fat (Malina 2004). Skinfold measures did not show change in this group while DXA was able to differentiate between body tissues and identify changes in fat, lean and bone mass. In this group using skinfolds and body mass measures may not provide a reliable picture of body composition over time and would be best used with measures such as body circumferences, lengths and bone breadths which provide additional information on growth during development. Selecting methods that are reliable, practical, and accessible and appropriately define change in this group are required. Also, body composition measurement in isolation only represents one part of the story and other measurements such dietary intake and training loads need to be considered in future studies.

	Elite Junior			Elite Senior
	16 years (n=16)	17 years (n=16)	18 years (n=16)	18+ years (n=30)
Age (yrs)	16.4 (0.3)	17.4 (0.3)	18.4 (0.3)	23.6 (3.7)
Height (cm)	187.0 (7.1)	188.1 (7)	188.7 (7.4)	187.2 (7.2)
Mass (kg)	77.7 (6.5)	81.0 (7.0)	82.9 (7.6)	85.93 (8.46)
Skinfolds (sum 7)	54.2 (14.5)	54.7 (13.1)	54.6 (13.5)	45.19 (6.54)
Fat mass (kg)	10.8 (2.8)	8.3 (2.4)	8.5 (2.2)	8.73 (1.78)
Fat mass (%)	14.0 (2.5)	10.4 (2.5)	10.4 (2.6)	10.4 (2.07)
Lean mass (kg)	63.3 (4.6)	67.7 (5.2)	69.3 (6.1)	71.73 (7.27)
Lean mass (%)	83.1 (3.7)	83.9 (2.9)	83.7 (2.5)	83.61 (2.38)
BMC (g)	3032.9 (251.7)	3139.0 (263.4)	3219.4 (315.7)	3477.88 (568.7)
BMD (g/cm^2)	1.257 (0.071)	1.290 (0.070)	1.298 (0.069)	1.348 (0.086)

Table 7. 1 Comparison of body composition data between elite junior and elite senior AF players. Mean ± SD

7.2 Practical Applications

- Total daily EE needs to be taken into consideration when nutrition programming, as energy expended outside of training provides a significant contribution to overall expenditure.
- Measurement of EE in the field is difficult and has limitations however accelerometers provide a good alternative as long as limitations are acknowledged.
- Energy intake and macronutrients need to be periodised according to the training day to ensure sufficient nutrition is provided for the goal of the training session and competition, body composition goals and health.
- Body composition needs to be monitored across the season. DXA provides detailed information on body composition and can be used to monitor changes in lean muscle mass, fat mass and bone mass and can be used 3-4 times in a season to monitor longitudinal change particularly in those who may experience significant change in body composition such as young athletes, those with body composition goals or those who sustain longer term injury.
- Body composition needs to be monitored closely in development athletes as significant changes are occurring during this time. DXA provide a detailed assessment of body composition changes while skinfolds provide limited information on change in this group.
- Physiological factors including anthropometric and body composition measures should be closely monitored during adolescence to ensure optimal growth and development and so training programs can be individualised to the athlete's needs.
- Use measurement methods or a combination of methods that provides sufficient information to monitor growth, development and response to programming.
- Understand methodological limitations. Interpret body composition results from all methods with caution.

7.3 Specific Conclusions

- AF players expend a significant amount of energy with a substantial amount coming from activity outside of training and competition.
- Accelerometers provide a practical and reliable measure of EE for ADL and on the football field.
- AF athletes do not consume enough energy in the diet on high expenditure days.
- AF athletes do not consume enough carbohydrate to properly prepare for competition.
- Body composition changes in the pre-season are greatest during periods of high training loads with the greatest changes occurring in Rugby Union players. AF and Soccer players experience small changes across the season.
- AF academy players experience significant changes in body composition with the greatest changes occurring from the age of 16-17 years.
- Body composition did not influence selection in the AF draft in this group or draft year.

7.4 Future Directions

7.4.1 How is body composition, throughout development, related to injury risk in young football athletes?

Young athletes are being identified early by professional clubs for selection at the higher level. The AF Stages of Development document specifies the ‘identification’ stage from the age of 15-16 years, the ‘specialisation’ stage from 17-18 years and the ‘investment’ stage from 19-22 years. This is a critical time for development in male athletes and care needs to be taken to ensure optimal health and growth for not only player welfare but also the investment clubs make in these athletes.

The injury incidence rate in first year AF players is 45.6% compared to 18.3% in players with 3 or more years experience (Fortington et al. 2016) however there is still a lack of understanding as to why this occurs. Once recruited to the professional level, training and game load substantially increases (Henderson et al. 2015; Veale, Pearce & Carlson 2007) and often body composition changes occur naturally from large running volumes, strength training and proper nutrition, or changes are targeted for an increase in lean mass and fat loss. When colliding with another player, a greater body mass exerts a greater impact force and a recent study in AF showed that injury incidence and severity increased with low body mass and they recommend to increase muscle mass in those with a low body mass (Gastin et al. 2015). However, in players with a low body mass, large and rapid gains in mass increase the load through the body and other soft tissue may not anatomically adapt at the same rate possibly increasing risk of injury. This risk is unknown however in a practical setting there have been anecdotal reports of this, leading to the setting of mass gain limits in young players in their first few years of career.

A study in this thesis measured the longitudinal changes in body composition of a small group of AF development athletes from the age of 16 to 18 years who were eligible for selection in the draft combine. In a separate study, the seasonal change in body composition of a professional AF, Soccer and Rugby Union team was measured. However, the athletes studied only represented a small percent of those who were actually selected in that draft that year or who competed in the professional leagues in Australia. Combining these studies and expanding variables measured in a longitudinal study would be of benefit.

A detailed longitudinal body composition analysis is required in conjunction with training load data and injury occurrence across the ‘specialisation’ and ‘investment’ stages of development. Increasing the number of study participants is required and would be open to all 16-year-old players who will be eligible for selection into professional AF, Soccer, Rugby Union and Rugby League teams. Anthropometric and body composition measures would be collected once annually (end of the competitive season) prior to selection in a professional team and biannually (beginning of pre-season and end of the competitive season) when selected to a team. Anthropometric measures will include height, body mass, girth measures and skinfolds and body composition assessed with DXA. Annual injury data already collected by the AF and training load data from each club will be collated. Correlations between body composition variables, training load and injury risk will be determined. This data will provide important information in profiling young athletes and assist in determining ‘best practice’ training and body composition guidelines to ensure optimal development and minimise injury risk.

7.4.2 What is the total daily energy expenditure and match expenditure of team sport athletes compared to gold standard methods?

In this thesis, the TDEE and match expenditure of AF players was estimated using tri-axial accelerometers. Research in this area is limited and results from this study contribute to a small body of knowledge however a number of limitations were identified and could be addressed in future studies. Measuring EE on the field during contact team sports is difficult as methods typically inhibit typical movement. The first study in this thesis created individual player algorithms to estimate on-field EE using accelerometer data and $\dot{V}O_{2max}$ data. The resulting match estimates of EE were compared with those calculated by a ‘metabolic power’ calculation that estimates energy cost based on acceleration and deceleration of running on a grass surface and is captured using GPS technology. There was a large correlation between methods however the 'metabolic power' calculation overestimated EE by approximately 9.5%. Also, creating individual regression equations for each individual athlete is not practical and would be time consuming in an elite sport environment.

To progress research in this area it is important to continue developing methods to estimate EE on the sporting field and to refine estimates that can be used in future studies and also in the practical environment. Portable calorimetry equipment such as the Cosmed calorimeter is more compact, allowing for usual movement however use in contact sports is still limited. Creating an AF specific on-field test that reflects a match activity profile with contact while wearing a GPS, tri-axial accelerometer and Cosmed calorimeter could aid in developing a new algorithm that can be applied without laboratory testing. This could also be applied to Soccer and Rugby Union specific on-field tests. It would also be worth exploring if the Cosmed could be modified so some form of contact and tackling could occur. It would also beneficial to measure body composition with DXA to obtain a lean mass measure that can be utilised in the algorithm as lean mass accounts for up to 70% of RMR.

In addition, the SenseWear™ Armband accelerometer needs to be validated in estimating TDEE in team sport athletes against the 'gold standard' method, DLW method. At a minimum, measurement would need to take place over a seven-day period in the pre-season during high volume training and another seven-day period during a typical week in the competitive season including a match. Combining this study with the study below would be of interest.

7.4.3 How is dietary intake related to illness and performance in team sport athletes?

In high performance sport where athletes are required to perform on a weekly basis, the health and wellness of athletes is important. A study in elite athletes competing in International athletics found that loss of training time due to illness or injury was a major determinant of success (Raysmith & Drew 2016). Competing at a high intensity in addition to strenuous and heavy training can depress the immune system. Further, an inadequate intake of nutrients or a poor quality diet can further compromise health and makes the athlete more susceptible to infection. Especially, in high performance team environments, illness can spread easily and can impact performance of a number of athletes. Macronutrient and micronutrient intake, diet quality and timing is important. A prolonged insufficient intake of energy and protein will be detrimental while insufficient intake of carbohydrate has been associated with greater levels of stress hormones and compromised immunity (Gleeson 2016). While the intake of carbohydrate during exercise can attenuate stress hormones, a number of vitamins and minerals are also essential for enhanced immune function, with vitamin B12, iron and zinc being the most prominent, while vitamin D and calcium are essential for bone health. Of recent interest is the impact of exercise and diet on gut microbial diversity which has been found to be greater in Rugby Union athletes versus controls (Clarke et al. 2014) and how gut health and probiotics are associated with upper respiratory tract infections.

While weight category and aesthetic sport athletes are at a greater risk of nutrient deficiency due to suboptimal energy and nutrient intakes, team sport athletes may still be at risk and may be restricting dietary intake on purpose or inadvertently, however few studies have not tracked dietary intake, biological blood measures and health in these athletes. In this thesis it was identified that AF players do not match dietary EI with expenditure on high expenditure days and do not periodise carbohydrate intake with differing training volumes. Expanding this research to occur throughout the season with additional measures is required.

A recent study in AF athletes by Bilsborough and colleagues (Bilsborough, JC et al. 2016) looked at energy and macronutrient intake at the beginning of pre-season, mid pre-season and beginning, middle and end of the competitive season along with strength and body composition measures. Expanding on this study and the study conducted in this thesis to include biological blood measures including iron, zinc, vitamin B12 and D and calcium in addition to stress hormones and inflammatory markers is necessary. Also, gut microbial diversity can be assessed with stool samples. Other measures to be included would be incidence and type of illness, 'wellness' ratings that are already collected by professional clubs, sleep quality, training load, travel information, dietary micronutrient intake and finally eating behaviours.

Collection of these variables will assist in answering the following:

1. Are players meeting dietary requirements (macro and micro-nutrient) for training and competition, how is this related to on field performance (high intensity running, repeat efforts), biological blood measures of nutrients, inflammation and stress and how is this related to the incidence of illness and infection?
2. How are these measurements related to training load and body composition measures?
3. What is the relationship of dietary intake (macro and micro-nutrient), training load and measures of gut microbiota and its relationship with wellness/illness?
4. Are players periodising nutrition intake throughout a training week and if so, does this impact performance and immunity?
5. And finally, what influences a player's eating behaviours?

Once this information is collected, nutrition intervention studies can be completed with prescription of carbohydrate levels and a probiotic supplement study and impact on gut health and illness.

This study will provide significant insight into the nutritional practices of team sport athletes and how this impacts performance and immune function. It will allow for the development of best practice guidelines to monitor immunity of athletes and prevent depression of the immune system with good nutrition and training practices. An understanding of player's behaviours around dietary intake will allow for better targeting of information to this group and adherence to nutrition programs that can aid in performance and health benefits.

7.4.4 How do components of body composition effect performance and injury in team sport athletes?

Body composition assessment in the high performance sports environment can be used in a number of ways. In this thesis, DXA, skinfolds and 3D scan technologies were used to measure body composition longitudinally in AF development athletes and in professional AF, Soccer and Rugby Union players. The most common method used in these environments are skinfolds as they are easily accessible however DXA technology although less accessible, more expensive and involves a small radiation exposure, provides a detailed body composition assessment of multiple tissues. This allows for greater individualisation of body composition goals and identification of variables that may impact performance or injury.

In team sport environments arbitrary cut-offs are set to determine what a player's body composition should be. For example, some clubs expect all players to have a sum of seven skinfolds less than 50 mm. However, not only does this just focus on one element of body composition, the relationship between a skinfold measure and absolute body fat can be quite different. It is unknown what the 'optimal' body composition of a team sport athlete is, or what an optimal composition is for a position within a sport. Also, if body composition changes are required, how does this quantify in performance on the field and in the gym. Finally, a DXA scan can identify elements of body composition that may compromise performance or increase injury risk for example, limb asymmetry and low BMC or BMD while 3D scan technology can identify girth and limb length differences. For example, leg asymmetry of 3% in lean mass can occur from differential loading patters during participation in football which can lead to kicking inaccuracy (Hart et al. 2014). This asymmetry may also increase injury risk however this is unknown.

To answer questions proposed above, a longitudinal study measuring body composition of a large group of AF players from a number of teams is required. Classification of body composition within playing positions and across playing experience can be defined. Other variables to be measured to determine effect of body composition change on running capacity would include endurance and intermittent running performance tests and strength measures. Asymmetry would be measured with DXA and 3D scan technology to determine if differences between legs composition and girth and length effects kicking and strength performance. Kicking performance parameters such as kicking accuracy, kicking velocity could be measured. Finally, injury type and occurrence can be correlated with total body composition and limb composition, girth and length.

Determining body composition classifications for team sport athletes and positions within these sports will allow for more targeted body composition goals but also moves away from the ‘one size fits all’ approach. Also, identifying limb asymmetry in an athlete may help to reduce the risk or injury while identifying this during the rehabilitation period allows for strength programming to correct the imbalance.

References

Achten, J & Jeukendrup, AE 2003, 'Heart rate monitoring: applications and limitations', *Sports Med*, vol. 33, no. 7, pp. 517-38.

Ackland, TR & Bloomfield, J 1996, 'Stability of human proportions through adolescent growth', *Aust J Sci Med Sport*, vol. 28, no. 2, pp. 57-60.

Ackland, TR, Lohman, TG, Sundgot-Borgen, J, Maughan, RJ, Meyer, NL, Stewart, AD & Muller, W 2012, 'Current status of body composition assessment in sport: review and position statement on behalf of the ad hoc research working group on body composition health and performance, under the auspices of the I.O.C. Medical Commission', *Sports Med*, vol. 42, no. 3, pp. 227-49.

Ainslie, P, Reilly, T & Westerterp, K 2003, 'Estimating human energy expenditure: a review of techniques with particular reference to doubly labelled water', *Sports Med*, vol. 33, no. 9, pp. 683-98.

Almeras, N, Mimeault, N, Serresse, O, Boulay, MR & Tremblay, A 1991, 'Non-exercise daily energy expenditure and physical activity pattern in male endurance athletes', *Eur J Appl Physiol Occup Physiol*, vol. 63, no. 3-4, pp. 184-7.

American College of Sports, M, American Dietetic, A & Dietitians of, C 2000, 'Joint Position Statement: nutrition and athletic performance. American College of Sports Medicine, American Dietetic Association, and Dietitians of Canada', *Med Sci Sports Exerc*, vol. 32, no. 12, pp. 2130-45.

Areta, JL, Burke, LM, Ross, ML, Camera, DM, West, DW, Broad, EM, Jeacocke, NA, Moore, DR, Stellingwerff, T, Phillips, SM, Hawley, JA & Coffey, VG 2013, 'Timing and distribution of protein ingestion during prolonged recovery from resistance exercise alters myofibrillar protein synthesis', *J Physiol*, vol. 591, no. 9, pp. 2319-31.

Argus, CK, Gill, N, Keogh, J, Hopkins, WG & Beaven, CM 2010, 'Effects of a short-term pre-season training programme on the body composition and anaerobic performance of professional rugby union players', *J Sports Sci*, vol. 28, no. 6, pp. 679-86.

Atwater, WO 1894, 'Foods: Nutritive value and cost', *Farmers Bulletin, US Department of Agriculture*, vol. 23.

Atwater, WO & Benedict, FG 1905, 'The Respiration Calorimeter', *Yearbook of the department of agriculture*.

Aughey, RJ 2010, 'Australian football player work rate: evidence of fatigue and pacing?', *Int J Sports Physiol Perform*, vol. 5, no. 3, pp. 394-405.

Aughey, RJ 2011, 'Applications of GPS technologies to field sports', *International Journal of Sports Physiology and Performance*, vol. 6, no. 3, pp. 295-310.

Australian Paediatric Endocrine Group *Australian Paediatric Endocrine Group. Growth and Growth Charts*, The Australian Paediatric Endocrine Group, viewed 16 March 2015, <http://www.apeg.org.au/clinicalresourceslinks/growthgrowthcharts/tabid/101/default.aspx>.

Balsom, PD, Wood, K, Olsson, P & Ekblom, B 1999, 'Carbohydrate intake and multiple sprint sports: with special reference to football (soccer)', *Int J Sports Med*, vol. 20, no. 1, pp. 48-52.

Bangsbo, J, Mohr, M & Krustrup, P 2006, 'Physical and metabolic demands of training and match-play in the elite football player', *J Sports Sci*, vol. 24, no. 7, pp. 665-74.

Bangsbo, J, Norregaard, L & Thorsoe, F 1992, 'The effect of carbohydrate diet on intermittent exercise performance', *Int J Sports Med*, vol. 13, no. 2, pp. 152-7.

Barrett, S, Midgley, A & Lovell, R 2014, 'PlayerLoad™: Reliability, Convergent Validity, and Influence of Unit Position during Treadmill Running', *Int J Sports Physiol Perform*, vol. 9, no. 6, pp. 945-52.

Bedale, E 1922, 'Energy Expenditure and food requirements of children at school', *Procedings Royal Society B*, vol. 94.

Bell, W, Evans, WD, Cobner, DM & Eston, RG 2005, 'Regional placement of bone mineral mass, fat mass, and lean soft tissue mass in young adult rugby union players', *Ergonomics*, vol. 48, no. 11-14, pp. 1462-72.

Benito, PJ, Neiva, C, Gonzalez-Quijano, PS, Cupeiro, R, Morencos, E & Peinado, AB 2012, 'Validation of the SenseWear armband in circuit resistance training with different loads', *Eur J Appl Physiol*, vol. 112, no. 8, pp. 3155-9.

Bentley, DJ, Millet, GP, Vleck, VE & McNaughton, LR 2002, 'Specific aspects of contemporary triathlon: implications for physiological analysis and performance', *Sports Med*, vol. 32, no. 6, pp. 345-59.

Berry, WT, Beveridge, JB & et al. 1949, 'The diet, haemoglobin values, and blood pressure of Olympic athletes', *Br Med J*, vol. 1, no. 4598, pp. 300-4.

Bilsborough, J, C., Greenway, K, Opar, D, Livingstone, S, Cordy, J & Coutts, A, J. 2014, 'The accuracy and precision of DXA for assessing body composition in team sport athletes', *J Sports Sci*, vol. 32, no. 19, pp. 1821-8.

Bilsborough, JC, Greenway, K, Livingston, S, Cordy, J & Coutts, AJ 2016, 'Changes in Anthropometry, Upper Body Strength and Nutrient Intake in Professional Australian Football Players During a Season', *Int J Sports Physiol Perform*, vol. 11, no. 3, pp. 290-300.

Bilsborough, JC, Greenway, K, Opar, DA, Livingstone, SG, Cordy, JT, Bird, SR & Coutts, AJ 2015, 'Comparison of anthropometry, upper-body strength, and lower-body power characteristics in different levels of Australian football players', *J Strength Cond Res*, vol. 29, no. 3, pp. 826-34.

Bisdee, JT, James, WP & Shaw, MA 1989, 'Changes in energy expenditure during the menstrual cycle', *Br J Nutr*, vol. 61, no. 2, pp. 187-99.

Black, AE 2001, 'Dietary assessment for sports dietetics', *Nutr Bull*, vol. 26, pp. 29-42.

Black, AE, Coward, WA, Cole, TJ & Prentice, AM 1996, 'Human energy expenditure in affluent societies: an analysis of 574 doubly-labelled water measurements', *Eur J Clin Nutr*, vol. 50, no. 2, pp. 72-92.

Black, AE, Goldberg, GR, Jebb, SA, Livingstone, MB, Cole, TJ & Prentice, AM 1991, 'Critical evaluation of energy intake data using fundamental principles of energy physiology: 2. Evaluating the results of published surveys', *Eur J Clin Nutr*, vol. 45, no. 12, pp. 583-99.

Bluck, LJC 2008, 'Doubly Labelled Water for the measurement of total energy expenditure in man- progress and applications in the last decade', *British Nutrition Foundation Nutrition Bulletin*, vol. 33, p. 10.

Bogardus, C, Lillioja, S, Ravussin, E, Abbott, W, Zawadzki, JK, Young, A, Knowler, WC, Jacobowitz, R & Moll, PP 1986, 'Familial dependence of the resting metabolic rate', *N Engl J Med*, vol. 315, no. 2, pp. 96-100.

Bouten, CV, Westerterp, KR, Verduin, M & Janssen, JD 1994, 'Assessment of energy expenditure for physical activity using a triaxial accelerometer', *Med Sci Sports Exerc*, vol. 26, no. 12, pp. 1516-23.

Boyd, LJ, Ball, K & Aughey, RJ 2011, 'The reliability of MinimaxX accelerometers for measuring physical activity in Australian football', *Int J Sports Physiol Perform*, vol. 6, no. 3, pp. 311-21.

Bradley, WJ, Cavanagh, B, Douglas, W, Donovan, TF, Twist, C, Morton, JP & Close, GL 2015, 'Energy intake and expenditure assessed 'in-season' in an elite European rugby union squad', *Eur J Sport Sci*, vol. 15, no. 6, pp. 469-79.

Brazeau, AS, Karelis, AD, Mignault, D, Lacroix, MJ, Prud'homme, D & Rabasa-Lhoret, R 2011, 'Accuracy of the SenseWear Armband during ergocycling', *Int J Sports Med*, vol. 32, no. 10, pp. 761-4.

Brewer, J & Davis, J 1995, 'Applied physiology of rugby league', *Sports Med*, vol. 20, no. 3, pp. 129-35.

Briggs, MA, Cockburn, E, Rumbold, PL, Rae, G, Stevenson, EJ & Russell, M 2015, 'Assessment of Energy Intake and Energy Expenditure of Male Adolescent Academy-Level Soccer Players during a Competitive Week', *Nutrients*, vol. 7, no. 10, pp. 8392-401.

Broad, EMC, G.R. 2008, 'What is the optimal composition of an athlete's diet?', *Eur J Sport Sci*, vol. 8, no. 2, p. 9.

Brodie, D, Moscrip, V & Hutcheon, R 1998, 'Body composition measurement: a review of hydrodensitometry, anthropometry, and impedance methods', *Nutrition*, vol. 14, no. 3, pp. 296-310.

Buchheit, M, Al Haddad, H, Simpson, BM, Palazzi, D, Bourdon, PC, Di Salvo, V & Mendez-Villanueva, A 2014, 'Monitoring Accelerations With GPS in Football: Time to Slow Down?', *Int J Sports Physiol Perform*, vol. 9, no. 3, pp. 442-5.

Buchholz, AC, Rafii, M & Pencharz, PB 2001, 'Is resting metabolic rate different between men and women?', *Br J Nutr*, vol. 86, no. 6, pp. 641-6.

Burgess, DJ, Naughton, G & Hopkins, W 2012, 'Draft-camp predictors of subsequent career success in the Australian Football League', *J Sci Med Sport*, vol. 15, no. 6, pp. 561-7.

Burgess, DJ & Naughton, GA 2010, 'Talent development in adolescent team sports: a review', *Int J Sports Physiol Perform*, vol. 5, no. 1, pp. 103-16.

Burke, LM 2001a, 'Energy needs of athletes', *Canadian Journal Applied Physiology*, vol. 26 Suppl, pp. S202-19.

Burke, LM 2001b, 'Nutritional practices of male and female endurance cyclists', *Sports Med*, vol. 31, no. 7, pp. 521-32.

Burke, LM 2007, 'Training and Competition Nutrition', in L Burke & V Deakin (eds), *Practical Sports Nutrition*, Human KInetics, Champaign, IL, pp. 1-26, <http://www.loc.gov/catdir/toc/fy0712/2006037750.html>.

Burke, LM 2015, 'Re-Examining High-Fat Diets for Sports Performance: Did We Call the 'Nail in the Coffin' Too Soon?', *Sports Med*, vol. 45 Suppl 1, pp. S33-49.

Burke, LM, Cox, GR, Culmmings, NK & Desbrow, B 2001, 'Guidelines for daily carbohydrate intake: do athletes achieve them?', *Sports Medicine*, vol. 31, no. 4, pp. 267-99.

Burke, LM, Gollan, RA & Read, RS 1986, 'Seasonal changes in body composition in Australian Rules footballers', *Br J Sports Med*, vol. 20, no. 2, pp. 69-71.

Burke, LM, Hawley, JA, Wong, SH & Jeukendrup, AE 2011, 'Carbohydrates for training and competition', *Journal of Sports Sciences*, vol. 29 Suppl 1, pp. S17-27.

Burke, LM, Loucks, AB & Broad, N 2006, 'Energy and carbohydrate for training and recovery', *J Sports Sci*, vol. 24, no. 7, pp. 675-85.

Burke, LM & Read, RS 1988, 'A study of dietary patterns of elite Australian football players', *Can J Sport Sci*, vol. 13, no. 1, pp. 15-9.

Burke, LM, Slater, G, Broad, EM, Haukka, J, Modulon, S & Hopkins, WG 2003, 'Eating patterns and meal frequency of elite Australian athletes', *Int J Sport Nutr Exerc Metab*, vol. 13, no. 4, pp. 521-38.

Burt, DG, Lamb, K, Nicholas, C & Twist, C 2014, 'Effects of exercise-induced muscle damage on resting metabolic rate, sub-maximal running and post-exercise oxygen consumption', *Eur J Sport Sci*, vol. 14, no. 4, pp. 337-44.

Bussau, VA, Fairchild, TJ, Rao, A, Steele, P & Fournier, PA 2002, 'Carbohydrate loading in human muscle: an improved 1 day protocol', *Eur J Appl Physiol*, vol. 87, no. 3, pp. 290-5.

Butte, NF, Ekelund, U & Westerterp, KR 2012, 'Assessing physical activity using wearable monitors: measures of physical activity', *Med Sci Sports Exerc*, vol. 44, no. 1 Suppl 1, pp. S5-12.

Byrne, HK & Wilmore, JH 2001, 'The relationship of mode and intensity of training on resting metabolic rate in women', *Int J Sport Nutr Exerc Metab*, vol. 11, no. 1, pp. 1-14.

Caballero, B 2007, 'The global epidemic of obesity: an overview', *Epidemiol Rev*, vol. 29, pp. 1-5.

Carling, C & Orhant, E 2010, 'Variation in body composition in professional soccer players: interseasonal and intraseasonal changes and the effects of exposure time and player position', *J Strength Cond Res*, vol. 24, no. 5, pp. 1332-9.

Cheng, HL, O'Connor, H, Kay, S, Cook, R, Parker, H & Orr, R 2014, 'Anthropometric characteristics of Australian junior representative rugby league players', *J Sci Med Sport*, vol. 17, no. 5, pp. 546-51.

Christensen, CC, Frey, HM, Foenstelien, E, Aadland, E & Refsum, HE 1983, 'A critical evaluation of energy expenditure estimates based on individual O2 consumption/heart rate curves and average daily heart rate', *Am J Clin Nutr*, vol. 37, no. 3, pp. 468-72.

Claessens, AL, Lefevre, J, Beunen, G & Malina, RM 1999, 'The contribution of anthropometric characteristics to performance scores in elite female gymnasts', *J Sports Med Phys Fitness*, vol. 39, no. 4, pp. 355-60.

Clarke, SF, Murphy, EF, O'Sullivan, O, Lucey, AJ, Humphreys, M, Hogan, A, Hayes, P, O'Reilly, M, Jeffery, IB, Wood-Martin, R, Kerins, DM, Quigley, E, Ross, RP, O'Toole, PW, Molloy, MG, Falvey, E, Shanahan, F & Cotter, PD 2014, 'Exercise and associated dietary extremes impact on gut microbial diversity', *Gut*, vol. 63, no. 12, pp. 1913-20.

Cole, CR, Salvaterra, GF, Davis, JE, Jr., Borja, ME, Powell, LM, Dubbs, EC & Bordi, PL 2005, 'Evaluation of dietary practices of National Collegiate Athletic Association Division I football players', *J Strength Cond Res*, vol. 19, no. 3, pp. 490-4.

Costill, DL, Pascoe, DD, Fink, WJ, Robergs, RA, Barr, SI & Pearson, D 1990, 'Impaired muscle glycogen resynthesis after eccentric exercise', *J Appl Physiol (1985)*, vol. 69, no. 1, pp. 46-50.

Coutts, AJ, Kempton, T, Sullivan, C, Bilsborough, J, Cordy, JC & Rampinini, E 2015, 'Metabolic power and energetic costs of professional Australian Football match-play', *J Sci Med Sport*, vol. 18, no. 2, pp. 219-24.

Coutts, AJ, Quinn, J, Hocking, J, Castagna, C & Rampinini, E 2010, 'Match running performance in elite Australian Rules Football', *J Sci Med Sport*, vol. 13, p. 6.

Coutts, AJ, Reaburn, P & Abt, G 2003, 'Heart rate, blood lactate concentration and estimated energy expenditure in a semi-professional rugby league team during a match: a case study', *J Sports Sci*, vol. 21, no. 2, pp. 97-103.

Cox, GR, Clark, SA, Cox, AJ, Halson, SL, Hargreaves, M, Hawley, JA, Jeacocke, N, Snow, RJ, Yeo, WK & Burke, LM 2010, 'Daily training with high carbohydrate availability increases exogenous carbohydrate oxidation during endurance cycling', *J Appl Physiol (1985)*, vol. 109, no. 1, pp. 126-34.

Coyle, EF, Coggan, AR, Hemmert, MK, Lowe, RC & Walters, TJ 1985, 'Substrate usage during prolonged exercise following a preexercise meal', *J Appl Physiol*, vol. 59, no. 2, pp. 429-33.

Crouter, SE, Clowers, KG & Bassett, DR, Jr. 2006, 'A novel method for using accelerometer data to predict energy expenditure', *J Appl Physiol*, vol. 100, no. 4, pp. 1324-31.

Crozier, SJ, Kimball, SR, Emmert, SW, Anthony, JC & Jefferson, LS 2005, 'Oral leucine administration stimulates protein synthesis in rat skeletal muscle', *J Nutr*, vol. 135, no. 3, pp. 376-82.

Cunniffe, B, Proctor, W, Baker, JS & Davies, B 2009, 'An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software', *J Strength Cond Res*, vol. 23, no. 4, pp. 1195-203.

Cunningham, JJ 1980, 'A reanalysis of the factors influencing basal metabolic rate in normal adults', *Am J Clin Nutr*, vol. 33, no. 11, pp. 2372-4.

Curtis, DE & Bradfield, RB 1971, 'Long-term energy intake and expenditure of obese housewives', *Am J Clin Nutr*, vol. 24, no. 12, pp. 1410-7.

Da Poian, A, El-Bacha, T & Luz, M 2010, 'Nutrient Utilization in Humans: Metabolism Pathways', *Nature Education*, vol. 3, no. 9.

de Jonge, L & Bray, GA 1997, 'The thermic effect of food and obesity: a critical review', *Obes Res*, vol. 5, no. 6, pp. 622-31.

de Oliveira, EP, Burini, RC & Jeukendrup, A 2014, 'Gastrointestinal complaints during exercise: prevalence, etiology, and nutritional recommendations', *Sports Med*, vol. 44 Suppl 1, pp. S79-85.

Deakin, V 2000, 'Measuring nutritional status of athletes: clinical and research perspectives', in L Burke & V Deakin (eds), *Clinical Sports Nutrition*, McGraw-Hill, Roseville, NSW, pp. 30-68.

Delahunt, E, Byrne, RB, Doolin, RK, McInerney, RG, Ruddock, CT & Green, BS 2013, 'Anthropometric profile and body composition of Irish adolescent rugby union players aged 16-18', *J Strength Cond Res*, vol. 27, no. 12, pp. 3252-8.

Denzer, CM & Young, JC 2003, 'The effect of resistance exercise on the thermic effect of food', *Int J Sport Nutr Exerc Metab*, vol. 13, no. 3, pp. 396-402.

Deutz, RC, Benardot, D, Martin, DE & Cody, MM 2000, 'Relationship between energy deficits and body composition in elite female gymnasts and runners', *Med Sci Sports Exerc*, vol. 32, no. 3, pp. 659-68.

di Prampero, PE, Atchou, G, Bruckner, JC & Moia, C 1986, 'The energetics of endurance running', *Eur J Appl Physiol Occup Physiol*, vol. 55, no. 3, pp. 259-66.

Dolezal, BA, Potteiger, JA, Jacobsen, DJ & Benedict, SH 2000, 'Muscle damage and resting metabolic rate after acute resistance exercise with an eccentric overload', *Med Sci Sports Exerc*, vol. 32, no. 7, pp. 1202-7.

Donahoo, WT, Levine, JA & Melanson, EL 2004, 'Variability in energy expenditure and its components', *Curr Opin Clin Nutr Metab Care*, vol. 7, no. 6, pp. 599-605.

Douglas, CG 1911, 'A method for determining the total respiratory exchange in man', *Journal of Physiology*, vol. 42, no. 17.

Drenowatz, C & Eisenmann, JC 2011, 'Validation of the SenseWear Armband at high intensity exercise', *Eur J Appl Physiol*, vol. 111, no. 5, pp. 883-7.

Drenowatz, C, Eisenmann, JC, Carlson, JJ, Pfeiffer, KA & Pivarnik, JM 2012, 'Energy expenditure and dietary intake during high-volume and low-volume training periods among male endurance athletes', *Appl Physiol Nutr Metab*, vol. 37, no. 2, pp. 199-205.

Drenowatz, C, Eisenmann, JC, Pivarnik, JM, Pfeiffe, KA & Carlson, JJ 2013, 'Differences in Energy Expenditure between high- and low-volume training', *Eur J Sport Sci*, vol. 13, no. 4, pp. 422-30.

Drenowatz, C, Eisenmann, JC, Pivarnik, JM, Pfeiffer, KA & Carlson, JJ 2013, 'Differences in energy expenditure between high- and low-volume training', *Eur J Sport Sci*, vol. 13, no. 4, pp. 422-30.

Durnin, JV 1967, 'Activity patterns in the community', *Can Med Assoc J*, vol. 96, no. 12, pp. 882-9.

Durnin, JV, Blake, EC & Brockway, JM 1957, 'The energy expenditure and food intake of middle-aged Glasgow housewives and their adult daughters', *Br J Nutr*, vol. 11, no. 1, pp. 85-94.

Duthie, G, Pyne, D & Hooper, S 2003, 'Applied physiology and game analysis of rugby union', *Sports Med*, vol. 33, no. 13, pp. 973-91.

Duthie, GM, Pyne, DB, Hopkins, WG, Livingstone, S & Hooper, SL 2006, 'Anthropometry profiles of elite rugby players: quantifying changes in lean mass', *Br J Sports Med*, vol. 40, no. 3, pp. 202-7.

Ebert, TR 2000, 'Nutrition for the Australian Rules football player', *J Sci Med Sport*, vol. 3, no. 4, pp. 369-82.

Ebine, N, Rafamantanantsoa, HH, Nayuki, Y, Yamanaka, K, Tashima, K, Ono, T, Saitoh, S & Jones, PJ 2002, 'Measurement of total energy expenditure by the doubly labelled water method in professional soccer players', *J Sports Sci*, vol. 20, no. 5, pp. 391-7.

Edholm, OG, Fletcher, JG, Widdowson, EM & Mccance, RA 1955, 'Energy expenditure and food intake of individual men', *Br J Nutr*, vol. 9, p. 15.

Edwards, JE, Lindeman, AK, Mikesky, AE & Stager, JM 1993, 'Energy balance in highly trained female endurance runners', *Med Sci Sports Exerc*, vol. 25, no. 12, pp. 1398-404.

Elloumi, M, Ben Ounis, O, Courteix, D, Makni, E, Sellami, S, Tabka, Z & Lac, G 2009, 'Long-term rugby practice enhances bone mass and metabolism in relation with physical fitness and playing position', *J Bone Miner Metab*, vol. 27, no. 6, pp. 713-20.

Favre, PA & Silbermann, JT 1952, 'Recherches sur les quantities de chaleur degagees dans les actions chimiques et moleculaires.', *Annales de Chimie et de Physique*, vol. 34, pp. 357-450.

Fernandez-Garcia, B, Perez-Landaluce, J, Rodriguez-Alonso, M & Terrados, N 2000, 'Intensity of exercise during road race pro-cycling competition', *Med Sci Sports Exerc*, vol. 32, no. 5, pp. 1002-6.

Ferraro, R & Ravussin, E 1992, 'Fat mass in predicting resting metabolic rate', *Am J Clin Nutr*, vol. 56, no. 2, pp. 460-1.

Flatt, JP 1992, 'The biochemistry of energy expenditure', in P Bjorntrop & BN Brodoff (eds), *Obesity*, JB Lippincott Co, New York, pp. 100-16.

Fleck, SJ 1983, 'Body composition of elite American athletes', *Am J Sports Med*, vol. 11, no. 6, pp. 398-403.

Fogelholm, M 1994, 'Effects of bodyweight reduction on sports performance', *Sports Med*, vol. 18, no. 4, pp. 249-67.

Fortington, LV, Berry, J, Buttifant, D, Ullah, S, Diamantopoulou, K & Finch, CF 2016, 'Shorter time to first injury in first year professional football players: A cross-club comparison in the Australian Football League', *J Sci Med Sport*, vol. 19, no. 1, pp. 18-23.

Fuller, CW, Taylor, AE, Brooks, JH & Kemp, SP 2013, 'Changes in the stature, body mass and age of English professional rugby players: a 10-year review', *J Sports Sci*, vol. 31, no. 7, pp. 795-802.

Gabbett, T, Kelly, J, Ralph, S & Driscoll, D 2009, 'Physiological and anthropometric characteristics of junior elite and sub-elite rugby league players, with special reference to starters and non-starters', *J Sci Med Sport*, vol. 12, no. 1, pp. 215-22.

Gabbett, TJ 2005a, 'Changes in physiological and anthropometric characteristics of rugby league players during a competitive season', *J Strength Cond Res*, vol. 19, no. 2, pp. 400-8.

Gabbett, TJ 2005b, 'Science of rugby league football: a review', *J Sports Sci*, vol. 23, no. 9, pp. 961-76.

Gabbett, TJ 2006, 'A comparison of physiological and anthropometric characteristics among playing positions in sub-elite rugby league players', *J Sports Sci*, vol. 24, no. 12, pp. 1273-80.

Gabbett, TJ, Jenkins, DG & Abernethy, B 2011, 'Relationships between physiological, anthropometric, and skill qualities and playing performance in professional rugby league players', *J Sports Sci*, vol. 29, no. 15, pp. 1655-64.

Galgani, J & Ravussin, E 2008, 'Energy metabolism, fuel selection and body weight regulation', *Int J Obes (Lond)*, vol. 32 Suppl 7, pp. S109-19.

Gamble, P 2006, 'Periodization of training for team sport athletes', *Strength Cond*, vol. 28, no. 5, p. 10.

Garlie, TN, Obusek, JP, Corner, BD & Zambraski, EJ 2010, 'Comparison of body fat estimates using 3D digital laser scans, direct manual anthropometry, and DXA in men', *Am J Hum Biol*, vol. 22, no. 5, pp. 695-701.

Garry, RC, Passmore, R, Warnock, GM & Durnin, JVGA 1952, 'Studies on Expenditure of Energy and Consumption of Food by Miners and Clerks, Fife, Scotland', in MR Council (ed.), *Special Report Series. Medical Research Council* Medical Research Council p. pp. vi + 70 pp.

Garthe, I, Raastad, T, Refsnes, PE, Koivisto, A & Sundgot-Borgen, J 2011, 'Effect of two different weight-loss rates on body composition and strength and power-related performance in elite athletes', *Int J Sport Nutr Exerc Metab*, vol. 21, no. 2, pp. 97-104.

Gastin, PB 2001, 'Energy system interaction and relative contribution during maximal exercise', *Sports Med*, vol. 31, no. 10, pp. 725-41.

Gastin, PB, McLean, O, Spittle, M & Breed, RV 2013, 'Quantification of tackling demands in professional Australian football using integrated wearable athlete tracking technology', *J Sci Med Sport*, vol. 16, no. 6, pp. 589-93.

Gastin, PB, Meyer, D, Huntsman, E & Cook, J 2015, 'Increase in injury risk with low body mass and aerobic-running fitness in elite Australian football', *Int J Sports Physiol Perform*, vol. 10, no. 4, pp. 458-63.

Georgeson, EC, Weeks, BK, McLellan, C & Beck, BR 2012, 'Seasonal change in bone, muscle and fat in professional rugby league players and its relationship to injury: a cohort study', *BMJ Open*, vol. 2, no. 6.

Ginty, F, Rennie, KL, Mills, L, Stear, S, Jones, S & Prentice, A 2005, 'Positive, site-specific associations between bone mineral status, fitness, and time spent at high-impact activities in 16- to 18-year-old boys', *Bone*, vol. 36, no. 1, pp. 101-10.

Gleeson, M 2016, 'Immunological aspects of sport nutrition', *Immunol Cell Biol*, vol. 94, no. 2, pp. 117-23.

Gore, CJ, Tanner, R & Sport., AIo 2013, *Physiological Tests For Elite Athletes [e-book]*, ed. H Kinetics, Human Kinetics, Champaign IL, viewed December 19, 2016, via eBook Collection (EBSCOhost), Ipswich, MA.

Gray, AJ & Jenkins, DG 2010, 'Match analysis and the physiological demands of Australian football', *Sports Med*, vol. 40, no. 4, pp. 347-60.

Greenwood, M, Hudson, C & Tebb, AE 1919, 'Report on the metabolism of female munition workers', *Proceedings of the Royal Society of London. Series B, Containing papers of a biological character*, vol. 91, no. 635, p. 20.

Gunnarsson, TP, Bendiksen, M, Bischoff, R, Christensen, PM, Lesivig, B, Madsen, K, Stephens, F, Greenhaff, P, Krustrup, P & Bangsbo, J 2013, 'Effect of whey protein- and carbohydrate-enriched diet on glycogen resynthesis during the first 48 h after a soccer game', *Scand J Med Sci Sports*, vol. 23, no. 4, pp. 508-15.

Hahn, A 1990, 'Identification and selection of talent in Australian rowing', *EXCEL*, vol. 6, pp. 5-11.

Haldi, J & Wynn, W 1946, 'Observations on efficiency of swimmers as related to some changes in pre-exercise nutriment', *J Nutr*, vol. 31, pp. 525-32.

Hargrove, JL 2007, 'Does the history of food energy units suggest a solution to "Calorie confusion"?', *Nutr J*, vol. 6, p. 44.

Harley, JA, Hind, K & O'Hara J, P 2011, 'Three-compartment body composition changes in elite rugby league players during a super league season, measured by dual-energy X-ray absorptiometry', *J Strength Cond Res*, vol. 25, no. 4, pp. 1024-9.

Harris, JA & Benedict, FG 1918, 'A biometric study of human basal metabolism ', *Proc Nat Acad Sci U.S.A*, vol. 4, no. 12, p. 3.

Hart, NH, Nimphius, S, Spiteri, T & Newton, RU 2014, 'Leg strength and lean mass symmetry influences kicking performance in Australian football', *J Sports Sci Med*, vol. 13, no. 1, pp. 157-65.

H Canada 2016, *Canadian Dietary Reference Intakes Tables*, by Health Canada, <http://www.hc-sc.gc.ca/fn-an/nutrition/reference/table/index-eng.php - rvm>.

Helge, JW 2002, 'Long-term fat diet adaptation effects on performance, training capacity, and fat utilization', *Med Sci Sports Exerc*, vol. 34, no. 9, pp. 1499-504.

Helms, ER, Zinn, C, Rowlands, DS & Brown, SR 2014, 'A systematic review of dietary protein during caloric restriction in resistance trained lean athletes: a case for higher intakes', *Int J Sport Nutr Exerc Metab*, vol. 24, no. 2, pp. 127-38.

Henderson, B, Cook, J, Kidgell, DJ & Gastin, PB 2015, 'Game and Training Load Differences in Elite Junior Australian Football', *J Sports Sci Med*, vol. 14, no. 3, pp. 494-500.

Higham, DG, Pyne, DB, Anson, JM, Dziedzic, CE & Slater, GJ 2014, 'Distribution of fat, non-osseous lean and bone mineral mass in international Rugby Union and Rugby Sevens players', *Int J Sports Med*, vol. 35, no. 7, pp. 575-82.

Higham, DG, Pyne, DB, Anson, JM & Eddy, A 2013, 'Physiological, anthropometric, and performance characteristics of rugby sevens players', *Int J Sports Physiol Perform*, vol. 8, no. 1, pp. 19-27.

Hill, RJ & Davies, PS 2001, 'The validity of self-reported energy intake as determined using the doubly labelled water technique', *Br J Nutr*, vol. 85, no. 4, pp. 415-30.

Hoare, DG 2000, 'Predicting success in junior elite basketball players--the contribution of anthropometic and physiological attributes', *J Sci Med Sport*, vol. 3, no. 4, pp. 391-405.

Hogberg, P 1952, 'How do stride length and stride frequency influence the energy-output during running?', *Arbeitsphysiologie*, vol. 14, no. 6, pp. 437-41.

Holway, FE & Spriet, LL 2011, 'Sport-specific nutrition: practical strategies for team sports', *J Sports Sci*, vol. 29 Suppl 1, pp. S115-25.

Howarth, KR, Moreau, NA, Phillips, SM & Gibala, MJ 2009, 'Coingestion of protein with carbohydrate during recovery from endurance exercise stimulates skeletal muscle protein synthesis in humans', *J Appl Physiol (1985)*, vol. 106, no. 4, pp. 1394-402.

Ivy, JL, Lee, MC, Brozinick, JT, Jr. & Reed, MJ 1988, 'Muscle glycogen storage after different amounts of carbohydrate ingestion', *J Appl Physiol (1985)*, vol. 65, no. 5, pp. 2018-23.

Jentjens, RL, Wagenmakers, AJ & Jeukendrup, AE 2002, 'Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise', *J Appl Physiol (1985)*, vol. 92, no. 4, pp. 1562-72.

Jequier, E & Tappy, L 1999, 'Regulation of body weight in humans', *Physiol Rev*, vol. 79, no. 2, pp. 451-80.

Jeukendrup, AE 2010, 'Carbohydrate and exercise performance: the role of multiple transportable carbohydrates', *Curr Opin Clin Nutr Metab Care*, vol. 13, no. 4, pp. 452-7.

Jeukendrup, AE 2014, 'A step towards personalized sports nutrition: carbohydrate intake during exercise', *Sports Med*, vol. 44 Suppl 1, pp. S25-33.

Jeukendrup, AE & Chambers, ES 2010, 'Oral carbohydrate sensing and exercise performance', *Curr Opin Clin Nutr Metab Care*, vol. 13, no. 4, pp. 447-51.

Jones, PJ & Leitch, CA 1993, 'Validation of doubly labeled water for measurement of caloric expenditure in collegiate swimmers', *J Appl Physiol (1985)*, vol. 74, no. 6, pp. 2909-14.

Kagan, EM, P., D, Kaplan, PM, Linetzkaja, CO, Lubarsky, JL, Neuman, MF, Semernin, JJ, Starch, JS & Spilberg, P 1928, 'Physiologische Vergleichsuntersuchung der Hand- und Fleiss-(conveyer) Arbeiten.', *Arch. Hyg.*, vol. 100, p. 30.

Kempton, T, Sirotic, AC, Rampinini, E & Coutts, AJ 2015, 'Metabolic power demands of rugby league match play', *Int J Sports Physiol Perform*, vol. 10, no. 1, pp. 23-8.

Keogh, J 1999, 'The use of physical fitness scores and anthropometric data to predict selection in an elite under 18 Australian rules football team', *J Sci Med Sport*, vol. 2, no. 2, pp. 125-33.

Kerr, DA, Ackland, TR & Schreiner, AB 1995, 'The elite athlete - assessing body shape, size, proportion and composition', *Asia Pac J Clin Nutr*, vol. 4, no. 1, pp. 25-9.

Kimber, NE, Ross, JJ, Mason, SL & Speedy, DB 2002, 'Energy balance during an ironman triathlon in male and female triathletes', *Int J Sport Nutr Exerc Metab*, vol. 12, no. 1, pp. 47-62.

Konopka, AR & Harber, MP 2014, 'Skeletal muscle hypertrophy after aerobic exercise training', *Exerc Sport Sci Rev*, vol. 42, no. 2, pp. 53-61.

Krishnan, S & Cooper, JA 2014, 'Effect of dietary fatty acid composition on substrate utilization and body weight maintenance in humans', *Eur J Nutr*, vol. 53, no. 3, pp. 691-710.

Lavoisier, AL 1780, 'Mémoire sur la chaleur', *Mémoires de l'Académie des sciences*, pp. 283–333.

Leibel, RL, Rosenbaum, M & Hirsch, J 1995, 'Changes in energy expenditure resulting from altered body weight', *N Engl J Med*, vol. 332, no. 10, pp. 621-8.

Leonard, WR 2012, 'Laboratory and field methods for measuring human energy expenditure', *Am J Hum Biol*, vol. 24, no. 3, pp. 372-84.

Levine, JA 2004, 'Non-exercise activity thermogenesis (NEAT)', *Nutr Rev*, vol. 62, no. 7 Pt 2, pp. S82-97.

Levine, JA 2005, 'Measurement of energy expenditure', *Public Health Nutr*, vol. 8, no. 7A, pp. 1123-32.

Levine, JA, Schleusner, SJ & Jensen, MD 2000, 'Energy expenditure of nonexercise activity', *Am J Clin Nutr*, vol. 72, no. 6, pp. 1451-4.

Leyton, RNA 1948, 'Some practical aspects of the nutrition for athletes', *Brit J Nutr*, vol. 2, no. 3, p. 3.

Lima, F, De Falco, V, Baima, J, Carazzato, JG & Pereira, RM 2001, 'Effect of impact load and active load on bone metabolism and body composition of adolescent athletes', *Med Sci Sports Exerc*, vol. 33, no. 8, pp. 1318-23.

Longland, TM, Oikawa, SY, Mitchell, CJ, Devries, MC & Phillips, SM 2016, 'Higher compared with lower dietary protein during an energy deficit combined with intense exercise promotes greater lean mass gain and fat mass loss: a randomized trial', *Am J Clin Nutr*, vol. 103, no. 3, pp. 738-46.

Loucks, AB 2004, 'Energy balance and body composition in sports and exercise', *J Sports Sci*, vol. 22, no. 1, pp. 1-14.

Loucks, AB, Kiens, B & Wright, HH 2011, 'Energy availability in athletes', *J Sports Sci*, vol. 29 Suppl 1, pp. S7-15.

Lundy, B, O'Connor, H, Pelly, F & Caterson, I 2006, 'Anthropometric characteristics and competition dietary intakes of professional rugby league players', *Int J Sport Nutr Exerc Metab*, vol. 16, no. 2, pp. 199-213.

Magkos, F & Yannakoulia, M 2003, 'Methodology of dietary assessment in athletes: concepts and pitfalls', *Curr Opin Clin Nutr Metab Care*, vol. 6, no. 5, pp. 539-49.

Malavolti, M, Pietrobelli, A, Dugoni, M, Poli, M, Romagnoli, E, De Cristofaro, P & Battistini, NC 2007, 'A new device for measuring resting energy expenditure (REE) in healthy subjects', *Nutr Metab Cardiovasc Dis*, vol. 17, no. 5, pp. 338-43.

Malina, RM 2004, *Growth, Maturation and Physical Activity*, 2nd ed. edn, Human Kinetics, Champaign, Ill.

Malina, RM 2005, 'Variation in body composition associated with sex and ethnicity', in SB Heymsfield, TG Lohman, ZM Wang & SB Going (eds), *Human Body Composition*, Human Kinetics, Champaign, IL, pp. 271-98.

Malina, RM, Bouchard, C & Bar-Or, O 2004, *Growth, Maturation and Physical Activity (2nd ed,)*, Human Kinetics, Champaign, IL.

Malina, RM & Geithner, CA 2011, 'Body composition of young athletes', *American Journal of Lifestyle Medicine*, vol. May/June, p. 17.

Manore, M & Thompon, J 2007, 'Energy requirements of the athlete: assessment and evidence of energy efficiency', in L Burke & V Deakin (eds), *Clinical Sports Nutrition*, Third edn, McGraw-Hill Australia, Australia, pp. 113-34.

Mara, JK, Thompson, KG & Pumpa, KL 2015, 'Assessing the Energy Expenditure of Elite Female Soccer Players: A Preliminary Study', *J Strength Cond Res*, vol. 29, no. 10, pp. 2780-6.

Marfell-Jones, M, Olds, T, Stewart, A & Carter, JE 2006, 'International Standards for Anthropomtric Assessment', *Int Soc Advan Kinanthr*, pp. 1-137.

Matthys, SP, Vaeyens, R, Coelho, ESMJ, Lenoir, M & Philippaerts, R 2012, 'The contribution of growth and maturation in the functional capacity and skill performance of male adolescent handball players', *Int J Sports Med*, vol. 33, no. 7, pp. 543-9.

Mayer, JR 1848, 'Celestial Dynamics', in BL Lindsay (ed.), *Julius Robert Mayer, prophet of energy*, Pergamon Press, Oxford, p. 238.

McArdle, WD, Katch, FI & Katch, VL 2001, *Exercise Physiology: Energy, Nutrition and Human Perfromance*, 5 edn, Lippincott Williams and Wilkins, Maryland.

McIntyre, MC 2005, 'A comparison of the physiological profiles of elite Gaelic footballers, hurlers, and soccer players', *Br J Sports Med*, vol. 39, no. 7, pp. 437-9.

Meir, R 1994, 'A model for the integration of macrocyle and microcycle structure in professional rugby league ', *Strength Cond Coach*, vol. 2, p. 6.

Melville, L-C 1910, 'Discussion on food requirements for sustenance and work', *Bri Med J*, vol. 2, no. 2600, p. 4.

Mertz, W, Tsui, JC, Judd, JT, Reiser, S, Hallfrisch, J, Morris, ER, Steele, PD & Lashley, E 1991, 'What are people really eating? The relation between energy intake derived from estimated diet records and intake determined to maintain body weight', *Am J Clin Nutr*, vol. 54, no. 2, pp. 291-5.

Mettler, S, Mitchell, N & Tipton, KD 2010, 'Increased protein intake reduces lean body mass loss during weight loss in athletes', *Med Sci Sports Exerc*, vol. 42, no. 2, pp. 326-37.

Milanese, C, Cavedon, V, Corradini, G, De Vita, F & Zancanaro, C 2015, 'Seasonal DXA-measured body composition changes in professional male soccer players', *J Sports Sci*, vol. 33, no. 12, pp. 1219-28.

Mitchell, JA, Pumpa, KL, Williams, KJ & Pyne, DB 2016, 'Variable Changes in Body Composition, Strength and Lower-Body Power During an International Rugby Sevens Season', *J Strength Cond Res*, vol. 30, no. 4, pp. 1127-36.

Mole, PA 1990, 'Impact of energy intake and exercise on resting metabolic rate', *Sports Med*, vol. 10, no. 2, pp. 72-87.

Montgomery, E 1978, 'Towards representative energy data: the Machiguenga study', *Fed Proc*, vol. 37, no. 1, pp. 61-4.

Moore, DR, Robinson, MJ, Fry, JL, Tang, JE, Glover, EI, Wilkinson, SB, Prior, T, Tarnopolsky, MA & Phillips, SM 2009, 'Ingested protein dose response of muscle and albumin protein synthesis after resistance exercise in young men', *Am J Clin Nutr*, vol. 89, no. 1, pp. 161-8.

Moreira, A, Bilsborough, JC, Sullivan, CJ, Ciancosi, M, Aoki, MS & Coutts, AJ 2015, 'Training Periodization of Professional Australian Football Players During an Entire Australian Football League Season', *Int J Sports Physiol Perform*, vol. 10, no. 5, pp. 566-71.

Morel, J, Combe, B, Francisco, J & Bernard, J 2001, 'Bone mineral density of 704 amateur sportsmen involved in different physical activities', *Osteoporos Int*, vol. 12, no. 2, pp. 152-7.

Morris, FL & Payne, WR 1996, 'Seasonal variations in the body composition of lightweight rowers', *Br J Sports Med*, vol. 30, no. 4, pp. 301-4.

Morris, JN, Heady, JA, Raffle, PA, Roberts, CG & Parks, JW 1953, 'Coronary heart-disease and physical activity of work', *Lancet*, vol. 265, no. 6796, pp. 1111-20; concl.

Motonaga, K, Yoshida, S, Yamagami, F, Kawano, T & Takeda, E 2006, 'Estimation of total daily energy expenditure and its components by monitoring the heart rate of Japanese endurance athletes', *J Nutr Sci Vitaminol (Tokyo)*, vol. 52, no. 5, pp. 360-7.

Mountjoy, M, Sundgot-Borgen, J, Burke, L, Carter, S, Constantini, N, Lebrun, C, Meyer, N, Sherman, R, Steffen, K, Budgett, R & Ljungqvist, A 2014, 'The IOC consensus statement: beyond the Female Athlete Triad--Relative Energy Deficiency in Sport (RED-S)', *Br J Sports Med*, vol. 48, no. 7, pp. 491-7.

Mujika, I & Burke, LM 2010, 'Nutrition in team sports', *Ann Nutr Metab*, vol. 57 Suppl 2, pp. 26-35.

Nana, A, Slater, GJ, Hopkins, WG & Burke, LM 2012a, 'Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people', *Med Sci Sports Exerc*, vol. 44, no. 1, pp. 180-9.

Nana, A, Slater, GJ, Hopkins, WG & Burke, LM 2012b, 'Techniques for undertaking dual-energy X-ray absorptiometry whole-body scans to estimate body composition in tall and/or broad subjects', *Int J Sport Nutr Exerc Metab*, vol. 22, no. 5, pp. 313-22.

Nana, A, Slater, GJ, Hopkins, WG & Burke, LM 2013, 'Effects of exercise sessions on DXA measurements of body composition in active people', *Med Sci Sports Exerc*, vol. 45, no. 1, pp. 178-85.

Nana, A, Slater, GJ, Stewart, AD & Burke, LM 2015, 'Methodology Review: Using Dual-Energy X-Ray Absorptiometry (DXA) for the Assessment of Body Composition in Athletes and Active People', *Int J Sport Nutr Exerc Metab*, vol. 25, no. 2, pp. 198-215.

Nana, A, Slater, GR, Hopkins, WG & Burke, LM 2011, 'Effects of daily activities on DXA measurments of body composition in active people', *Medicine And Science In Sports And Exercise*, vol. E-Pub.

DoHa Aging 2006, *Nutrient Reference Values For Australia and New Zealand*, by National Health and Medical Research Council, Commonwealth of Australia.

Naughton, G, Farpour-Lambert, NJ, Carlson, J, Bradney, M & Van Praagh, E 2000, 'Physiological issues surrounding the performance of adolescent athletes', *Sports Med*, vol. 30, no. 5, pp. 309-25.

Nicholas, CW 1997, 'Anthropometric and physiological characteristics of rugby union football players', *Sports Med*, vol. 23, no. 6, pp. 375-96.

Nichols, J, Ross, S & Patterson, P 1988, 'Thermic effect of food at rest and following swim exercise in trained college men and women', *Ann Nutr Metab*, vol. 32, no. 4, pp. 215-9.

Nordstrom, P, Pettersson, U & Lorentzon, R 1998, 'Type of physical activity, muscle strength, and pubertal stage as determinants of bone mineral density and bone area in adolescent boys', *J Bone Miner Res*, vol. 13, no. 7, pp. 1141-8.

Norton, K, Craig, NP & Olds, TS 1999, 'The evolution of Australian football', *J Sci Med Sport*, vol. 2, no. 4, pp. 389-404.

Norton, K & Olds, TS 2001, 'Morphological evolution of athletes over the 20th century: causes and consequences', *Sports Med*, vol. 31, no. 11, pp. 763-83.

Novas, AM, Rowbottom, DG & Jenkins, DG 2003, 'A practical method of estimating energy expenditure during tennis play', *J Sci Med Sport*, vol. 6, no. 1, pp. 40-50.

Olds, T 2001, 'The evolution of physique in male rugby union players in the twentieth century', *J Sports Sci*, vol. 19, no. 4, pp. 253-62.

Oppliger, RA & Bartok, C 2002, 'Hydration testing of athletes', *Sports Med*, vol. 32, no. 15, pp. 959-71.

Oppliger, RA, Case, HS, Horswill, CA, Landry, GL & Shelter, AC 1996, 'American College of Sports Medicine position stand. Weight loss in wrestlers', *Med Sci Sports Exerc*, vol. 28, no. 6, pp. ix-xii.

Osgnach, C, Poser, S, Bernardini, R, Rinaldo, R & di Prampero, PE 2010, 'Energy cost and metabolic power in elite soccer: a new match analysis approach', *Med Sci Sports Exerc*, vol. 42, no. 1, pp. 170-8.

Ostojic, SM 2003, 'Seasonal alterations in body composition and sprint performance of elite soccer players', *J Exerc Physiol Online*, vol. 6, no. 3, p. 3.

Passmore, R & Durnin, JVGA 1955, 'Human Energy Expenditure', *Physiol Rev*, vol. 35, no. 4, p. 39.

Pearson, DT, Naughton, GA & Torode, M 2006, 'Predictability of physiological testing and the role of maturation in talent identification for adolescent team sports', *J Sci Med Sport*, vol. 9, no. 4, pp. 277-87.

Pettenkofer, MV & Voit, C 1866, 'Untersuchungen über den Stoffwechselverbrauch des normalen Menschen', *Z Biol*, vol. 2, pp. 459-573.

Phillips, SM 2004, 'Protein requirements and supplementation in strength sports', *Nutrition*, vol. 20, no. 7-8, pp. 689-95.

Phillips, SM 2012, 'Dietary protein requirements and adaptive advantages in athletes', *Br J Nutr*, vol. 108 Suppl 2, pp. S158-67.

Phillips, SM 2014, 'A brief review of higher dietary protein diets in weight loss: a focus on athletes', *Sports Med*, vol. 44 Suppl 2, pp. S149-53.

Phillips, SM, Tipton, KD, Aarsland, A, Wolf, SE & Wolfe, RR 1997, 'Mixed muscle protein synthesis and breakdown after resistance exercise in humans', *Am J Physiol*, vol. 273, no. 1 Pt 1, pp. E99-107.

Phillips, SM & Van Loon, LJ 2011, 'Dietary protein for athletes: from requirements to optimum adaptation', *J Sports Sci*, vol. 29 Suppl 1, pp. S29-38.

Plasqui, G, Bonomi, AG & Westerterp, KR 2013, 'Daily physical activity assessment with accelerometers: new insights and validation studies', *Obes Rev*, vol. 14, no. 6, pp. 451-62.

Plasqui, G, Joosen, AM, Kester, AD, Goris, AH & Westerterp, KR 2005, 'Measuring free-living energy expenditure and physical activity with triaxial accelerometry', *Obes Res*, vol. 13, no. 8, pp. 1363-9.

Plasqui, G & Westerterp, KR 2007, 'Physical activity assessment with accelerometers: an evaluation against doubly labeled water', *Obesity (Silver Spring)*, vol. 15, no. 10, pp. 2371-9.

'Position of Dietitians of Canada, the American Dietetic Association, and the American College of Sports Medicine: Nutrition and Athletic Performance', 2000, *Can J Diet Pract Res*, vol. 61, no. 4, pp. 176-92.

Pumpa, KL, Murphy, J, Corish, CA & Wood Martin, RE 2012, 'Anthropometric and body composition analysis: the comparsion between different positions and competition levels of successful rugby union players', *Int J Body Comp Res*, vol. 10, no. 4, pp. 115-21.

Pyne, DB, Gardner, AS, Sheehan, K & Hopkins, WG 2005, 'Fitness testing and career progression in AFL football', *J Sci Med Sport*, vol. 8, no. 3, pp. 321-32.

Pyne, DB, Gardner, AS, Sheehan, K & Hopkins, WG 2006, 'Positional differences in fitness and anthropometric characteristics in Australian football', *J Sci Med Sport*, vol. 9, no. 1-2, pp. 143-50.

Quarrie, KL & Wilson, BD 2000, 'Force production in the rugby union scrum', *J Sports Sci*, vol. 18, no. 4, pp. 237-46.

Rankin, JW 2002, 'Weight loss and gain in athletes', *Curr Sports Med Rep*, vol. 1, no. 4, pp. 208-13.

Rankin, JW 2006, 'Making weight in sports', in L Burke & V Deakin (eds), *Clinical Sports Nutrition* McGraw Hill Australia Pty Ltd, Australia, pp. 175-99.

Raysmith, BP & Drew, MK 2016, 'Performance sucess or failure is influenced by weeks lost to injury and illness in elite Australian track and field athletes: A 5-year prospective study', *J Sci Med Sport*.

Reeve, MD, Pumpa, KL & Ball, N 2013, 'Accuracy of the SenseWear Armband Mini and the BodyMedia FIT in resistance training.', *J Sci Med Sport*, p. 5.

Reeves, S & Collins, K 2003, 'The nutritional and anthropometric status of Gaelic football players', *Int J Sport Nutr Exerc Metab*, vol. 13, no. 4, pp. 539-48.

Reilly, T, Bangsbo, J & Franks, A 2000, 'Anthropometric and physiological predispositions for elite soccer', *J Sports Sci*, vol. 18, no. 9, pp. 669-83.

Reilly, T, Williams, AM, Nevill, A & Franks, A 2000, 'A multidisciplinary approach to talent identification in soccer', *J Sports Sci*, vol. 18, no. 9, pp. 695-702.

Res, PT, Groen, B, Pennings, B, Beelen, M, Wallis, GA, Gijsen, AP, Senden, JM & LJ, VANL 2012, 'Protein ingestion before sleep improves postexercise overnight recovery', *Med Sci Sports Exerc*, vol. 44, no. 8, pp. 1560-9.

Riley, PO, Dicharry, J, Franz, J, Della Croce, U, Wilder, RP & Kerrigan, DC 2008, 'A kinematics and kinetic comparison of overground and treadmill running', *Med Sci Sports Exerc*, vol. 40, no. 6, pp. 1093-100.

Robertson, S, Woods, C & Gastin, P 2015, 'Predicting higher selection in elite junior Australian Rules football: The influence of physical performance and anthropometric attributes', *J Sci Med Sport*, vol. 18, no. 5, pp. 601-6.

Rodriguez FA, IX (ed.) 1998, *The energy cost of Soccer: Telemetric oxygen uptake measurements versus heart rate- VO2 estimations*, vol. 15, J Sports Sci.

Rodriguez, NR, Di Marco, NM & Langley, S 2009, 'American College of Sports Medicine position stand. Nutrition and athletic performance', *Med Sci Sports Exerc*, vol. 41, no. 3, pp. 709-31.

Rodriguez, NR, DiMarco, NM, Langley, S, American Dietetic, A, Dietitians of, C, American College of Sports Medicine, N & Athletic, P 2009, 'Position of the American Dietetic Association, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance', *J Am Diet Assoc*, vol. 109, no. 3, pp. 509-27.

Rogol, AD, Clark, PA & Roemmich, JN 2000, 'Growth and pubertal development in children and adolescents: effects of diet and physical activity', *Am J Clin Nutr*, vol. 72, no. 2 Suppl, pp. 521S-8S.

Rolls, BJ, Bell, EA & Thorwart, ML 1999, 'Water incorporated into a food but not served with a food decreases energy intake in lean women', *Am J Clin Nutr*, vol. 70, no. 4, pp. 448-55.

Rosenbloom, C 2014, 'Popular Diets and Athletes: Premises, Promises, Pros, and Pitfalls of Diets and What Athletes Should Know About Diets and Sports Performance', *Nutrition Today*, vol. 49, no. 5, pp. 244 - 8.

Rubner, M 1885a, 'Calorimetrische Untersuchungen I', *Ztschrft der Biologie*, vol. 21, pp. 250-334.

Rubner, M 1885b, 'Calorimetrische Untersuchungen II', *Ztschr der Biologie*, vol. 21, pp. 337-410.

Rutishauser, IH 2005, 'Dietary intake measurements', *Public Health Nutr*, vol. 8, no. 7A, pp. 1100-7.

Ryder, JaB, SD 2012, 'Three-dimensional body scanning as a novel technique for body composition assessment: A preliminary investigation', *J Exerc Physiol Online*, vol. 15, no. 1.

Saltzman, E & Roberts, SB 1995, 'The role of energy expenditure in energy regulation: findings from a decade of research', *Nutr Rev*, vol. 53, no. 8, pp. 209-20.

Santos, DA, Dawson, JA, Matias, CN, Rocha, PM, Minderico, CS, Allison, DB, Sardinha, LB & Silva, AM 2014, 'Reference values for body composition and anthropometric measurements in athletes', *PLoS One*, vol. 9, no. 5, p. e97846.

Schoeller, DA & van Santen, E 1982, 'Measurement of energy expenditure in humans by doubly labeled water method', *J Appl Physiol Respir Environ Exerc Physiol*, vol. 53, no. 4, pp. 955-9.

Schokman, CP, Rutishauser, IH & Wallace, RJ 1999, 'Pre- and postgame macronutrient intake of a group of elite Australian football players', *Int J Sport Nutr*, vol. 9, no. 1, pp. 60-9.

Schranz, N, Tomkinson, G, Olds, T & Daniell, N 2010, 'Three-dimensional anthropometric analysis: differences between elite Australian rowers and the general population', *J Sports Sci*, vol. 28, no. 5, pp. 459-69.

Scott, CB 2005, 'Contribution of anaerobic energy expenditure to whole body thermogenesis', *Nutr Metab (Lond)*, vol. 2, no. 1, p. 14.

Seale, JL & Rumpler, WV 1997, 'Comparison of energy expenditure measurements by diet records, energy intake balance, doubly labeled water and room calorimetry', *Eur J Clin Nutr*, vol. 51, no. 12, pp. 856-63.

Sedeaud, A, Marc, A, Schipman, J, Tafflet, M, Hager, JP & Toussaint, JF 2012, 'How they won Rugby World Cup through height, mass and collective experience', *Br J Sports Med*, vol. 46, no. 8, pp. 580-4.

Siders, WA, Lukaski, HC & Bolonchuk, WW 1993, 'Relationships among swimming performance, body composition and somatotype in competitive collegiate swimmers', *J Sports Med Phys Fitness*, vol. 33, no. 2, pp. 166-71.

Silvestre, R, Kraemer, WJ, West, C, Judelson, DA, Spiering, BA, Vingren, JL, Hatfield, DL, Anderson, JM & Maresh, CM 2006, 'Body composition and physical performance during a National Collegiate Athletic Association Division I men's soccer season', *J Strength Cond Res*, vol. 20, no. 4, pp. 962-70.

Slater, GJ, Rice, AJ, Mujika, I, Hahn, AG, Sharpe, K & Jenkins, DG 2005, 'Physique traits of lightweight rowers and their relationship to competitive success', *Br J Sports Med*, vol. 39, no. 10, pp. 736-41.

Smith, JW, Zachwieja, JJ, Peronnet, F, Passe, DH, Massicotte, D, Lavoie, C & Pascoe, DD 2010, 'Fuel selection and cycling endurance performance with ingestion of [13C]glucose: evidence for a carbohydrate dose response', *J Appl Physiol (1985)*, vol. 108, no. 6, pp. 1520-9.

Sparti, A, DeLany, JP, de la Bretonne, JA, Sander, GE & Bray, GA 1997, 'Relationship between resting metabolic rate and the composition of the fat-free mass', *Metabolism*, vol. 46, no. 10, pp. 1225-30.

Speakman, JR & Selman, C 2003, 'Physical activity and resting metabolic rate', *Proc Nutr Soc*, vol. 62, no. 3, pp. 621-34.

Sporis, G, Jukic, I, Ostojic, SM & Milanovic, D 2009, 'Fitness profiling in soccer: physical and physiologic characteristics of elite players', *J Strength Cond Res*, vol. 23, no. 7, pp. 1947-53.

St-Onge, M, Mignault, D, Allison, DB & Rabasa-Lhoret, R 2007, 'Evaluation of a portable device to measure daily energy expenditure in free-living adults', *Am J Clin Nutr*, vol. 85, no. 3, pp. 742-9.

Steen, SN, Oppliger, RA & Brownell, KD 1988, 'Metabolic effects of repeated weight loss and regain in adolescent wrestlers', *JAMA*, vol. 260, no. 1, pp. 47-50.

Stellingwerff, T 2015, *Nutrition and body composition periodisation for elite athletes*, Dietitians of Canada, viewed 11 May 2016 2016, <http://www.dietitians.ca/Downloads/Public/Readings/Nutr-and-Body-Comp.aspx>.

Stellingwerff, T, Boit, MK, Res, PT & International Association of Athletics, F 2007, 'Nutritional strategies to optimize training and racing in middle-distance athletes', *J Sports Sci*, vol. 25 Suppl 1, pp. S17-28.

Stellingwerff, T, Boon, H, Jonkers, RA, Senden, JM, Spriet, LL, Koopman, R & van Loon, LJ 2007, 'Significant intramyocellular lipid use during prolonged cycling in endurance-trained males as assessed by three different methodologies', *Am J Physiol Endocrinol Metab*, vol. 292, no. 6, pp. E1715-23.

Stellingwerff, T, Maughan, RJ & Burke, LM 2011, 'Nutrition for power sports: middle-distance running, track cycling, rowing, canoeing/kayaking, and swimming', *J Sports Sci*, vol. 29 Suppl 1, pp. S79-89.

Stewart, A, Marfell-Jones, M, Olds, T & de Ridder, H 2011, *International Standards for Anthropometric Assessment*, vol. 3, 3 vols., The International Society for the Advancement of Kinanthropometry, New Zealand.

Stolen, T, Chamari, K, Castagna, C & Wisloff, U 2005, 'Physiology of soccer: an update', *Sports Med*, vol. 35, no. 6, pp. 501-36.

Survey, NHaNE 2011-2012, 'Body Composition Procedures Manual', viewed 10 September 2015, <http://www.cdc.gov/nchs/data/nhanes/nhanes_11_12/Body_Composition_Procedures_Manual.pdf>.

Sutton, L, Scott, M, Wallace, J & Reilly, T 2009, 'Body composition of English Premier League soccer players: influence of playing position, international status, and ethnicity', *J Sports Sci*, vol. 27, no. 10, pp. 1019-26.

Swinburn, BA, Sacks, G, Lo, SK, Westerterp, KR, Rush, EC, Rosenbaum, M, Luke, A, Schoeller, DA, DeLany, JP, Butte, NF & Ravussin, E 2009, 'Estimating the changes in energy flux that characterize the rise in obesity prevalence', *Am J Clin Nutr*, vol. 89, no. 6, pp. 1723-8.

Tang, JE, Moore, DR, Kujbida, GW, Tarnopolsky, MA & Phillips, SM 2009, 'Ingestion of whey hydrolysate, casein, or soy protein isolate: effects on mixed muscle protein synthesis at rest and following resistance exercise in young men', *J Appl Physiol (1985)*, vol. 107, no. 3, pp. 987-92.

Tarnopolsky, MA 2006, 'Protein and amino acid needs for training and bulking up', in L Burke & V Deakin (eds), *Clinical Sports Nutrition*, Mc Graw Hill, Australia.

Thomas, DT, Erdman, KA & Burke, LM 2016, 'American College of Sports Medicine Joint Position Statement. Nutrition and Athletic Performance', *Med Sci Sports Exerc*, vol. 48, no. 3, pp. 543-68.

Thompson, J, Manore, MM & Skinner, JS 1993, 'Resting metabolic rate and thermic effect of a meal in low- and adequate-energy intake male endurance athletes', *Int J Sport Nutr*, vol. 3, no. 2, pp. 194-206.

Till, K, Cobley, S, O'Hara, J, Brightmore, A, Cooke, C & Chapman, C 2011, 'Using anthropometric and performance characteristics to predict selection in junior UK Rugby League players', *J Sci Med Sport*, vol. 14, no. 3, pp. 264-9.

Till, K, Cobley, S, Wattie, N, O'Hara, J, Cooke, C & Chapman, C 2010, 'The prevalence, influential factors and mechanisms of relative age effects in UK Rugby League', *Scand J Med Sci Sports*, vol. 20, no. 2, pp. 320-9.

Till, K, Jones, B, Emmonds, S, Tester, E, Fahey, J & Cooke, C 2014, 'Seasonal changes in anthropometric and physical characteristics within English academy rugby league players', *J Strength Cond Res*, vol. 28, no. 9, pp. 2689-96.

Tipton, KD, Ferrando, AA, Phillips, SM, Doyle, D, Jr. & Wolfe, RR 1999, 'Postexercise net protein synthesis in human muscle from orally administered amino acids', *Am J Physiol*, vol. 276, no. 4 Pt 1, pp. E628-34.

Tooley, E, Bitcon, M, Briggs, MA, West, DJ & Russell, M 2015, 'Estimates of energy intake and expenditure in professional rugby league players', *Int J Sport Sci Coach*, vol. 10, no. 2+3, p. 11.

UDoHaHSaUDo Agriculture December 2015, *2015 – 2020 Dietary Guidelines for Americans. 8th Ed.*, by US Dept of Health and Human Services, 8th Edition edn, US Dept of Health and Human Services, <http://health.gov/dietaryguidelines/2015/guidelines/>.

Vaeyens, R, Lenoir, M, Williams, AM & Philippaerts, RM 2008, 'Talent identification and development programmes in sport : current models and future directions', *Sports Med*, vol. 38, no. 9, pp. 703-14.

van Loon, LJ, Greenhaff, PL, Constantin-Teodosiu, D, Saris, WH & Wagenmakers, AJ 2001, 'The effects of increasing exercise intensity on muscle fuel utilisation in humans.', *Journal Physiology*, vol. 536, p. 9.

van Loon, LJ, Saris, WH, Kruijshoop, M & Wagenmakers, AJ 2000, 'Maximizing postexercise muscle glycogen synthesis: carbohydrate supplementation and the application of amino acid or protein hydrolysate mixtures', *Am J Clin Nutr*, vol. 72, no. 1, pp. 106-11.

Varley, MC, Gabbett, T & Aughey, RJ 2014, 'Activity profiles of professional soccer, rugby league and Australian football match play', *J Sports Sci*, vol. 32, no. 20, pp. 1858-66.

Veale, JP, Pearce, AJ, Buttifant, D & Carlson, JS 2010, 'Anthropometric profiling of elite junior and senior Australian football players', *Int J Sports Physiol Perform*, vol. 5, no. 4, pp. 509-20.

Veale, JP, Pearce, AJ & Carlson, JS 2007, 'Player movement patterns in an elite junior Australian rules football team: an exploratory study', *J Sports Sci Med*, vol. 6, no. 2, pp. 254-60.

Vogel, M 1933, 'Nutrition and Sport', *Deutsche Medizinische Wochenschrift*, vol. 59, p. 2.

Vogt, M, Puntschart, A, Howald, H, Mueller, B, Mannhart, C, Gfeller-Tuescher, L, Mullis, P & Hoppeler, H 2003, 'Effects of dietary fat on muscle substrates, metabolism, and performance in athletes', *Med Sci Sports Exerc*, vol. 35, no. 6, pp. 952-60.

Vogt, S, Heinrich, L, Schumacher, YO, Grosshauser, M, Blum, A, Konig, D, Berg, A & Schmid, A 2005, 'Energy intake and energy expenditure of elite cyclists during preseason training', *Int J Sports Med*, vol. 26, no. 8, pp. 701-6.

Voigt, G 1936, 'Work capacity without coffee and following coffee with and without caffeine.', *Deutsche Medizinische Wochenschrift*, vol. 62, p. 3.

Voit, C 1866, 'Untersuchungen űber die Ausscheidungswege der stickstoffhaltigen Zersetzungs-Produkte aus dem theirischen Organismus', *Ztschr der Biologie*, vol. 2, pp. 189-243.

Volek, JS, Sharman, MJ, Love, DM, Avery, NG, Gomez, AL, Scheett, TP & Kraemer, WJ 2002, 'Body composition and hormonal responses to a carbohydrate-restricted diet', *Metabolism*, vol. 51, no. 7, pp. 864-70.

Walker, EJ, McAinch, AJ, Sweeting, A & Aughey, RJ 2016, 'Inertial sensors to estimate the energy expenditure of team-sport athletes', *J Sci Med Sport*, vol. 19, no. 2, pp. 177-81.

Wang, J, Gallagher, D, Thornton, JC, Yu, W, Horlick, M & Pi-Sunyer, FX 2006, 'Validation of a 3-dimensional photonic scanner for the measurement of body volumes, dimensions, and percentage body fat', *Am J Clin Nutr*, vol. 83, no. 4, pp. 809-16.

Wank, V, Frick, U & Schmidtbleicher, D 1998, 'Kinematics and electromyography of lower limb muscles in overground and treadmill running', *Int J Sports Med*, vol. 19, no. 7, pp. 455-61.

Wehbe, GM, Hartwig, TB & Duncan, CS 2014, 'Movement analysis of Australian national league soccer players using global positioning system technology', *J Strength Cond Res*, vol. 28, no. 3, pp. 834-42.

Welle, S & Nair, KS 1990, 'Relationship of resting metabolic rate to body composition and protein turnover', *Am J Physiol*, vol. 258, no. 6 Pt 1, pp. E990-8.

Westerterp, KR 1999, 'Body composition, water turnover and energy turnover assessment with labelled water', *Proc Nutr Soc*, vol. 58, no. 4, pp. 945-51.

Westerterp, KR 2003, 'Impacts of vigorous and non-vigorous activity on daily energy expenditure', *Proc Nutr Soc*, vol. 62, no. 3, pp. 645-50.

Westerterp, KR 2008, 'Physical activity as determinant of daily energy expenditure', *Physiol Behav*, vol. 93, no. 4-5, pp. 1039-43.

Westerterp, KR 2009, 'Assessment of physical activity: a critical appraisal', *Eur J Appl Physiol*, vol. 105, no. 6, pp. 823-8.

Westerterp, KR, Saris, WH, van Es, M & ten Hoor, F 1986, 'Use of the doubly labeled water technique in humans during heavy sustained exercise', *J Appl Physiol (1985)*, vol. 61, no. 6, pp. 2162-7.

Westerterp, KR & Speakman, JR 2008, 'Physical activity energy expenditure has not declined since the 1980s and matches energy expenditures of wild mammals', *Int J Obes (Lond)*, vol. 32, no. 8, pp. 1256-63.

Westerterp-Plantenga, MS, Nieuwenhuizen, A, Tome, D, Soenen, S & Westerterp, KR 2009, 'Dietary protein, weight loss, and weight maintenance', *Annu Rev Nutr*, vol. 29, pp. 21-41.

Widdowson, EM 1962, 'Nutritional Individuality', *Proc Nutr Soc*, vol. 21, no. 2, pp. 121-8.

Wisbey, B, Montgomery, PG, Pyne, DB & Rattray, B 2010, 'Quantifying movement demands of AFL football using GPS tracking', *J Sci Med Sport*, vol. 13, no. 5, p. 5.

Wixted, AJ, Thiel, DV, Hahn, AG, Gore, CJ, Pyne, DB & James, DA 2007, 'Measurement of Energy Expenditure in Elite Athletes Using MEMS-Based Triaxial Accelerometers. ', *IEEE Sens J*, vol. 7, no. 4, p. 8.

Wojtaszewski, JF, Nielsen, P, Kiens, B & Richter, EA 2001, 'Regulation of glycogen synthase kinase-3 in human skeletal muscle: effects of food intake and bicycle exercise', *Diabetes*, vol. 50, no. 2, pp. 265-9.

Wright, DA, Sherman, WM & Dernbach, AR 1991, 'Carbohydrate feedings before, during, or in combination improve cycling endurance performance', *J Appl Physiol (1985)*, vol. 71, no. 3, pp. 1082-8.

Young, WB, Newton, RU, Doyle, TL, Chapman, D, Cormack, S, Stewart, G & Dawson, B 2005, 'Physiological and anthropometric characteristics of starters and non-starters and playing positions in elite Australian Rules Football: a case study', *J Sci Med Sport*, vol. 8, no. 3, pp. 333-45.

Young, WB & Pryor, L 2007, 'Relationship between pre-season anthropometric and fitness measures and indicators of playing performance in elite junior Australian Rules football', *J Sci Med Sport*, vol. 10, no. 2, pp. 110-8.

Zanetti, S, Pumpa, KL, Wheeler, KW & Pyne, DB 2014, 'Validity of the SenseWear Armband to Assess Energy Expenditure During Intermittent Exercise and Recovery in Rugby Union Players', *J Strength Cond Res*, vol. 28, no. 4, p. 5.

Zderic, TW, Davidson, CJ, Schenk, S, Byerley, LO & Coyle, EF 2004, 'High-fat diet elevates resting intramuscular triglyceride concentration and whole body lipolysis during exercise', *Am J Physiol Endocrinol Metab*, vol. 286, no. 2, pp. E217-25.

Zemski, AJ, Slater, GJ & Broad, EM 2015, 'Body composition characteristics of elite Australian rugby union athletes according to playing position and ethnicity', *J Sports Sci*, vol. 33, no. 9, pp. 970-8.

Zuntz, N & Leowy, A 1909, 'Lehrbuch der physiologie bes menschem', *Leipzig*.