Bone mineral density and body composition in high-performing cricket players; an exploratory study

A thesis presented in partial fulfilment of the requirements for the degree of

Master of Science

In

Nutrition and Dietetics

at Massey University, Albany

New Zealand

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2017

Abstract

Background/Aim: Cricket is a popular sport both in New Zealand, and internationally. Cricketers have a high prevalence of stress fractures, which may in part be linked to bone mineral density. However, little research exists investigating bone health in this group. The primary aim of this study was to investigate determinants of bone mineral density (BMD) in a group of high-performing cricketers. Secondary aims included measuring musculoskeletal differences in the dominant versus non-dominant arm, and monitoring pre and postseason body composition.

Methods: Healthy male (n=27) and female (n=11) cricketers aged 16-33y were recruited. BMD was measured using DXA, and body composition was measured pre and post-season using bioelectrical impedance analysis (BIA). Food frequency questionnaires (FFQ's) and a lifestyle & health questionnaire were completed. Determinants of BMD were tested using hierarchical multiple regression analysis. A dependent samples t-test was used to determine differences between dominant and non-dominant arms and changes in body composition over the season.

Results: Skeletal muscle mass was a significant predictor of BMD and accounted for 31, 18, and 38 percent of BMD variation at the hip, spine, and total body, respectively. Age and calcium intake did not predict BMD at any site. BMD and lean mass were significantly greater ($p<0.05$) in the dominant arms of both males (+0.056g/cm^2 and +308.4g) and females (+0.078g/cm^2 and +254.2g). A 0.8kg reduction in post-season skeletal muscle mass was found in females ($p<0.05$), with no differences found in males.

Conclusions: Skeletal muscle was the strongest predictor of BMD in this group, while age and calcium intake showed no effect. Significant differences in BMD and lean mass were observed between dominant and non-dominant arms. Skeletal muscle in males remained unchanged from beginning to end of season, and was reduced in females. Training methods in this group should target development and maintenance of muscle mass in order to optimise BMD.

Acknowledgements

I would like to express my gratitude to a number of people who made this project possible.

Firstly, a big thank you to every participant who gave up their time to take part in this study – without your contributions none of this could have taken place. Also to the coaching staff at Auckland cricket; Nick White, Andre Adams, and Elfriede Chooi, who helped facilitate initial data collection and follow-up sessions – your assistance is greatly appreciated.

To my supervisors, Dr Kathryn Beck and Dr Pamela von Hurst, I am extremely grateful for your support, encouragement, valuable feedback, and your honesty – not to mention the amount of time you both spent assisting in data collection and working behind the scenes.

To my fellow researcher Shelley McDonald, thank you for all of your hard work during the recruiting and data collection process, and assistance throughout the entire journey.

Thank you to Owen Mugridge and P.C Tong for your assistance with data entry and analysis.

Lastly, thank you to my family and friends for your continued support and encouragement throughout this experience.

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List of abbreviations

BIA: Bioelectrical Impedance Analysis

BMC: Bone Mineral Content

BMD: Bone Mineral Density

BMI: Body Mass Index

Cm: Centimetre

CSA: Cross-sectional area

DXA: Dual X-ray Absorptiometry

FFM: Fat Free Mass

FFQ: Food Frequency Questionnaire

GFR: Glomerular filtration rate

IGF-I: Insulin-Like Growth Factor-I

IU: International units

Kg: Kilogram

Mcg: Micrograms

Mg/dL: milligrams per decilitre

Nmol/L: Nanomol per litre

UcOC: Under-Carboxylated Osteocalcin

UVB: Ultraviolet B

NASA: National Aeronautics and Space Administration

RDI: Recommended Dietary Intake

SD: Standard Deviation

SMM: Skeletal muscle mass

P: p-value (statistical analysis)

PTH: Parathyroid hormone

UL: Tolerable Upper Intake level

µg: Microgram

Contributions to research

Researchers	Contributions to the thesis
Corey Payne	Main researcher, data collection, data entry, statistical analysis, interpretation and discussion of results
Shelley McDonald	Co-ordination of participant recruitment, DXA testing, data collection, participant liaison
Dr Kathryn Beck	Main academic supervisor, data collection, guidance with structure, content, and statistical analysis, questionnaire design, interpretation of results, editing and formatting
Dr Pamela von Hurst	Academic supervisor and assistance with statistical procedures and analysis, DXA testing, BMD expertise, interpretation of results, editing and formatting
Owen Mugridge	DXA testing, equipment calibration, data analysis
P.C Tong	DXA testing and analysis, equipment calibration, assistance with online questionnaires, data storage
Julie Knight	DXA testing

Chapter 1

Introduction

1.1 Background

Cricket is a game involving two teams of eleven players each, competing to try and score more runs than their opponent using a bat and ball. It is played on a flat piece of grass known as a 'pitch', and is primarily played in summer months, with the New Zealand cricket season spanning from the beginning of October, through to the end of March (Walker et al., 2010). It is one of the more popular sports in the world, and is played professionally in many different countries including India, England, South Africa, Australia, New Zealand, and Jamaica among others (Walker et al., 2010, Frost and Chalmers, 2014). It is considered one of the most popular team sports in New Zealand, with approximately 5.4% of people aged sixteen and over participating at some level (Haughey, 2015). For unknown reasons, research involving elite cricketers as a primary population group is scarce. As a result, despite its global popularity, little is known about the eating habits, lifestyle factors, and bone health of these athletes. What has been well-documented, is that cricketers of all levels, but specifically those playing at a high level, are susceptible to a high rate of injury (Frost and Chalmers, 2014). Among the most common types of injury are stress fractures, particularly of the spine and lower limb, which are more common in cricket than many other sports, including soccer (Gregory et al., 2004). A recent New Zealand study investigating elite cricketers found that stress injuries of the lower back contributed to the highest proportion of match days (22%) lost through injury (Frost and Chalmers, 2014).

Stress fractures are common lesions that typically occur due to increased muscular load on bones that are not adequately developed to deal with the increased force placed upon them (Daffner and Pavlov, 1992). Such injuries account for between 10% (Philipson and Parker, 2009) and 20% (Fredericson et al., 2006) of all sporting injuries. In cricket, these loading forces are experienced predominantly in fast bowlers who are required to sprint towards the pitch before jumping and landing on one foot in order to release the ball onto the pitch (Johnson et al., 2012). In addition to

the repetitive loading sustained during the bowling action, biomechanical aspects may also increase the risk of such injuries. Recent studies suggest that a 'mixed' bowling action – involving lumbar side flexion and counter-rotation of the shoulder coupled with ground reaction forces - is more likely to contribute to stress injury than either the traditional front-on or side-on approach (Johnson et al., 2012, Annear et al., 1992). Overuse is another factor likely to contribute to high injury prevalence in this population, with high bowling workload being associated with increased prevalence of stress injury in fast bowlers (Dennis et al., 2005, Johnson et al., 2012).

Although certain training and biomechanical aspects of cricket have been examined, there appears to be a need for a focus on other modifiable factors such as overall bone health relating to dietary and lifestyle factors. These components are important, as bone health is widely considered to play a major role in development of stress fractures (Bennell et al., 1999, Myburgh et al., 1990, Nattiv, 2000, Behrens et al., 2013), and general fractures (Karlsson et al., 2008, Marshall et al., 1996). Bone mineral density (BMD) may account for up to 55-80% in ultimate bone strength variation, and is therefore considered a major determinant of bone strength (Ammann and Rizzoli, 2003). With this in mind, it is important to investigate determinants of BMD in elite cricketers to determine whether they are likely to be optimising their bone health through a combination of diet and lifestyle factors, and therefore minimising their risk of fracture or stress fracture.

Several studies have demonstrated that increased body mass – particularly lean mass – generally corresponds with greater BMD at various sites (Gjesdal et al., 2008, Pietrobelli et al., 2002, Frost, 2000, Aloia et al., 1995). Cricketers are generally known to have a tall, lean body type, with greater lean mass than sedentary individuals (Micklesfield et al., 2012). It is unknown whether BMD in elite cricketers would benefit from the development of extra lean mass, although it has been shown that increased BMD can be expected in rugby players with greater lean mass (Elloumi et al., 2009). Furthermore, no studies have investigated changes in body composition of cricket players over the course of the season.

Increases in BMD as a result of greater lean mass are likely due to increased mechanical loading placed upon the skeleton, which trigger a greater degree of bone modelling and remodelling (Frost, 2001). This physiological adaptation contributes to enhanced bone strength, and may

therefore contribute to injury prevention. In vivo evidence of the benefits of mechanical loading on BMD has been demonstrated in both tennis and squash players, in which lean mass and BMD were shown to be greater in the dominant arms of these athletes (Kontulainen et al., 1999, Kontulainen et al., 2001, Ducher et al., 2005, Haapasalo et al., 1998, Calbet et al., 1998, Ducher et al., 2011, Kannus et al., 1995). A recent study also found this to be the case in the dominant (bowling) arms of elite cricketers, suggesting that muscular forces exerted on bone during the bowling action my be sufficient to trigger a site-specific osteogenic response (Lees et al., 2016). This adaptation is likely to enhance performance through bowling velocity, and possibly injury prevention (Lees et al., 2016). Although it is unknown whether these changes occur in non-bowlers, all players would likely benefit from this physiological response due to the fact that all players are required to throw the ball with speed and accuracy when fielding.

1.2 Purpose of the study

As BMD may be linked to high rates of stress fracture, this study aimed to obtain and understanding of determinants of BMD in high-performing cricket players. Identifying risk factors for low BMD among this group could allow for recommendations aimed at reducing injury rates, along with achieving and maintaining optimum long-term bone health, and hopefully a reduction in injury rates. This study also aimed to investigate musculoskeletal difference in dominant versus non-dominant arms, and determine whether any changes in body composition took place throughout the course of the season in high-performing cricket players.

1.3 Aim

To investigate the associations between diet, and other lifestyle factors with bone mineral density and body composition in high-performing cricketers.

1.4 Objectives

1. To investigate determinants of bone mineral density (BMD) in high-performing cricket players.

2. To analyse and compare muscle and bone content between dominant and non-dominant arms in high-performing cricket players.

3. To compare pre and post-season body composition (skeletal muscle mass, and fat mass) in high-performing cricket players.

1.5 Thesis structure

This thesis has been structured into six chapters. Chapter one introduces the concepts included in this study, and identifies the aims and objectives. Chapter two contains a review of the current literature of diet and lifestyle factors relating to BMD, with particular focus placed on athletic populations. Chapter three describes the methods used for data collection and analysis of dietary information. Chapter four contains the results of this study. This is followed by chapter five, which discusses the key findings of this study. To conclude, chapter six provides a brief summary, including strengths and limitations and recommendations for future research.

Chapter 2

Review of the literature

2.1 Determinants of bone mineral density

2.1.1 Background

Although some debate still exists, a growing number of experts agree that peak bone mass is attained during late adolescence, with a period of consolidation taking place in early adulthood (Zhu and Prince, 2012, Henry et al., 2004). Many factors contribute to bone mineral density and overall bone health, with heredity and genetics being a strong predictor of overall bone health (Bailey et al., 1996, Boot et al., 1997). Just as important are non-genetic determinants such as dietary and lifestyle factors, which may contribute to as much as half the variance in BMD (Bailey et al., 1996). Although adequate calcium intake has been well established as one of, if not the most important dietary component of bone health, it is now known that many other dietary factors also contribute to varying degrees. Emerging evidence confirms the importance of a well-rounded combination of dietary and lifestyle components in the development and maintenance of bone. A variety of micronutrients are now believed to play a role in bone health, although when compared with other important nutrients such as calcium and vitamin D, the evidence base is less well developed (Cashman, 2007).

The importance of achieving and maintaining optimal BMD can be explained by the link between BMD and fracture risk, as low BMD is associated with decreased bone strength (Bennell et al., 1999). BMD is considered a moderate independent risk factor for osteoporotic fracture risk, but increases substantially when combined with other factors such as occurrence of previous fracture (Cummings et al., 1995). In fact, BMD is generally considered to be the best predictor of eventual fracture (Bennell et al., 1999), and a meta-analysis of prospective cohort studies concluded that BMD can predict fracture risk in elderly populations (Marshall et al., 1996).

There also appears to be a clear relationship between BMD and stress fractures, although many factors are believed to play a part in such injuries (Bennell et al., 1999, Bennell and Brukner, 2005). Prevention of stress fractures likely involves optimizing peak bone mass in children and young adults, as well as maintaining adequate calcium intake (Nattiv, 2000, Behrens et al., 2013, Nieves et al., 2010). However, these studies are cross-sectional and therefore provide limited evidence indicating a causal relationship between BMD and stress fracture (Bennell et al., 1999). One such study in female track and field athletes found runners who had suffered a stress fracture had significantly lower BMD at the lumbar spine, foot, and tibia/fibula, than runners who did not sustain a stress fracture (Bennell et al., 1996). In regards to cricket, the relationship between BMD and fracture risk also warrants further investigation. Although cricketers are believed to be affected by stress fractures more than athletes in other sports, they have also been shown to have greater BMD than non-athletic controls by as much as thirteen percent (Micklesfield et al., 2012). This suggests that although BMD may play a role in risk of stress fractures, other factors such as biomechanics likely play an important role. Indeed, the extent to which BMD affects the risk of stress fracture remains inconclusive. With more information available regarding BMD and its determinants, the greater our understanding of the relationship between BMD and injury will become. When looking at the totality of the literature, it would appear that BMD is indeed predictive of fracture risk to some extent, although further research may provide a more comprehensive understanding of this relationship.

A review of the literature relating to nutrition and lifestyle factors and BMD will be detailed below. Although certain predictors of bone health including ethnicity, Vitamin D status, and disordered eating are beyond the scope of this study, they are discussed briefly to provide a comprehensive overview of bone health and its determinants.

2.1.2 Calcium

With 99% of the body's total calcium being stored in bone, calcium intake is considered one of the most modifiable factors of BMD (Tucker et al., 1999). It is associated with higher rates of bone mineral accretion in all ethnic groups (Zhu and Prince, 2012) and reduced rates of bone loss during adulthood (Cumming, 1990). Further, supplementation in children with low base-line intakes has

been shown to improve bone mineral content (Huncharek et al., 2008, Chan et al., 1995, Johnston Jr et al., 1992). It has been suggested that calcium supplements are less effectively absorbed in doses greater than 500mg meaning dietary calcium is crucial for optimal bone health (Zhu and Prince, 2012). Adequate calcium intake also reduces the risk of fracture and osteoporosis in later life through its influence on bone density and remodelling (Zhu and Prince, 2012, Bennell et al., 1999). There is some evidence to support low calcium intake as a risk factor for stress fractures, with a meta-analysis of 17 trials concluding that calcium supplementation of ≥1200mg was associated with a 10% reduction in fracture risk of all types (Tang et al., 2007). It should be noted that this study looked exclusively at men and women over the age of 50 years, and therefore does not consider bone mineral accrual during peak growth periods. It does, however, support the belief that stress fracture risk can be reduced through dietary measures.

Bone mineral density in children has been positively associated with calcium intake (Chan, 1991), with similar findings in the athletic population in a study by Wolman et al. (1992), who found a positive correlation between calcium intake and spinal BMD in female athletes aged 20-40 years (Wolman et al., 1992). This supports earlier research by Myburgh et al. (1990), who investigated 25 athletes with a stress fracture, compared with 25 controls. Mean calcium intake was found to be lower in the athlete group - 697mg/day versus 832mg/day, respectively. BMD was also found to be lower in the athlete group leading the researchers to conclude that high calcium intake may provide some protection against stress fractures (Myburgh et al., 1990).

Even with extensive research available to support the importance of a calcium-sufficient diet, there are still believed to be a number of population groups who fail to achieve recommended intakes (Cashman, 2002), and this is also thought to be the case across all age groups in New Zealand (Ministry of Health, 2010). Recent findings from the 2007/08 National Nutrition Survey estimate average daily intake of 919 mg for males, and 745 mg for females (Ministry of Health, 2010). This may also be the case for Vitamin D, another important nutrient associated with bone health, with a 2008 report finding 5% of adults experiencing vitamin D deficiency (serum Vitamin D levels of less than 25nmol/L), and a further 27% below the recommended level of 50nmol/L (Ministry of Health, 2012). When considering the overall impact of these two nutrients on bone

health, these findings suggest that as a whole, New Zealanders are not optimising their bone health through dietary measures, and those among athletic populations may be at similar risk.

Another interesting consideration when assessing optimal calcium intake for bone health, is the apparent response of bone to reach calcium saturation. Although adolescents require more calcium due to high rates of growth (1300mg), they may be unlikely to contribute to skeletal health by consuming calcium in quantities greater than 1500mg. Urinary calcium begins to rise more rapidly at this threshold, suggesting that calcium saturation has been reached, and no skeletal benefits will be seen with intakes greater than 1500mg per day (Matkovic and Heaney, 1992, Matkovic et al., 1995). The threshold for adults appears to be 1100mg (Matkovic and Heaney, 1992), which is still slightly higher than the recommended daily intake of 1000mg. It should also be noted that the requirements for athletes may be greater, and the maximal osteogenic effects of calcium in this group may only be seen with intakes of approximately 1400mg/day (Specker, 1996). Although athletes require replenishment of calcium and other electrolytes lost in sweat, it is currently unclear exactly how much of these losses are required through extra dietary calcium. Athletes should therefore aim for a diet containing adequate protein, fat, energy, vitamins and minerals, and fluids to successfully replenish physiologic losses as a result of training and competition (Kunstel, 2005). Amenorrheic female athletes are at particular risk of impaired bone formation and osteoporosis due to hormonal imbalances, which trigger reduced calcium absorption. For this reason, amenorrheic athletes of all ages are advised to consume 1500mg/day dietary calcium to prevent calcium deficits, and maintain bone health (Heaney, 2000, Kunstel, 2005).

2.1.3 Vitamin D:

The link between adequate vitamin D status and bone health is an area of considerable interest. There is a current consensus that vitamin D levels are strongly associated with bone health (Suda et al., 2003, St-Arnaud, 2008, Holick, 2004, Collins et al., 1998, Bikle, 2012). Although the extent to which these effects are achieved through direct or indirect action remains uncertain, both are clearly involved (Bikle, 2012). Prolonged Vitamin D deficiency, often combined with calcium

deficiency, can result in rickets in children, and osteomalacia in adults (Bikle, 2012, Holick, 2004), and is also likely to be a risk factor for bone loss and fractures (Bikle, 2012).

Vitamin D occurs naturally in foods in only small quantities. It can be found in foods such as egg yolk, fatty fish, and liver (Bikle, 2012, Holick, 2004). Due to its limited availability, various food products in New Zealand now have vitamin D added to them. These include some margarines and spreads, reduced-fat dairy products, soy drinks, and liquid meal replacements (Ministry of Health, 2012). Although there are few dietary sources of significant levels of Vitamin D, it can be synthesised biologically as a result of direct exposure to sunlight (Bikle, 2012, Holick et al., 2011, Glerup et al., 2000). It is believed that approximately 90% of the total requirement for vitamin D comes from exposure to sunlight (Holick, 2004). During exposure to direct sunlight, UVB radiation is absorbed by the skin and converted to an inactive precursor, before being transformed to its active form by a series of biochemical reactions in the liver, then the kidney before being released into the circulation (Holick, 2004). It then circulates in its active form, exerting its effects on the intestine, bone, and kidneys to achieve tight regulation of serum calcium to between 9-10 mg/dL (Suda et al., 2003).

Vitamin D exerts direct effects on bone by binding to vitamin D receptors present in bone tissue, and regulates the transcription of genes responsible for physiological actions, such as increasing calcium absorption and osteogenesis (St-Arnaud, 2008). As much as 30% total dietary calcium may be absorbed in a vitamin D-sufficient state, compared with 10-15% during vitamin D deficiency (Holick, 2004). In the presence of adequate vitamin D, more calcium is made available for muscle function and bone mineralisation, resulting in less resorption and mineral loss from bone (Bikle, 2012). Vitamin D also exerts indirect effects on bone by stimulating increased intestinal absorption of calcium, therefore promoting bone mineralisation indirectly (St-Arnaud, 2008, Bikle, 2012, Suda et al., 2003). In addition, adequate concentrations of serum vitamin D contribute to the maintenance of bone tissue by inhibiting bone mineral resorption, induced by parathyroid hormone (PTH) (Suda et al., 2003).

Although considerable debate remains regarding optimal levels of serum vitamin D, New Zealand recommendations currently sit at 50nmol/L, with levels <25nmol/L constituting a deficiency

(Ministry of Health, 2012). It has been suggested that this level may be insufficient to provide the full benefits for skeletal health. Several researchers investigating vitamin D are now encouraging serum levels of 70-80nmol/L to provide optimal intestinal calcium transport and bone health in the presence of adequate dietary calcium (Dawson-Hughes et al., 2005, Holick, 2004, Bikle, 2012). Findings from a recent meta-analysis suggest 70-80nmol/L may be required for fracture prevention, indicating optimal levels may in fact be higher than current recommendations (Bischoff-Ferrari et al., 2005). In order to reach a level of 75nmol/L, approximately 20-25mcg of vitamin D, or 800-1000 international units (IU) is required (Dawson-Hughes et al., 2005).

2.1.4 Protein:

Protein is one nutrient commonly believed to improve bone growth in children, teenagers, and adults (Nieves et al., 2010). Not all experts agree, and although research into the relationship between protein and bone health has been ongoing for 50 years, a clear consensus regarding optimal levels of protein intake for bone health has not been reached (Thorpe and Evans, 2011).

Bone tissue is extremely sensitive to its environment, and several studies have demonstrated increased acid production with a high protein diet, leading to an altered acid-base balance (Rizzoli and Bonjour, 2004, Thorpe and Evans, 2011). This is caused by the metabolism of sulphur-containing amino acids into sulphuric acid, and is likely to cause increased rates of bone mineral resorption (Thorpe and Evans, 2011, Dawson-Hughes, 2003). High protein intake has also been associated with increased urinary calcium excretion resulting in negative calcium balance (Ilich and Kerstetter, 2000, Rizzoli and Bonjour, 2004, Tucker, 2014), but this may be offset to some degree by increased calcium absorption (Dawson-Hughes, 2003). This increased rate of calcium excretion may be caused, in part by an elevated glomerular filtration rate (GFR) in the kidney, as seen with increased protein consumption (Thorpe and Evans, 2011). It is for these reasons that high-protein diets are considered by some to contribute to bone loss, and to be a risk factor for osteoporotic fractures (Rizzoli and Bonjour, 2004).

Not all studies point to high protein intake as being detrimental to bone health, and there is some literature to suggest that the potential negative effects of protein on bone are offset by increased

calcium absorption (Thorpe and Evans, 2011). High protein intake has been shown to correspond to increased IGF-1 (Insulin-like growth factor-1), which has an anabolic effect on bone (Rizzoli and Bonjour, 2004, Thorpe and Evans, 2011) and promotes mineralization of the bone matrix (Mangels, 2014). Protein may also exert its effects indirectly, by increasing lean mass, which in turn, improves bone strength (Thorpe and Evans, 2011). Lean mass and muscle strength are directly related to both fall and fracture risk among the elderly (Tucker, 2014). Recent findings from two epidemiologic trials found that higher protein intakes were associated with greater BMD and lower risk of fracture. One study observed changes in BMD in 800 elderly men and women over four years, and found bone loss to be lowest in participants with the highest protein intakes (Hannan et al., 2000a). These findings are supported by the Iowa Women's Health Study, which found increased incidence of hip fracture in post-menopausal women with low-protein diets (Munger et al., 1999), with similar effects being shown in elderly men (Hannan et al., 2000b). Similar findings in female cross-country runners found protein intake was related to increased total body bone mass and lower risk of stress fracture (Nieves et al., 2010). However, it should be noted that stress fracture risk was only reduced in women with irregular menstruation.

Despite various studies suggesting increased protein intake to be beneficial for bone health, most research appears to consistently support moderate protein intake for optimal bone health, and it is likely that bone health is only impacted when protein intake is inadequate (Dawson-Hughes, 2003). Such findings point to moderate protein intake of 1 - 1.5g/kg/day likely to be optimal for bone health (Cuenca-Sánchez et al., 2015, Ilich and Kerstetter, 2000), and although protein is important during skeletal growth and development, adequate protein intake is likely to be sufficient for maintaining optimal bone health. Daily intakes of approximately 1g/kg have minimal impact on calcium homeostasis (Ilich and Kerstetter, 2000). Furthermore, it has been suggested that the effects of protein intake on bone may only be favourable in those with adequate calcium intakes (Dawson-Hughes, 2003).

A recent meta-analysis may provide the best evidence for protein intake and bone health. Darling et al. (2009) analysed a number of cross-sectional studies involving healthy adults to find that protein intake may account for 1-2% of BMD variation. In this meta-analysis there was little evidence of a deleterious effect of protein intake on BMD, with either no influence or a slightly

positive influence with most cross-sectional and cohort studies. At worst, a neutral relationship likely exists between protein intake and bone health. At best, a slight positive association exists between protein intake and BMD, although the authors clearly state that confounding may partly explain the positive findings due to heterogeneity between studies. Further, evidence does not support a relationship between protein intake and fracture risk. The authors of this meta-analysis conclude that further research is needed to resolve the debate, and state that current dietary guidelines provide adequate protein for bone health (Darling et al., 2009).

2.1.5 Fruit and vegetables

Fruit and vegetables contain a number of nutrients that may have a beneficial impact on bone. These nutrients include vitamin K, potassium, magnesium, and vitamin C. Some of these micronutrients are required for skeletal growth and development by acting as co-enzymes that allow the formation of new cartilage and collagen fibres (Mangels, 2014). In addition to individual actions of various nutrients, fruit and vegetables exert a positive influence on bone through their alkali-forming properties, which increases extracellular pH, and contributes to a favourable acid-base balance, and reduced bone mineral resorption (Ilich and Kerstetter, 2000, Mangels, 2014, Prynne et al., 2006). This may lead to increased osteoblastic cell formation and improved bone function (Bushinsky, 2001). Even a slight increase in metabolic acidosis will have a negative impact on bone, by stimulating osteoclast activity, whilst inhibiting osteoblastic activity (Buclin et al., 2001). It is likely that the antioxidants contained in fruit and vegetables may reduce bone loss by reducing oxidative stress (Mangels, 2014). It also appears likely that fruit and vegetable consumption contributes to the buffering effect of endogenous acid production (McGartland et al., 2004, New, 2003). As mentioned earlier, nutrients such as animal protein are metabolised to produce sulphuric acid, which is buffered, in part by bone (Bushinsky, 2001, Buclin et al., 2001). The presence of dietary buffering compounds including potassium, vitamin C, and vitamin K, are therefore likely to reduce bone dissolution and maintain BMD (McGartland et al., 2004). A recent clinical trial clearly demonstrated the effects of diet-induced acidosis on the skeleton. Participants were instructed to adhere to one of two diets: diet A, which primarily consisted of acid-forming foods such as minced beef, turkey, and cheese; or diet B, which primarily consisted of alkali-forming foods including green salad, carrots, whole-corn bread, and a commercial bicarbonate-

based water. Diets were matched for protein, calcium and total energy, and the acid diet was shown to increase average urinary calcium excretion by 74%. This translated to a 19% increase in C-telopeptide excretion, which is likely directly related to increased bone mineral resorption (Buclin et al., 2001). Although well-conducted clinical trials are a robust style of research method, this particular study consisted of only eight participants, which is very few by most scientific standards.

A range of studies is emerging to support the positive skeletal effects of fruit and vegetable intake. The 'Northern Ireland Young Hearts Project', for example, found significantly higher BMD at the heel in twelve-year old girls with a high fruit intake, when compared to those with a moderate intake (McGartland et al., 2004). The author of this study found no differences in wrist BMD, and noted that the heel is composed mainly of trabecular bone, compared to the forearm, which consists primarily of cortical bone. Trabecular bone is more metabolically active (Rauch and Schoenau, 2001), and may therefore be more responsive to nutritional factors (Rauch and Schoenau, 2001). Similar findings were observed in a cross-sectional study of BMD in healthy 45-55 year-old women. This particular study found high previous intake of fruit to be an important determinant of bone health, with greater intakes of fruit and vegetables being associated with increased BMD in post-menopausal women (New et al., 2000).

2.1.6 Potassium

It appears potassium may be one of the more important nutrients regarding bone health, with a prospective cohort study of female cross-country runners finding high potassium intake was associated with greater gains in hip and total body BMD, independent of calcium intake (Nieves et al., 2010). One study in particular found potassium intake accounted for 7% of total variation in forearm BMD, although this was not seen in the lumbar spine or femoral neck (New, 2003). Potassium bicarbonate has been shown to decrease urinary calcium excretion, decrease bone resorption, and increase bone formation (New et al., 2000, Reid and New, 1997), suggesting individual nutrients and/or supplements may help improve bone health and provide added benefit to increased fruit and vegetable intake. A four-year follow up in one longitudinal study found that men with higher baseline intakes of potassium experienced less bone loss at the femoral neck and

trochanter (Tucker et al., 1999). Similar results were found in those with higher baseline magnesium intakes, although no association was found in women (Tucker et al., 1999).

2.1.7 Vitamin K

Another nutrient of particular interest is vitamin K, which can be classified into two categories: K1 (phylloquinone) is the main form found in large quantities in green leafy vegetables and some vegetable oils (Shea and Booth, 2008, Kalkwarf et al., 2004); K2 (menaquinone) is synthesized by bacteria (Weber, 2001), and is also found in small amounts in chicken, cheese, butter, egg yolk, and fermented soy bean (natto) (DiNicolantonio et al., 2015). It is an important co-factor in the formation of osteocalcin, one of the predominant proteins found in bone (Vermeer et al., 1995, Weber, 2001). High serum levels of undercarboxylated osteocalcin (UcOC) indicate low vitamin K status, and this is believed to be among the most sensitive measures of vitamin K deficiency (Weber, 2001). Although the mechanism responsible for the role of vitamin K in bone health is still not fully understood, it may also influence bone metabolism indirectly through its ability to improve calcium balance, leading to increased calcium retention (Weber, 2001).

Much of the existing literature regarding vitamin K intake and bone health involves elderly participants. A number of epidemiologic studies have shown a consistent positive relationship between serum vitamin K levels and BMD in elderly males (Tamatani et al., 1998) and post-menopausal women (Kanai et al., 1997), as well as hip fracture risk in both sexes (Hart et al., 1985, Hodges et al., 1993). Various intervention studies have also demonstrated the relationship between low vitamin K intake and increased UcOC levels in post-menopausal women (Schaafsma et al., 2000, Douglas et al., 1995) and osteoporotic patients (Takahashi et al., 2001). Studies directly measuring UcOC concentrations also support the benefits of vitamin K on bone health. Elevated UcOC levels have been shown to correlate with reduced BMD (Jie et al., 1996, Szulc et al., 1994), increased fracture risk in elderly subjects (Szulc et al., 1993, Szulc et al., 1996), and overall bone health in children aged 7-12 (Sugiyama and Kawai, 2001).

Similar findings have been observed in healthy 18-30 year olds regardless of age or sex, with 1mg daily phylloquinone supplementation resulting in mean UcOC reduction from 7.6 to 3.4% (Binkley

et al., 2000). This may indicate that current dietary intakes of vitamin K are insufficient to achieve maximal osteocalcin carboxylation. A recent intervention study found significant reductions in UcOC in healthy adults aged 19-36 years, when supplemented with 1000µg phylloquinone, compared with 500µg, which is significantly greater than average dietary intake of 80-150µg (Binkley et al., 2002). This led the researchers to conclude that high vitamin K intake may improve bone health by enhancing y-carboxylation, although the physiologic importance of this remains unknown (Binkley et al., 2002).

Perhaps the most comprehensive body of literature to date is the meta-analysis conducted by Cockayne et al. (2006), in which thirteen randomised control trials investigating vitamin K supplementation on bone loss were included, and all but one showed beneficial effects. Seven of the studies also included data on fracture risk and collectively showed a strong correlation with vitamin K supplementation, with an 80% reduction in fracture risk (Cockayne et al., 2006). The authors note that some of the studies included are of poor quality, and had high attrition rates, which suggests the possibility of bias. The unusually high reduction in hip fractures, may also come down to chance due to a small number of hip fractures present in the studies (Cockayne et al., 2006). It should also be noted that all studies that included data on fracture risk were conducted in Japan. It is therefore possible that the findings are influenced by alternative dietary differences, making them not applicable in other populations (Cockayne et al., 2006). For a better understanding of the relationship between vitamin K supplementation and fracture risk, the authors suggest a need for large randomised control trials with fractures as the main outcome (Cockayne et al., 2006).

Not all research supports the benefits of vitamin K on bone health. A prospective cohort study involving 115 female endurance athletes assessed BMD at the lumbar spine and femoral neck, found no reduction in bone loss over a 2-year period in those receiving vitamin K supplementation (Braam et al., 2003).

Further research is needed to determine whether there is a direct relationship between vitamin K intake and fracture risk before recommendations to vitamin K intake can be modified (Binkley et al., 2002, Sugiyama and Kawai, 2001) . More supplementation studies will also help determine the

validity of observational studies, and whether vitamin K status is simply a marker of generally poor diet patterns (Binkley et al., 2002).

2.1.8 Other micronutrients

Trace elements including iron, zinc, and magnesium have also been shown to positively correlate with bone mineral content in pre-menopausal women (Angus et al., 1988). The importance of zinc for optimal bone formation has been particularly well documented, with two studies demonstrating a relationship between zinc deficiency and osteoporosis (Atik, 1983, Herzberg et al., 1990). These and other micronutrients including manganese are known to play important roles as cofactors required for enzymatic reactions during synthesis of bone matrix proteins (Reid and New, 1997, Ilich and Kerstetter, 2000). Greater BMD has been found in elderly subjects who were given diets high in fruit and vegetables aimed at increasing consumption of potassium and magnesium (Tucker et al., 1999). This may be attributed, in part to the alkaline-producing effects of a high fruit and vegetable diet, and the antioxidant effect produced by a variety of nutrients, providing a favourable environment for bone homeostasis (Ilich and Kerstetter, 2000) as discussed previously. Therefore, overall dietary patterns, including quantity and variety of fruit and vegetables may be a better predictor of bone health than individual nutrients alone. It should also be noted that not all micronutrients are present in fruit and vegetables in sufficient quantities. For example, dietary zinc is most abundant in protein foods of animal origin, as well as milk, legumes, and whole-grain breads (Ilich and Kerstetter, 2000).

2.1.9 Calorie restriction and disordered eating

The link between eating disorders and impaired skeletal health has been well established. There are several mechanisms thought to be responsible, with most being associated with severe weight loss (Iketani et al., 1995). Moderate weight loss of 10% has been shown to cause small increases in bone loss by 1-2% (Ilich and Kerstetter, 2000). Extreme weight loss is a primary characteristic of most eating disorders. Although eating disorders are thought to be relatively rare among the general population (Smink et al., 2012), they may affect up to 5% of adolescents. Traditionally, females aged 15-19 years have been considered a high-risk group (Smink et al., 2012), although

there is evidence to suggest that eating disorders may now be almost as common in males (Andersen et al., 2000, Byrne and McLean, 2002). Those with an eating disorder are at far greater risk of developing osteoporosis, which occurs in up to 50% of cases (Legroux-Gerot et al., 2005) Low BMD typically seen in those with some type of disordered eating typically occurs due to a combination of multiple diet and lifestyle factors including low body mass, inadequate calcium intake, minimal physical activity, and hormonal disturbances including disruptions in estrogen and IGF-I concentrations, which collectively play a crucial role in bone formation (Legroux-Gerot et al., 2005, Gordon, 2007).

There is also increasing concern regarding the prevalence of eating disorders in athletes, with some research suggesting that athletes may be more likely to develop some type of eating disorder than those in the general population, affecting both males and females in various sports (Dale and Landers, 1999, Thiel et al., 1993, Byrne and McLean, 2002). This may be due to a variety of factors, particularly the pressure of achieving an 'ideal' body shape, or low body weight for competition (Byrne and McLean, 2002). A recent study involving 263 elite athletes from a variety of sports, found higher rates of eating disorders in athletes compared with non-athletes, and those athletes who felt most pressure to be thin or lean were at the highest risk (Byrne and McLean, 2002). The average age of the athletes involved in this study is of particular interest. At 19.7 and 17.4 years for males and females respectively, they are at an age when peak bone mass is being attained, and may have been limiting bone development for several years (Byrne and McLean, 2002). As far as we are aware no studies have investigated the prevalence of eating disorders in cricket players.

2.1.10 Physical activity

The link between physical activity and bone health is an area of considerable interest, and is considered one of the more modifiable aspects of bone health (Bailey et al., 1996). Mechanical loading resulting from various forms of physical activity triggers permanent bone reformation, resulting in increased osteoblastic activity and the formation of new bone through a process known as remodelling (Khan, 2001). It is during this process that new bone is formed, resulting in increased strength and mineralization of the existing structure (Khan, 2001, Ducher et al., 2011,

Zernicke et al., 2006). It appears that even small increases in bone quality correspond to significant increases in bone strength. A recent clinical trial applied mechanical loading (3x/week over 16 weeks) on rats, and found that a 5.4% increase in BMD resulted in a 64% increase in strength (Robling et al., 2002). This adaptive response requires progressively increasing loading generated by ground-reaction forces, and these osteogenic effects seen with dynamic loading, are unlikely to occur with static loading (application of a single, sustained force) (Zhu and Prince, 2012, Kohrt, 2004). This osteogenic response is limited by the naturally slow turnover of bone tissue. This means it may take 3-4 months to complete one remodelling cycle of resorption, formation, and mineralization, and such changes may not be measurable for up to 8 months (Kohrt, 2004).

The benefits of physical activity on the human skeleton are prevalent across all age groups. It has been shown both in adults (Stillman et al., 1986, Bernecker et al., 2014, Khan, 2001), and children (Bailey et al., 1999, Bachrach, 2001, Khan, 2001) that individuals with high levels of physical activity are more likely to have greater bone mineral density than those with lower levels of physical activity. It has been suggested that physical activity during childhood may be the single most important lifestyle factor associated with optimal bone health. Vandenbergh et al. (1995) studied 1359 boys and girls aged 7-11 yrs, and found that increased bone mineral content was seen only in those with high levels of physical activity (VandenBergh et al., 1995).

Athletes have generally been found to have higher BMD at various sites than those in non-athletic populations (Vuori, 2001). Sports of particular benefit typically involve high-intensity loading forces such as weight-lifting and body building, and gymnastics (Kohrt, 2004), which subject the body to a high degree of mechanical loading. One study comparing the BMD of female athletes from different sports found gymnasts to have 11% greater total-arm BMD than that of volleyball players, due to exposure to ground-reaction forces of 3-5 times the athletes body weight (Fehling et al., 1995). This type of high-strain, short duration loading is responsible for increased osteogenesis, resulting in greater bone mass (Lanyon, 1992).

The high intensity loading experienced during these sports has been shown to positively correlate with BMD, and low impact sports such as swimming, in which minimal resistance and loading is placed on the joints have negligible impact on bone mineral density (Taaffe et al., 1995, Andreoli et al., 2001). Perhaps the most telling effects of physical activity on bone health can be observed in

astronauts. DXA scans and overall bone health assessments have been mandatory at NASA since 2009, after it was found that astronauts experienced average monthly reductions in BMD of 1.0-1.5% whilst in orbit (Orwoll et al., 2013). This represents an accelerated rate when compared with older individuals on earth, who typically lose BMD at a rate of 0.5%-1.0% per year (Hernandez et al., 2003). This revelation led to the installation of specific machinery onto all spacecraft, which allowed astronauts to experience regular weight-bearing activity, even at zero gravity.

Although the importance of regular load-bearing activity on bone health is widely accepted, it is likely to be more effective when utilised in conjunction with adequate calcium intake (Karlsson et al., 2008, Lanyon et al., 1986). It has been proposed that the positive exercise-induced skeletal effects are only seen with adequate calcium intake – approximately 1000mg in adults (Specker, 1996, Karlsson et al., 2008), and 1300mg in adolescents due to higher rates of growth (Karlsson et al., 2008). A recent randomised control trial involving 88 peri/pre-pubertal boys found a 2% increase in femur bone mineral content (BMC), and 3% increase in tibia/fibula BMC in those who received calcium supplements, and underwent moderate exercise when compared with control groups for calcium or exercise alone. In this study, no increase in BMC was seen in non-loading sites, including the humorus, radius, and ulna (Bass et al., 2007), supporting the theory that non-weight-bearing activities, such as swimming or cycling do not produce significant skeletal benefits (Karlsson et al., 2008). This trial also supports the hypothesis posed earlier in an analysis by Specker et al. (1996), who suggested 1; the positive effect of physical activity on BMD appears to exist only when calcium intakes are greater than 1000mg/day, and 2; benefits from high calcium intake are only present when there is a sufficient amount of physical activity to stimulate an anabolic effect on bone (Specker, 1996). This reaffirms the importance of considering a combination of dietary and lifestyle factors when assessing bone health in the general and athletic populations, instead of focusing on individual factors alone.

2.1.11 Smoking/tobacco use

Smoking is one of the most widely accepted risk factors for osteoporosis and risk of fracture, with an overwhelming body of evidence to support this belief. It has been suggested that bone loss may increase two-fold in smokers compared to non-smokers (Krall and Dawson-Hughes, 1999). Possible

mechanisms for the deleterious effect of smoking on bone health include toxic effects on bone collagen synthesis (Krall and Dawson-Hughes, 1999), and reduced calcium absorption (Krall and Dawson-Hughes, 1999, Ward and Klesges, 2001). It may also exert effects on hormone metabolism (Yoon et al., 2012, Krall and Dawson-Hughes, 1999), particularly parathyroid hormone and Vitamin D, which play an important part in calcium homeostasis (Yoon et al., 2012). It has been shown that those who smoke regularly will experience accelerated bone mineral resorption (Yoon et al., 2012), and reduced intestinal calcium absorption (Krall and Dawson-Hughes, 1999).

A 2001 meta-analysis compiled data from more than 40,000 participants across 80 cross-sectional studies, found that smokers had significantly lower BMD at all sites (Ward and Klesges, 2001). These deficits were particularly prevalent at the hip and were found to be dose-dependent, meaning the lowest BMD values were generally seen in the most frequent smokers. Deleterious effects were more pronounced in men, and those over the age of 60. It was suggested that smoking may increase the lifetime risk of vertebral fracture by 13% in women and 32% in men, and hip fractures by 31% in women and 40% in men (Ward and Klesges, 2001). These effects are seen across all age groups even after adjusting for confounding factors such as BMI, age, and activity levels (Yoon et al., 2012). Although the effects of smoking on bone health may affect older adults to a higher degree, significant differences in BMD were found in premenopausal smokers compared to non-smokers (Jones and Scott, 1999), and in males aged 20-45 years (Ortego-Centeno et al., 1997).

2.1.12 Alcohol

Although there is some evidence for modest alcohol consumption having a protective effect on bone (Cummings et al., 1995, Williams et al., 2005), excessive alcohol consumption is believed to contribute to lower BMD and increased fracture risk (Ilich and Kerstetter, 2000, Maurel et al., 2012). Alcohol is therefore considered a major risk factor for osteoporosis worldwide (Chen et al., 2010). Several mechanisms are thought to be responsible for the direct effect of alcohol on bone metabolism. These include increased PTH levels, as seen with prolonged, moderate drinking; and impaired vitamin D metabolism resulting in low serum vitamin D levels, as found among chronic alcoholics (Laitinen and Välimäki, 1991, Ilich and Kerstetter, 2000). This ultimately results in

reduced malabsorption of calcium, magnesium and zinc, and reduced circulating levels of these nutrients (Maurel et al., 2012, Ilich and Kerstetter, 2000). Ethanol-induced oxidative stress is believed to contribute to the suppression of bone formation by inhibiting certain biochemical pathways required for the formation of new bone cells (Chen et al., 2010). Alcohol has also been shown to reduce osteoblastic activity, and increase osteoclast concentration resulting in increased resorption (Maurel et al., 2012, Laitinen and Välimäki, 1991, Chavassieux et al., 1993). Daily consumption of 1 standard drink for women, and 2 for men remains unlikely to negatively impact bone health, but some damage to bone tissue may occur with consumption levels of 2-4 daily drinks, respectively. When more than 4 daily glasses are consumed, the effects on bone are likely to be detrimental (Maurel et al., 2012).

2.1.13 Ethnicity

As mentioned previously, there are some determinants of bone health that are hereditary, and therefore not related to diet or lifestyle. Ethnicity is one hereditary factor believed to be a strong predictor of bone size and quality, with much of the current literature suggesting significant differences in BMD between people of various ethnic groups. Due to various rates of osteoporosis-related hip fractures across different ethnic groups, researchers have begun investigating bone status in ethnicities across a range of age groups in an attempt to understand why this occurs (Araujo et al., 2007).

An American study examining men aged 30-79 years, found African-American males to have higher BMC and BMD than Hispanic and Caucasian men at all sites, and similar values between Hispanic and Caucasian males (Araujo et al., 2007). Rates of age-related loss of BMC and BMD were greatest in Hispanics. It is likely that these findings partly explain the reduced incidence of fractures rates among elderly black men compared to other ethnic groups (Araujo et al., 2007). Similar results have been found in paediatric studies, suggesting there may be differences in rates of bone mineral accrual and peak bone mass, as well as age-related bone loss in various ethnic groups (Bachrach et al., 1999). Variation in BMD among children of different ethnic groups has also been shown to increase with age, suggesting the impact of puberty and hormonal changes to be a contributing factor (Kalkwarf et al., 2007).

The ethnic variance in BMD may be greater among males than in females according to a recent study investigating BMD in young African-Caribbean and Caucasian adults aged 20-37 years. The results found those of African-Caribbean ethnicity to have greater BMD at the lumbar spine, femoral neck, and total body in men (8, 12, & 14%, respectively) and to a slightly lesser degree in women (6% at all sites) (Henry and Eastell, 2000). BMD at various sites may also be lower in Asian (Bachrach et al., 1999), and Indian populations (Dheda et al., 2004).

2.1.14 Body composition

Total body mass has been suggested to have a strong relationship with bone mass (Khosla et al., 1996, Aloia et al., 1995), and reduced rates of bone loss (Khosla et al., 1996). Higher body mass index (BMI) is believed to correlate with denser bone (Papakitsou et al., 2004), and reduced risk of osteoporosis (Ong et al., 2014). These findings do not appear to correspond to reduced fracture risk in those with a higher BMD, as BMI is not a direct marker of bone strength (Ong et al., 2014).

More specifically, recent evidence suggests it is actually total body fat-free mass (FFM) that is the better predictor of BMD, and may account for approximately 50% of bone mass variability (Aloia et al., 1995). There is some literature suggesting fat mass (FM) to be a significant predictor of BMD and vertebral fracture, although this may be limited to post-menopausal women (Aloia et al., 1995). FFM also appears to contribute to bone health in athletic populations, and has been shown to directly correlate with BMD in cricketers (Micklesfield et al., 2012), as well as rugby players (Elloumi et al., 2009). The effect of body mass in rugby players becomes evident when comparing the differences in BMD by playing position, between forwards and backs. Forwards generally have higher total mass, fat mass, and lean mass than backs, which also corresponded to greater spinal and total body BMD (Elloumi et al., 2009), despite similar amounts of sport-specific training in both groups. Research involving elite cricket players also supports lean mass as an independent factor associated with bone. When compared to a control group, cricket players were found to have similar values for fat mass but significantly greater whole body lean mass and bone mineral content. Further, correlations between lean mass and BMC was significant in both groups (Micklesfield et al., 2012).

A similar relationship between body composition and bone health has been documented in children and adolescents. An early study by Nelson and Barondess (1997) found total mass to be predictive of bone mass, but did not differentiate between lean or fat mass (Nelson and Barondess, 1997). A different study involving 133 children and adolescents aged from 5 to 17 years, found both lean and fat mass to be independently associated with BMC, although lean mass showed a stronger positive association. This was found to be the case in both boys and girls, regardless of age (Pietrobelli et al., 2002). A strong correlation between lean mass and bone mineral content was also found in prepubertal girls, whereas body weight had little or no influence (Courteix et al., 1998).

2.2 Differences in composition between dominant and non-dominant arms in athletes

With mechanical loading showing a consistently strong effect on bone metabolism throughout the literature, the importance of well-designed studies investigating the relationship between body composition and bone becomes apparent. A comparison of body composition between dominant and non-dominant arms of athletes allows clear conclusions to be drawn from the effects of exercise-induced mechanical loading on muscle and bone content. Favourable effects on muscle and bone have been demonstrated in the dominant arms of both tennis (Calbet et al., 1998, Ducher et al., 2005, Fehling et al., 1995, Haapasalo et al., 1998, Kannus et al., 1995), and squash players (Haapasalo et al., 1994, Kannus et al., 1995). Using the non-dominant arm as a control allows nutritional, genetic, hormonal, and other variables contributing towards bone remodelling to be considered equal. This allows direct effects of unilateral loading on muscle and bone adaptations to be investigated (Calbet et al., 1998).

Most studies have shown varying degrees of BMD in dominant arms of athletes involved in racquet sports, with unilateral differences of up to 20% (Calbet et al., 1998) or 25% (Kohrt, 2004) being found. Similar increases can also be expected in muscle mass (Calbet et al., 1998). Furthermore, a 4-year follow-up in former tennis players has shown minimal bone loss in the dominant arm even after significant reductions in training and competition (Kontulainen et al., 1999), suggesting osteogenic effects triggered with this type of training may be long-lasting or even permanent (Calbet et al., 1998, Kontulainen et al., 1999).

It appears that although exercise-induced skeletal benefits can be seen to varying degrees throughout life, these benefits may be most advantageous if started from an early age. Osteogenic effects exerted through exercise are believed to be significantly more prolific during childhood. This is likely due to a greater rate of growth during childhood, and a higher proportion of osteoblasts found on bone surfaces during childhood when compared to a mature skeleton (Turner and Robling, 2003). One cross-sectional study involving 105 female squash/tennis players has shown this to be the case. Participants were arranged into three groups based on the age at which they began training. These groups were pre-menarchal (<10.5yrs), peri-menarchal (10.5-18.5yrs), and postmenarchal (>18.5 yrs). Not only did the players exhibit greater overall bone mineral content at various sites than their age-matched controls, but greater side-to-side (dominant versus non-dominant arm) variation was also seen in players who began training at an earlier age. In fact, side-to-side variation in humeral BMC in the pre-menarchal group was more than double that in the post-menarchal group; 22.1 and 8.5% respectively. In the peri-menarchal group 15.5% greater BMC was present in the dominant arm (Kannus et al., 1995). These findings are supported by another study involving 91 junior female tennis players aged 7-17 years. The authors of this study found that skeletal benefits associated with unilateral activity were evident as early as the adolescent growth spurt (Haapasalo et al., 1998). To date, only one study appears to have investigated the differences in dominant and non-dominant arms in cricket players. Lees, et al. (2016) investigated differences in body composition between twelve fast bowlers and twelve age-matched controls, and found the fast bowlers to have significantly greater bone mineral content in the dominant arm. Bowlers were also found to have greater total lean mass and bone mineral content than the control group (Lees et al., 2016).

2.3 Body composition and BMD in cricketers

Cricketers are generally reported to have a tall, athletic build (Koley et al., 2012), and considered to have superior physical fitness compared to sedentary individuals (Stretch, 1987). There are several studies investigating certain anthropometric and physiological characteristics of cricket players (Stuelcken et al., 2007, Koley et al., 2012, Micklesfield et al., 2012, Johnstone and Ford, 2010, Lees et al., 2016). Few studies have investigated the body composition of cricket players,

and none and have analysed changes from the beginning to end of the season. High-performing cricketers have generally been shown to have greater lean mass and lower body fat percentage than the general population. Micklesfield et al (2002) compared 34 cricketers to 23 physically active controls and found cricketers to have significantly greater lean mass (61.4 ± 6.0kg versus 56.8 ± 7.1kg, p=0.010), than 23 physically active age-matched controls. A trend was also seen towards lower body fat percentage (15.7 ± 4.9% versus 18.4 ± 6.0%), although this difference did not reach statistical significance (p=0.068). Cricketers in this study were also found to have significantly greater bone mineral content (BMC) than controls (3.1 ± 4.1kg versus 2.7 ± 3.5kg) (Micklesfield et al., 2012). Another study in India involving 271 inter-district level male cricketers from several Indian districts found total body fat percentage ranged from 13.8 ± 3.9% to 17.2 ± 5.2% (Koley et al., 2012). A recent study including only fast bowlers found these players to have significantly greater total lean mass than non-athletic controls (67.0 ± 5.8kg versus 56.5 ± 3.8kg, p=0.001), whilst also seeing a trend towards lower body fat percentage (17.4 ± 2.9% versus 20.5 ± 5.0%). BMC was found to be significantly greater in cricketers in the arms, legs, and trunk when compared to controls (Lees et al., 2016).

A recent study involving cricketers in South Africa found participants to have 10-13% greater BMD at various sites compared with physically active controls. Cricketers were also found to have significantly greater whole body lean mass than controls, with no significant difference found in fat mass (Micklesfield et al., 2012). A similar study investigating body composition in fast bowlers found them to have greater total lean mass and bone mineral content than non-athletic controls (Lees et al., 2016). It has been suggested that increased lean mass may help to enhance performance through improved bowling velocity and accuracy (Stuelcken et al., 2007, Johnstone et al., 2014). Given that all players must field and throw the ball throughout one half of the match, this increased performance would therefore remain relevant across all positions. Development of lean mass may also be beneficial in regards to injury prevention (Stuelcken et al., 2007).

Although it is widely accepted that physically active individuals generally possess greater BMD than sedentary individuals, resistance training provides a more effective osteogenic effect than endurance training (Heinonen et al., 1993). While it has been shown that resistance training can lead to significant increases in muscle strength and mass (Chilibeck et al., 1997, Seynnes et al.,

2007, Hubal et al., 2005, Chesley et al., 1992, Westcott et al., 2001, Biolo et al., 1995), it remains to be seen whether training programs undertaken by elite cricketers incorporate appropriate techniques to provide these adaptations. This may be particularly important when considering bone health, with findings from a meta-analysis concluding that resistance training positively impacts BMD at the lumbar spine, hip, and radius (Kelley et al., 2001). Whilst most current studies involving cricketers speculate that the greater bone mineral density seen in cricketers is a result of increased mechanical forces exerted through muscle, there appears to be a need to determine the extent to which muscle mass is responsible for such an effect.

2.4 Summary

The modifiable and hereditary factors associated with bone are vast in number, and influence skeletal health in a complex fashion. Dietary and lifestyle factors contribute significantly to the attainment of peak bone mass, and long-term maintenance of skeletal health. As far as we are aware no studies have investigated the dietary intakes of cricket players and their associations with bone mineral density. By assessing the dietary and lifestyle factors of a group of athletes, it may be possible to determine whether they are likely to be taking all reasonable steps to achieve and maintain optimal skeletal benefits. Considering these factors in combination with their current bone status could potentially be used to identify the risk of sporting injuries, and possibly their risk of developing osteoporosis in later life. By assessing differences in composition of dominant versus non-dominant arms, as well as changes in body composition from beginning to end of the season, this study will also contribute to the paucity of information available regarding high-performing cricket players. It is possible this will help to identify areas of concern in this group regarding bone health, potentially increasing knowledge on how to reduce injury rates.

Chapter 3

Methods

'Bone mineral density and body composition in high-performing cricket players; an exploratory study' is an observational study investigating determinants of bone mineral density. Additional aims included comparisons of bone mineral density (BMD), lean mass, and fat mass between dominant and non-dominant arms and investigating changes in body composition from the beginning to the end of the season.

3.1 Participants and recruitment

This study included both males and females all of whom were currently playing representative cricket, aged 16 years and above. At the time of recruitment all participants were free of injury or any physical condition that may have prevented them from participating in training or competition.

All participants were recruited through Auckland cricket, and were associated with one of three representative teams. Adult males were recruited from the Auckland A's domestic-level cricket team, and junior male players (<18 years) were recruited from the Developing Future Ace's (DFA's) team. Female participants were recruited from first class domestic team (the Auckland Hearts). Participants were recruited prior to the commencement of the 2015/2016 season, where players were provided with an information sheet containing details about the study at one of their training sessions.

3.2 Ethical approval

Ethical approval for this study was granted from the Massey University Human Ethics Committee (MUHEC): Southern A, Application 13/13. Informed written consent was also gained from each participant prior to participating in this study.

3.3 Research design and phases of data collection

There were two main phases of data collection in this observational study– at the beginning of the season (initial phase) and at the end of the season (follow-up phase). In addition, injuries were monitored throughout the course of the season using an email questionnaire.

3.3.1 Initial phase

Participants attended the Massey University Human Research Unit on various days for approximately 2 hours throughout October and November 2015. All participants signed and dated a consent form before proceeding with data collection. Participants were asked to refrain from eating and drinking within the two hours prior to their appointment. At this appointment total body and compartmental BMD and body composition were measured. Following these measurements, participants were offered something to eat and drink. Participants then completed questionnaires about their lifestyle and health, and current dietary intake.

<u>Bone mineral density and body composition (Dual X-ray Absorptiometry)</u>

Bone density was conducted using DXA scan (Hologic discovery A) by a trained researcher strictly adhering to a standard operating procedure (see appendix G). Measurement sites included hip, lumbar spine, and total body. Prior to the scan, each participant was requested to remove their clothing and any jewellery, and dress in a hospital gown to remove bias created by artefacts in clothing. The participants then lay supine on the scan table, and were checked to ensure that the centre line of the scan table aligned with the centre line of the participant to allow accurate cut locations when analysing the scan at a later date. Their head was positioned directly below the horizontal line that runs across the top of the scan table, and the entire body was checked to ensure the participant was within the scan lines on the table, with their arms slightly abducted from the trunk and palms resting downwards. Participants were instructed to remain completely still throughout the scan, and if there was any body movement, the scan was aborted and re-started. Bone mineral density (BMD) was calculated as mineral content of bone tissue divided by total area of bone in centimeters squared. The whole-body scan was used to compare musculoskeletal difference between dominant versus non-dominant arms.

Bone scan results were reported as bone mineral density (BMD) in grams per cm^2 and Z-score. The latter compares each participant to a large database of age- and gender-matched controls and indicates deviation from the mean.

Body composition (Bioelectrical Impedance Analysis)

Bioelectrical impedance analysis (InBody 230. Airspace Co., Ltd, Korea) was used to assess body composition including fat and skeletal muscle mass, along with weight. Although these measurements can be recorded with DXA, this method was used to allow mobile testing at the conclusion of the season to prevent participants having to return to the lab. Participants were asked to remove shoes and socks, and remove any long or baggy items of clothing to provide an accurate weight and eliminate interference with the BIA machine.

Participants were asked to step onto the platform of the BIA machine with their feet squarely placed on the scale pads, while the researcher entered the participant's height, age, gender, and participant number into the computer. The participant was then requested to grip the handles with thumbs squarely on the thumb-pads, and asked to remain completely still, with their arms away from their body until the analysis was complete. Each participant's weight, BMI, skeletal muscle, and body fat content were recorded. See appendix F for the standard operating procedure.

Height

Height was measured using a portable stadiometer (SECA, Hamburg, Germany). Participants were asked to remove their shoes and socks. Hair was checked to ensure it wasn't adding height, feet were positioned together with heels pressed against the stadiometer, and the participants jaw was lifted with both hands so the orbitale and ear canal were horizontally aligned. The participant was asked to inhale, and the measurement was recorded after bringing the headboard down to the top of the skull. Three height measures were taken, then averaged and recorded to the nearest 0.1 cm.

Athlete Diet Index (ADI)

A secondary dietary questionnaire (known as the Athlete Diet Index (ADI)) was used to determine the consumption of various food groups and calculate the amount of daily servings for each participant. The ADI has demonstrated reasonable validity and high reproducibility for consumption of food groups in high-performing athletes (data unpublished). The ADI was used in conjunction with the FFQ in order to provide a thorough account of dietary intake. The specific questions from the ADI that were used in this study are shown in Appendix A.

Food frequency questionnaire (FFQ)

This was an electronic and shortened version of a food frequency questionnaire validated for nutrient intake in a previous study (Houston, 2014). The FFQ is currently being validated for use in athletic populations. It was completed online via survey monkey (www.surveymonkey.com) and designed to provide accurate details regarding the dietary intake of each participant, and how often they consumed certain foods, and the amounts consumed. A variety of foods from all food groups were listed, and each participant could list any that were not included at the end of the questionnaire. To provide consistent interpretation of the questions, and explanation on how to complete the FFQ was provided, based on a standard operating procedure. The researcher also worked through an example question with each participant to ensure thorough understanding of each question.

Lifestyle and health questionnaire

A hand-written lifestyle questionnaire was designed to collect relevant bone health information such as ethnicity, smoking status, alcohol consumption, and training type and frequency. Injury and medical history was also included, as well as family history of osteoporosis. Information regarding menstrual status in female athletes was also obtained (Appendix D).

3.3.2 Follow-up phase

At the completion of the season, all participants were requested to take part in a follow-up session to assess height, weight and body composition using the BIA. Follow-up sessions were completed

on two separate days, with half of the participants attending each session. An additional session was arranged for all players who were unable to attend either of the initial dates. Appointments were scheduled via email, and reminders were sent the day prior to testing via phone call. These group sessions were carried out on March 21st, April 4th, and April 9th 2016 at a training session at a training facility at Eden Park sports stadium in Auckland.

All body composition measurements were recorded using the same protocol as at the initial session. A follow-up bone scan was not conducted due to the short duration of the season and minimal likelihood of changes in bone density.

3.3.3 Injury questionnaire

Injury questionnaires were completed monthly throughout the course of the season. Each player was sent a reminder to complete these via email. Players were requested to provide detailed information about any injuries sustained in training or competition. This included type and severity of injury, how it was sustained, amount of playing time missed, and how it was treated. (Appendix E). In addition to monthly questionnaires, participants were given the chance to provide details of any unreported injuries at the aforementioned follow-up appointment.

3.4 Dietary analysis

Questions from the FFQ used to determine the calcium intake of participants are shown in Appendix B. Calcium intake was calculated by adding the total amount of calcium from milk and dairy products using the *Foodworks 8* dietary analysis software programme (NZ FOODfiles 2010. The calcium contents of these foods are displayed in Appendix C. Total daily servings of each food group (fruit and vegetables, breads and cereals, milk/milk alternatives, and meat/meat alternatives) were calculated using responses from the ADI. If a participant reported eating 5 servings of fruit per week, this was divided by seven to provide a daily amount. Similarly, if a participant selected 'monthly' then this was divided by thirty for an estimated daily amount.

3.5 Statistical analyses

Statistical analyses were completed using SPSS (v.24, IBM corporation, New York, USA). Prior to conducting the analysis, the assumption of normally distributed means was examined using the Shapiro-Wilk test. All values were found to be normally distributed and were therefore reported as the mean ± standard deviation (SD). Statistical significance was set at $P \leq 0.05$. A forced-entry multiple regression model was used to investigate determinants of bone mineral density (total, spine, and hip) among male participants. Variables tested included age, calcium intake, and skeletal muscle mass. Multicollinearity was tested by comparing correlation values of the independent variables used in the analysis model. Values >0.8 were considered indicative of multicollinearity, and therefore not used together in regression models. Resistance training showed collinearity with skeletal muscle mass and was therefore excluded. For multiple regression analysis, it is usually recommended that one independent variable is used for every 10-15 participants included in the study (Field, 2009). Differences between dominant and non-dominant arms were compared using a dependent-samples t-test. Variables tested included BMD, lean mass, and fat mass. Changes in body composition throughout the season were also assessed using a dependent-samples t-test. Variables tested included weight, height, BMI, skeletal muscle mass, fat mass, and body fat percentage.

Chapter 4

Results

4.1 Characteristics of high-level cricket players

A total of 38 cricketers (27 male, 11 female) took part in this study. The majority were of Caucasian ethnicity (n=33, 86.8%), with the remainder being of South Asian ethnicity (n=5, 13.2%). Players ranged in age from 16-33 years, with an even spread between playing position (batsmen, bowlers, all-rounders). Time spent in weekly training varied from 330 to 1500 minutes/week, with females completing more total, and resistance-based training than males. Both males and females began training at similar ages; 12.3 ± 3.1, and 12.4 ± 2.4 years, respectively. Age, ethnicity, and training characteristics are displayed in table 1.

Table 4.1 Participant characteristics.

Characteristic	All players **(n=38)**	Male **(n=27)**	Female **(n=11)**
Age (years)	20.8 ± 4.4	18.7 ± 2.5	25.8 ± 3.9
Ethnicity (n(%))	-	-	-
Caucasian	33 (86.8%)	22 (81.5%)	11 (100%)
South Asian	5 (13.2%)	5 (18.5%)	0
Playing position (n(%))	-	-	-
Batsmen	13 (34.2%)	9 (33.3%)	4 (36.4%)
Bowlers	11 (29.0%)	8 (29.6%)	3 (27.3%)
All-rounders	14 (36.8%)	10 (37.0%)	4 (36.4%)
Total training time per week (minutes)	619 ± 211	604.6 ± 231.5	652.7 ± 157.7
Resistance-based training per week (minutes)	201 ± 105	183.9 ± 117.0	241.8 ± 64.0
Age training began (years)	12.3 ± 2.9	12.3 ± 3.1	12.4 ± 2.4

Values are reported as mean and standard deviation.

4.2 Body composition and bone mineral density

On average, males were heavier (78.1 ± 8.4 versus 68.8 ± 8.3 Kg) and taller (180.4 ± 10.0 versus 169 ± 4.0 cm) than the female participants. Body mass index was the same for males and females, but body composition differed, with male participants having greater skeletal muscle mass (38.2 ± 4.2 versus 29.3 ± 3.0 Kg) and lower fat mass (11.3 ± 3.9 versus 16.4 ± 4.5 Kg) than female participants.

Females had greater total (1.21 ± 0.15 versus 1.15 ± 0.07 g/cm^2) and spine BMD than males (1.22 ± 0.10 versus 1.16 ± 0.13 g/cm^2), with males having greater BMD at the hip (1.20 ± 0.14 versus 1.17 ± 0.09). In the absence of a control group, BMD values were compared with age/gender-matched means from the Hologic database using Z-scores. Males were found to have Z-scores above the mean for spine (0.87 ± 1.06) and hip (1.10 ± 0.97), and less than the mean for total body (-0.23 ± 0.80). In females, Z-scores were found to be above the mean for total body (0.65 ± 0.79), spine (1.77 ± 0.83), and hip (1.94 ± 0.64).

Table 4.2 Bone mineral density and body composition.

	Male (n=27)	Female (n=11)
Body composition	-	-
Weight (kg)	78.1 ± 8.4	68.8 ± 8.3
Height (cm)	180.4 ± 10.0	169 ± 4.0
BMI (kg/m^2)	23.9 ± 2.4	23.9 ± 2.2
Lean mass (kg)	60.9 ± 5.9	48.8 ± 4.5
Skeletal muscle mass (kg)	38.2 ± 4.2	29.3 ± 3.0
Fat Mass (kg)	11.3 ± 3.9	16.4 ± 4.5
Bone mineral density	-	-

Total body BMD (g/cm^2)	1.15 ± 0.07	1.21 ± 0.15
Total body Z-score	-0.23 ± 0.80	0.65 ± 0.79
Spine BMD (g/cm^2)	1.16 ± 0.13	1.22 ± 0.10
Spine Z-score	0.87 ± 1.06	1.77 ± 0.83
Hip BMD (g/cm^2)	1.20 ± 0.14	1.17 ±0.09
Hip Z-score	1.10 ± 0.97	1.94 ± 0.64

Values are reported as mean and standard deviation.

4.3 Lifestyle and health factors

Only one player reported being a current smoker (2 cigarettes per month). On average, 1.6 ± 2.5 units of alcohol were consumed per week across both groups. Consumption ranged from 0-12 standard drinks in males, and from 0-3 standard drinks per week among females. Thirteen participants did not drink at all. Fifty percent of all participants reported a history of stress fractures (male n= 11, female n=8), although none sustained a stress fracture during the season. Having a previous stress fracture was distributed across playing positions. Nine players (23.7%) reported an injury during the season. These injuries included muscle sprains, bruising, inflammation of joints, and one fractured knuckle caused by impact from a ball. Two female players (5.3%) reported a family history of osteoporosis. BMD in both participants was found to be within the normal range. All females participants reported regular having regular menstrual cycles.

Table 4.3 Lifestyle & health factors including injury.

	All players (n=38)	Males (n=27)	Females (n=11)
Lifestyle factors			
Current smokers n (%)	1 (3.8)	1 (1.1)	0 (0)
Number of cigarettes per month among smokers	2	2	0
Average units of alcohol/week	1.6 ± 2.5	1.8 ± 2.92	1.1 ± 1.0
Health factors			
Number of players injured during the season n (%)	9 (23.7)	7 (18.4)	2 (5.3)
Number of stress fractures sustained during the season	0	0	0
Family history of osteoporosis n (%)	2 (5.3)	0 (0)	2 (5.3)
History of stress fracture n (%) Batsmen Bowlers All-rounders	19 (50.0) 7 (18.4) 5 (13.2) 7 (18.4)	11 (28.9) 3 (7.9) 4 (10.5) 4 (10.5)	8 (21.1) 4 (10.5) 1 (2.6) 3 (7.9)

4.4 Dietary intake

Table 4.4 shows daily consumption of each food group compared to current Eating and Activity Guidelines for New Zealand adults (Ministry of Health, 2003). On average, male participants were meeting the recommendations for fruit (2.9 serves/day ± 2.6), but were not meeting recommendations for vegetables (2.0 serves/day ± 1.6), breads and cereals (3.7 serves/day ± 3.2), and milk/dairy products (1.8 serves/day ± 1.5). They were also found to be meeting the guidelines for meat and alternatives (2.4 serves/day ± 1.0). Females were, on average, meeting requirements for fruit (3.0 serves/day ± 1.4), vegetables (3.2 serves/day ± 1.1), and meat and alternatives (2.9 serves/day ± 1.2), but were not meeting the guidelines for breads and cereals (2.3 serves/day ± 1.3) or milk and dairy products (1.4 serves/day ± 1.0). Females were found to be choosing whole grain breads and cereals more frequently than male participants (86.4 ± 13 versus 70.2 ± 20.8 %).

Nutrient analysis (Foodworks 8, Xyris Software) revealed that participants were achieving 82% of the RDI for calcium from dairy products (819mg/day ± 477).

Table 4.4 Daily consumption of food groups compared to guidelines.

Food group/nutrient	Recommendations	All players Daily servings	Males Daily servings	Females Daily servings
Daily servings of fruit	≥ 2	2.9 ± 2.3	2.8 ± 2.6	3.0 ± 1.4
Daily servings of vegetables	≥ 3	2.4 ± 1.3	2.0 ± 1.6	3.2 ± 1.1
Daily servings of breads and cereals	≥ 6	3.2 ± 3.0	3.7 ± 3.2	2.3 ± 1.3
Percentage of Wholegrain breads and cereals (%)[a]	n/a	75 ± 22	70.2 ± 20.8	86.4 ± 13.0
Daily servings of Meat and alternatives[b]	≥ 1	2.5 ± 1.1	2.4 ± 1.0	2.9 ± 1.2
Daily servings of milk and dairy	≥ 2	1.7 ± 1.4	1.8 ± 1.5	1.4 ± 1.0
Daily calcium intake from dairy products (mg)[c]	1000mg (total recommended daily intake)	819 ± 477	896 ± 482	751 ± 367

Values are reported as mean and standard deviation.

[a] Wholegrains calculated as the percentage of time wholegrain options are chosen in response to question number 14 from the ADI – see appendix A.

[b] Eating and Activity Guidelines for New Zealand Adults (Ministry of Health, 2015)

[c] Recommended dietary intake (RDI) is the standard recommendation in New Zealand for a specific nutrient in order to achieve optimal health outcomes. Sourced from the Nutrient Reference Values (NRV's) for Australia and New Zealand (Ministry of Health, 2006).

4.5 Determinants of bone mineral density

Regression analysis was used to identify determinants of BMD (tables 4.5-4.7). Independent variables were included based on findings from previous research and scientific rationale. The regression models for total body, hip, and spine BMD included age, skeletal muscle mass, and calcium intake. Female participants were excluded from the analysis due to insufficient sample size (n=11). As shown in table 4.5 (below), the multiple regression model accounts for 38% of all variation in total BMD in male participants after adjusting for the number of variables used in the model (adjusted R^2 = .380). Skeletal muscle mass was the only statistically significant variable (P=.001). The model predicts that an increase of .012g/cm^2 in total BMD can be expected with every 1 kilogram of extra skeletal muscle mass (β= .012), holding all other independent variables fixed.

Table 4.5 Multiple regression analysis to determine factors associated with total bone mineral density in male cricketers.

Total body BMD (g/cm^2)	β	Standardised β^2	95% CI β	P-value
Age	-.002	-.085	-.012, .007	.598
Skeletal muscle mass	.012	.670	.006, .017	.001
Calcium intake	-9.299E-6	-.056	.000 - .000	.760

R^2 = .428 (Adjusted R^2 = .380); Regression P=0.01; p<0.05

Table 4.6 shows a similar relationship between independent variables and BMD at the spine. The regression model predicts that participant age, skeletal muscle mass, and calcium intake accounted for 18% of spine BMD (Adjusted R^2 = .179). Skeletal muscle mass was found to be the only significant predictor of total BMD (P=.011). An increase of .015g/cm^2 in spine BMD can be expected with every 1 kilogram of extra skeletal muscle (β= .015), holding all other independent variables fixed.

Table 4.6 Multiple regression analysis to determine factors associated with bone mineral density at the spine in male cricketers.

Spine BMD (g/cm^2)	β	Standardised β^2	95% CI β	P-value
Age	-.008	-.149	-.027, .012	.426
Skeletal muscle mass	.015	.508	.004, .027	.011
Calcium intake	-2.220E-5	.000	.000, .000	.736

R^2 = .242 (Adjusted R^2 = .179); Regression P=0.036; p<0.05

Table 4.7 shows a clear relationship between skeletal muscle mass and BMD at the hip. The model included age, skeletal muscle mass, and calcium intake. This regression model suggests that these independent variables account for 31% of all variation in hip BMD (Adjusted R^2 = .312). Again, skeletal muscle mass was found to be the only significant variable (p= .003). An increase in hip BMD of .018cm^2 will be seen with every 1 kilogram of extra skeletal muscle (β= .018), holding all other independent variables fixed.

Table 4.7 Multiple regression analysis to determine factors associated bone mineral density at the hip in male cricketers.

Hip BMD (g/cm^2)	β	Standardised β^2	95% CI β	P-value
Age	-.023	-.422	-.043, -.004	.052
Skeletal muscle mass	.018	.551	.007, .030	.003
Calcium intake	-2.854E-5	-.109	.000, .000	.563

R^2 = .365 (Adjusted R^2 = .312); Regression P=0.004; p<0.05

4.6 Composition of dominant versus non-dominant arms

Thirty-five players reported a dominant right arm, and three a dominant left arm. Table 4.8 displays a comparison of lean mass, bone, and fat mass between dominant and non-dominant arms in all participants using dual x-ray absorptiometry (DXA). Both lean mass (3668.1 ± 748.9g versus 3375.4 ± 707.1g) and BMD (0.866 ± .06 g/cm^2 versus .804 ± .06 g/cm^2) were found to be significantly greater (P=.001) in the dominant arm in all players. Differences in lean mass and BMD were also significant in both male and female subgroups. Males were found to have significantly greater fat mass in their dominant arm (892.0 ± 272.8g versus 861.6 ± 257.8g), whereas females were found to have marginally greater fat mass in the non-dominant arm (1038.6 ± 286.1g versus 1036.1 ± 341.3g).

Table 4.8 Composition of dominant versus non-dominant arms

	Dominant	Non-dominant	P-value
All players (n=38)	-	-	-
Lean mass (g)	3668.1 ± 748.9	3375.4 ± 707.1	.001*
BMD (g/cm^2)	0.87 ± 0.06	0.80 ± 0.06	.001*
Fat mass (g)	933.7 ± 296.9	912.8 ± 274.7	0.087
Males (n=27)	-	-	-
Lean mass (g)	4028.5 ± 554.3	3720.1 ± 494.3	.001*
BMD (g/cm^2)	0.88 ± 0.06	0.82 ± 0.06	.001*
Fat mass (g)	892.01 ± 272.8	861.55 ± 257.8	.001*
Females (n=11)	-	-	-
Lean mass[a] (g)	2783.5 ± 254.9	2529.3 ± 326.0	.001*
BMD (g/cm^2)	0.84 ± 0.07	0.76 ± 0.05	.001*
Fat mass (g)	1036.1 ± 341.3	1038.6 ± 286.1	.001*

Values displayed are reported as mean and standard deviation. P<0.05

[a] Lean mass is a measure of all components in the arm except for fat.

4.7 Changes in body composition over the season

Table 4.9 displays changes to body composition in female players over the course of the season resulting from regular training and competition. A total of 5 participants were unavailable for postseason analysis due to withdrawal from the study. Only data from participants who completed the study (n=6) were included in the analysis. Skeletal muscle mass was shown to significantly decrease over the course of the season by an average of 0.86kg (P = 0.03). No significant differences were found in weight (P=.147), height (P=.261), BMI (P=.208), or fat mass (p=.598). Body fat is also reported as a percentage to allow for population comparisons across a range of other studies.

Table 4.9 Female changes in body composition (n=6)

	Pre-season	Postseason	P-value
Weight (kg)	68.5 ± 3.7	66.7 ± 4.0	.147
Height (cm)	169.6 ± 5.1	169.4 ± 4.9	.261
BMI (Kg/m^2)	23.8 ± 1.1	23.10 ± 0.8	.208
Skeletal muscle mass (kg)	29.5 ± 2.4	28.7 ± 2.2	.030*
Fat Mass (kg)	15.8 ± 2.8	15.2 ± 2.5	.598
Body fat %	23.0 ± 4.1	22.8 ± 3.4	.859

Values are reported as mean and standard deviation. P<0.05

Table 4.10 shows changes to body composition in male players at the beginning and end of the season. Six participants were unavailable for postseason analysis, so only data from participants who completed the study (n=21) were included. No significant changes were observed in any variable.

Table 4.10 Male changes in body composition (n=21)

	Pre-season	Postseason	P-value
Weight (kg)	78.9 ± 8.5	78.9 ± 7.0	.932
Height (cm)	181.1 ± 6.0	180.9 ± 6.1	.291
BMI (Kg/m^2)	24.0 ± 2.2	24.1 ± 2.1	.659
Skeletal muscle mass (kg)	38.6 ± 4.1	38.8 ± 3.7	.447
Fat Mass (kg)	11.4 ± 4.0	10.8 ± 3.3	.290
Body fat %	14.3 ± 4.3	13.6 ± 3.8	.245

Values are reported as mean and standard deviation. $P<0.05$

Chapter 5

Discussion

5.1 Summary of key findings

The overall aim of this study was to investigate determinants of BMD in high-performing cricket players. Sites measured included hip, spine, and total body. We found skeletal muscle mass to be the only significant predictor, accounting for up to thirty-eight percent of total variance in total BMD. We also set out to determine whether there were any differences in musculoskeletal composition of dominant versus non-dominant arms. Males were found to have significantly greater lean mass, BMD, and fat mass in the dominant arm. Females were found to have greater lean mass and BMD, but lower fat mass in the dominant arm. Changes in body composition throughout the season were also measured, with a significant reduction in skeletal muscle being found in females, and no change in males.

5.2 Determinants of bone mineral density - Skeletal muscle mass

According to findings from the multiple regression model used in the present study, skeletal muscle mass appears to be a significant predictor of BMD at the hip, spine, and for total body in male participants accounting for 31, 18, and 38% of total variance in BMD, respectively. Our results suggest that increased skeletal muscle corresponds to greater BMD, whereas age and calcium intake showed no statistical significance at any site. Our findings suggest that for every kilogram of skeletal muscle, an increase in BMD can be expected in hip (+0.018g/cm^2), spine (+0.015g/cm^2), and total body BMD (+0.012g/cm^2). Similar results from a study involving over 5000 healthy men and women found increases of femoral BMD of 0.0083g/cm^2 for every one kilogram of lean mass in both middle-aged and elderly participants (Gjesdal et al., 2008). The same study also found that although lean mass was the strongest predictor of BMD in both males and females, fat mass was associated with a greater increase in BMD in women than in men.

Similarly, Micklesfield et al (2012) found that the correlation between lean mass and BMD in elite cricketers and age-matched controls was significant in both groups. These researchers suggested the greater BMD in cricketers to be a consequence of their high lean mass – a result of their regular strength-training programme (Micklesfield et al., 2012). This can be explained by the mechanostat theory, which hypothesizes that the size and strength of bone is influenced by increasing muscle forces that occur during growth (Frost, 2000). Male participants in our study demonstrated lower BMD at the spine (1.16 ± 0.13 versus 1.19 ± 0.15g/cm^2), and total body (1.15 ± 0.07 versus 1.25 ± 0.11g/cm^2) than what was found by Micklesfield et al (2012). This is likely due in part to a lower mean age of the participants in this study of 18.7 ± 2.5 versus 22.0 ± 3.0 years. Since the participants in our study had a mean age of 12.3 years at the beginning of their current training, this was likely contributing to an increased rate of bone formation during peak growth periods. Muscular forces are responsible for the greatest strain placed upon bone, which triggers increased bone turnover, size, and strength (Frost, 2001, Ducher et al., 2011, Fredericson et al., 2007). The age cricket players started training at was not reported in the study by Micklesfield et al (2012).

The relationship between lean mass and bone has been well established in healthy (Pietrobelli et al., 2002) and obese children who undergo physical training (Gutin et al., 1999), adults (Travison et al., 2008, Aloia et al., 1995, Wang et al., 2005), as well as athletic populations from other sports such as rugby (Hind et al., 2015, Bell et al., 2005). A recent study in rugby players and age-matched controls found forwards to have greater lean mass and BMD than backs, and backs to have greater lean mass and BMD than controls (Bell et al., 2005). Generally speaking, forwards possess a heavier, less mobile body type geared towards strength and the ability to withstand multiple collisions. Backs are generally lighter, faster, and require a greater degree aerobic fitness (Scott et al., 2003) Although the participants involved in our study are unlikely to benefit from some of the larger body types found in rugby players, there appears to be a linear relationship between lean mass and BMD. Even the smaller rugby players were found to have greater lean mass and BMD than controls, suggesting skeletal benefits may be obtained without a significant change in body shape.

Another study using regression analysis to determine the relationship between muscle mass and BMD suggests lean mass predicts total variance in bone content to an even greater degree than our results have shown. Researchers analysing the contribution of fat, and lean mass on total body calcium content in women aged 24-79 years found lean mass alone explained 50-55% of the total variability in total body calcium content (Aloia et al., 1995). It was also suggested that fat mass (FM) as a predictor of BMD may be limited to post-menopausal women only (Aloia et al., 1995). For this reason, skeletal muscle mass (rather than fat mass) was included as a potential predictor of BMD in our multiple regression models.

It can therefore be argued that the increased lean mass commonly seen in athletes from a variety of sports has a significant impact on bone mass, and training programs should be aimed at building and maintaining muscle mass in an attempt to preserve bone and minimise risk of injury. In fact, within this study the amount of resistance training undertaken was highly correlated with skeletal muscle mass. Considering cricket is a non-contact sport, with no real need for extra body mass in the form of fat, players should aim for a lean body type with a focus on preserving and/or building muscle through a variety of resistance-based training methods.

5.3 Nutritional considerations - Calcium intake

Although calcium intake was not found to be a significant determinant of BMD in this study, the vast majority of research confirms the importance of adequate dietary calcium for optimal bone health. In women undertaking resistance training, calcium intake was found to account for up to 24% variation in spine BMD, and 48% variation at the hip (Kelly et al., 1990).

A limitation of this study was considering the intake from dairy sources of calcium only. According to the 2008/09 New Zealand Adult Nutrition Survey, an estimated 40.3% of total dietary calcium comes from milk, cheese, and dairy products. Bread and non-alcoholic beverages were also estimated to contribute approximately 19.5% of total dietary calcium (Ministry of Health, 2010). There are also some plant-based foods that contain considerable amounts of calcium including broccoli, kale, oranges, and almonds, and tofu (Mangels, 2014, Ministry of Health, Kunstel, 2005). Certain calcium-enriched products including fortified bread, fruit juice and energy bars have not

been accounted for, meaning actual calcium intake could be significantly higher than estimated. As the calcium in plant foods is not as easily absorbed as calcium found in milk and dairy products (Guéguen and Pointillart, 2000), and the bioavailability of calcium in fortified food products depends on the calcium compound used (Mangels, 2014), it was decided that this study would focus on dairy sources of calcium only.

The current recommended dietary intake (RDI) for calcium in both males and females aged 19-50 years has been set 1000 mg/day. It has been established that intakes at or above this level provide a low probability of inadequacy in individuals. This differs from the estimated average requirement (EAR) of 840mg calcium per day, which is used to estimate the prevalence of inadequate intakes within a group (Ministry of Health, 2006). Mean calcium intake from dairy products in our participants was found to be 819mg/day and 751mg/day for males and females respectively. As previously mentioned, because we only investigated dairy sources of calcium in the diet, we are unable to estimate total dietary calcium intake. In addition, several participants involved in the current study were under the age of 19, meaning they require a minimum of 1300mg/day of dietary calcium according to the current RDI. Therefore, further investigation into total calcium intake in this group is warranted.

It is also important to note that guidelines for calcium intake have been designed for the general population, and no guidelines specific to athletes currently exist. While there is no clear physiological need for increased calcium intake in athletic populations, electrolytes lost in sweat during high intensity exercise means that dietary calcium intake must be sufficient to compensate for these losses (Kunstel, 2005, Petrie et al., 2004). One study in particular highlights the importance of adequate dietary calcium, and suggests that recommended general guidelines may be insufficient in sports involving a high degree of impact or mechanical loading. A study by Specker (1996) found that increases in rates of bone turnover due to environmental factors, such as increased physical activity, were only seen when sufficient calcium was available. In this study, Specker et al (1996) state that no mean differences in BMD were observed at calcium intakes less than 1000mg/day, and the greatest increases in BMD were seen with daily calcium intake of 1400mg/day. A similar relationship between comparably high calcium consumption and bone mineral accretion and increased BMD has been shown in adolescents (Johnston Jr et al., 1992),

and pre-menopausal women (Baran et al., 1990). Female athletes may be at particular risk of low BMD due to changes in hormone levels as a result of intense physical training, leading to amenorrhea. It has been suggested that athletes in this particular group aim for 1500mg calcium per day (Kunstel, 2005). Therefore, it is possible that all athletes would benefit from greater calcium intake than that provided by current guidelines, and there appears to be an inter-relationship between the effects of calcium and physical activity on BMD (Bass et al., 2007). All female athletes in the present study were found to be menstruating normally, and are therefore unlikely to be at increased risk of reduced BMD or osteoporosis compared with non-athletic females. Further, it appears likely that calcium availability provides a permissive effect on bone remodelling, allowing environmental and genetic factors to exert their full effect on bone development (Kelly et al., 1990, Andreoli et al., 2001, Zhu and Prince, 2012), which may be more pronounced in the athletic population.

5.4 Age as a predictor of BMD

Age was not found to be a predictor of BMD. A small age range of only fourteen for participants in this study may partly explain this finding. In addition, rapid bone growth and calcification occur during adolescence, and slows between the ages of 20 and 30 years of age (Cashman, 2002).
Twenty-one of the athletes involved in the present study were aged 19 years or younger, meaning peak bone mass may not yet have been reached. The bone growth of these adolescents is likely to be occurring at different rates, which may partly explain why age was not found to be a predictor of BMD.

5.5 Other considerations when assessing stress fracture risk

Although dietary and lifestyle factors are widely regarded as key determinants of bone health, it is important to consider other factors that are likely to contribute to reduce BMD and high rates of injury in the cricketing population. Biomechanical aspects of the bowling action are believed to contribute to stress fractures in cricketers, particularly bowlers, with particular importance being placed on the twisting motion of the trunk during the delivery stride (Micklesfield et al., 2012). Counter rotation of the shoulders during the delivery action in fast-bowlers has been suggested to

be the major technical factor associated with lumbar stress fractures, despite being an important component for the production of greater ball speeds after release (Portus et al., 2004)

Greater incidence of lower back stress injuries in cricketers has been associated with high workload and insufficient rest periods (Dennis et al., 2003), in addition to incomplete development and closure of ossification centres of the lower spine in young bowlers (Micklesfield et al., 2012). It would seem logical to expect the mechanical loading experienced by cricketers may provide protection against injury. Considering the greater BMD seen in cricketers compared to non-athletic controls, it is likely that both technique and bowling workload contribute to the increased prevalence of stress injuries in this group (Dennis et al., 2003). These considerations cannot be discounted when assessing overall risk of stress injury in this group, as workload and lack of rest may contribute to stress injuries even with optimal dietary and training methods. In addition, athletes with hamstring tightness and poor flexibility of the lower back are more likely to experience a stress injury (Elliott et al., 1992, Olivier et al., 2015). The approach to these injuries in elite cricketers is multifaceted and requires a broad approach, inclusive of diet, lifestyle, and suitable training and recovery methods. Physical indicators including lower back pain should be identified and treated as early as possible, particularly in fast bowlers, as this is believed to be among the most common symptoms of stress fractures in athletes (Olivier et al., 2015).

5.6 Composition of dominant versus non-dominant arms

Our results indicate significantly different compositions for dominant arms, compared with non-dominant arms in high-performing cricket players. We found males to have greater dominant-arm BMD (+0.056 g/cm^2), lean mass (+292.7g), and fat mass (+30.6g). Similar differences were seen in dominant-arm BMD (+0.078 g/cm^2) and lean mass (+254.2g) in females, dominant-arm fat mass was marginally lower (-2.5g). Our findings for BMD and lean mass are consistent with the majority of the current literature that illustrates physiological adaptations due to repetitive mechanical loading. Dominant-arm BMD and lean mass have been shown to be greater in tennis players (Ducher et al., 2005, Ducher et al., 2011, Calbet et al., 1998, Haapasalo et al., 1998, Kannus et al., 1994), and cortical bone thickness of the fore-arm has been shown to increase on the playing side due to skeletal hypertrophy by 34.9 (Jones et al., 1977) and 40% (Turner and Robling, 2003). Side

to side differences in the humeral shaft BMD of male tennis players has been shown to be as much as 25.4% (Kannus et al., 1994). Differences in forearm BMD may be less pronounced, with differences between 6.5% (Ducher et al., 2005) and 10% (Kannus et al., 1994) being found.

Analysing the entire dominant arm of cricketers (humerus, radius, and ulna) we found a 7.2% increase in BMD compared to the non-dominant arm. Another study involving squash players displayed similar results, finding both humeral (+ 15.6%) and ulnar (+5.6%) BMD to be greater in the dominant arm (Haapasalo et al., 1994). All of these findings demonstrate greater side to side variation than has been found in sedentary individuals, with differences in BMD ranging from 0 – 6.4% (Kannus et al., 1994). This suggests there are in fact beneficial site-specific effects on bone health that occur as a result of prolonged physical training.

This osteogenic effect on weight-bearing bones likely occurs due to mechanical stress exerted on bones and tendons during muscular contraction (Ducher et al., 2005). Our findings support this theory as the dominant arm lean mass was found to be greater in both male (+7.7%) and female (+9.1%) participants. Given that greater lean mass typically results in increased BMD, this represents an important finding; with animal models showing a 5.4% increase in ulna BMD corresponding to a 64% increase in the amount of force resistance before fracture (Lanyon, 1992). This is particularly relevant to cricket players given their high rates of stress fractures. Therefore, it is likely that a small increase in bone density may result in a significant increase in bone strength and reduced risk of stress fracture – however, this was not tested in the current study.

Follow-up studies looking at the effects of de-training on BMD suggest that the increases in bone mass remain even with the cessation of physical activity. This has been shown in a 5-year follow-up in tennis players (Kontulainen et al., 1999) and a 4-year follow up in squash players (Kontulainen et al., 2001). In addition, it appears that these benefits are closely linked to the age when training began. One study found side-to-side differences in BMD of female tennis and squash players to be two to four times greater in those who began their playing careers at or before menarche compared with those who began after menarche (Kannus et al., 1995). This is consistent with the majority of literature investigating the effects of physical activity on total BMD

(Grimston et al., 1993, Kohrt, 2004, Duncan et al., 2002), suggesting age of initial training to be a key determinant of bone mass accrual and long-term bone mineral density.

The majority of the current literature assesses racquet sports, in which one arm is clearly subjected to greater mechanical loading than the other. From our findings, it appears that this adaptation is not exclusively limited to racquet sports, and suggests the strain placed on the upper limbs of cricket players is sufficient to trigger a similar physiological response. This may be partly explained by the fact that even players who do not bowl, are still required to use their dominant arm to throw the ball when fielding, and this adaptation may result from the cumulative effects of previous training and competition. Considering participants were not professional cricketers, it is entirely possible that they are participating in other sports or training programs during the offseason. As we did not collect such information, this cannot be ruled out as a contributing factor to the differences seen in the dominant arms of these athletes. The extent to which playing position contributes to these unilateral differences in composition remains to be determined. No significant differences were found in dominant arm BMD between batsmen and bowlers in this study (data not reported).

5.7 Changes in total body composition throughout the season

Mean total lean mass of athletes in the current study was 60.9 ± 6.0kg in males, and 47.8 ± 4.5kg in females. Body fat percentage in males was 14.3 ± 4.2%, and higher in females at 23.6 ± 4.5%. Although data is scarce regarding female cricketers, our findings are comparable to other studies involving male cricketers. Micklesfield et al (2012) found male cricketers to have similar total lean mass (61.4kg ± 6.0kg), and slightly greater body fat percentage (15.7 ± 4.9%) than our participants. Another study by Koley et al (2012), also found similar results regarding body fat percentage, with values ranging from 13.8 ± 3.9% to 17.2 ± 5.2% when comparing inter-district level cricketers from various Indian districts (Koley et al., 2012). A recent study found fast bowlers to have greater lean mass and body fat percentage than our participants, with values of 67.0 ± 5.8kg and 17.4 ± 2.9%, respectively. Fast bowlers in the study by Lees et al (2016) were found to have significantly greater lean mass than non-athletic, age-matched controls. Although body fat percentage was found to be lower in fast bowlers, it did not reach significance (p=0.081). Whilst our study did not include a

control group, one obvious point of difference was our ability to compare pre and postseason body composition and assess any changes.

It has been shown that resistance training leads to increases in muscle strength and size, with these changes being shown to commonly occur in as little as 8-12 weeks from the commencement of training (Narici et al., 1989, Häkkinen et al., 1998, Akima et al., 1999, Young et al., 1983, Higbie et al., 1996, Hubal et al., 2005). This physiological adaptation has been shown to occur even more rapidly at higher intensities, and may be seen within 35 days (Seynnes et al., 2007). Initial increases in strength before hypertrophy occurs can be attributed to enhanced neural activity of the existing muscle fibers (Hubal et al., 2005, Sale, 2008). It therefore seems logical to expect the participants involved in the current study to experience increased muscle mass in response to resistance training conducted throughout the season. This was not reflected in our results. Whilst we observed general trends towards reductions in fat mass and total weight, no increases in skeletal mass were found. In fact, females demonstrated a significant reduction in muscle mass (-0.86kg) throughout the duration of the season. It is possible that this was a result of insufficient energy intake as opposed to inadequate training. Female participants were found to be consuming less than half of the recommended daily servings of breads and cereals. This suggests they may be struggling to meet energy requirements as breads and cereals are a major source of energy in the diet, contributing to approximately 18% of total energy intake in the general population (Ministry of Health, 2010).

Although male participants showed a slight increase in muscle mass (0.17kg), this did not reach statistical significance, meaning that no changes in skeletal muscle mass were found in males throughout 12 weeks of training and competition. This suggests that training programs for both male and female participants do not incorporate an adequate amount of resistance training to stimulate muscle hypertrophy and increases in muscle size. It must be noted that this study did not monitor dietary intake and training over the course of the season, so reasons for any changes or lack of changes must be interpreted with caution.

To date, this appears to be first study to assess changes in body composition over the course of a season. Given that skeletal muscle was shown to be a valid predictor of BMD, there is considerable

need to further investigate commonly used training programs in this group. This would make it possible to determine the extent and type of training required to enable cricketers to build and maintain muscle mass to help promote BMD.

5.8 Gender differences in BMD between males and females

Although it is widely accepted that males have greater muscle mass and bone mineral density than females, our results yielded contrary findings. Total body BMD in males was found to be 0.23 standard deviations below age-matched reference values from the Hologic database. This suggests that total body BMD in male participants is lower than that of healthy male individuals, and potentially placing them at increased risk of stress injury. The explanation for this is likely multi-faceted, occurring through a combination of genetic, hormonal, and diet and lifestyle factors. Variation in bone mass accrual among such a young group of players may also contribute to low total BMD. Given the average age of male participants (18.7 yrs), it is likely they have not yet reached peak bone mass, therefore mean BMD values may be skewed by the younger individuals included in the study. The average age of female participants was 25.8 yrs, suggesting peak bone mass had been already been achieved.

Chapter 6

Conclusion

6.1 Strengths and Limitations of this study

A key strength of this study is accuracy of bone measurements achieved through the use of DXA scanning, which has been shown to be a precise method of bone mineral density analysis, while exposing participants to extremely low levels of radiation (Fewtrell, 2003). The ability to record follow-up measurements is another strength of this study, with many cross-sectional studies being limited to only a single phase of data collection. This allowed us to track any changes to body composition and relate them back to initial measurements to gain a quantitative understanding of how participants responded to increased physical activity. Although it was possible to use DXA to evaluate body composition including lean and fat mass, BIA was used for logistical reasons. BIA is portable, and was able to be transported to training facilities post season to allow for follow-up measurements. BIA has been shown to be a valid and accurate predictor of lean mass and fat mass, however it is not considered to be as accurate as other techniques such as magnetic resonance imaging (MRI) (Janssen et al., 2000). BIA is a quick, non-invasive procedure that has been demonstrated to be reliable in healthy subjects who are not at extremes of BMI ranges. Results may be affected by recent physical activity, hydration status, and whether the participant is in a fed or fasted state (Kyle et al., 2004). Although we requested participants to refrain from eating, drinking, and exercising prior to analysis, this was not controlled for, and therefore may have affected our results.

Another limitation of this study is the use of self-reported questionnaires for information regarding dietary intake. This method is subject to under-reporting and is therefore not the most accurate means of collecting dietary information. Total nutrient intake is therefore an estimate, and does not allow for accurate quantitative analysis, which is particularly problematic when trying to determine a clear relationship between calcium intake (as well as other nutrients) and bone mineral density. We also did not account for non-dairy sources of calcium, potentially

allowing further underestimation of actual intake. Another limitation is the lack of assessment of dietary intake and training patterns over the course of the season. With only a one-off assessment at the beginning of the season, it is impossible to determine any changes that took place such as increases in training frequency and intensity or changes in dietary intake. As highlighted in the literature review, there are a number of other nutrients that play an important role in bone health which were not investigated in this study. We chose to focus on calcium intake as research suggests this nutrient to have the greatest impact on bone mineral density (Cashman, 2002). It is unlikely that vitamin D status has a negative impact on bone mineral density in cricket players due to long periods of time spent outdoors. However, we did not determine this in the current study.

Being a cross-sectional study design, it is also difficult to account for confounding variables that may contribute to a particular outcome. For example, we provided no intervention throughout the season, but saw changes to body composition that may not be exclusively attributed to training methods or dietary intake. This inherent flaw can be addressed in future studies by using randomised control trials and allowing control over external factors, such as dietary intake. Information regarding other sporting ventures or physical activity during the offseason would also be useful when determining the extent of physiological changes attributed to cricket. The use of a randomised control trial would further help identify the extent of a causal relationship between certain variables and BMD.

The present study was an exploratory study, limited by a relatively small sample size, and therefore conclusions must be interpreted with caution. Low numbers of female participants meant we were unable to investigate determinants of BMD in females using regression models. The fact that postseason data collection was performed on participants on different dates increases the likelihood of variation in body composition due to detraining. Ideally, future studies of similar design should aim to collect follow-up data for all participants in the same session to ensure accurate measurements regarding changes in body composition.

6.2 Recommendations for future research

Our results are in agreement with most of the literature indicating that bone mineral density is associated with greater muscle mass. Skeletal muscle mass did not significantly increase in males during the season, and in females it was reduced. Therefore, it seems logical to incorporate a resistance-based training program aimed at increasing skeletal muscle mass in high-performing cricketers of all ages, in an attempt to improve bone health and potentially minimise the risk of stress injuries. It may also be advisable to maintain some level of resistance training throughout the offseason so as to minimise losses in muscle mass and BMD associated with reduced training frequency. Utilising resistance training in young athletes might result in even greater gains in muscle and bone tissue. Further research should investigate the efficacy of various resistance-based training programs for increased muscle mass in elite cricketers, and both short and long-term changes in BMD. This would help to shed light on the most effective combination of training methods to help improve bone health and potentially reduce injury rates.

Calcium intake should also be further investigated through randomised control trials to determine whether higher levels of calcium intake (>1000mg/day) lead to greater BMD in this group. Finally, intervention trials may also help to determine a dose-response relationship between BMD and various other key bone nutrients, and could shed more light on the importance of dietary factors through detailed quantitative analysis.

Finally, given its considerable impact on bone health, serum vitamin D levels should also be investigated to gain a thorough understanding of the broad range of environmental factors known to influence bone, and whether all possible means of improving bone health are being utilised to their full extent.

6.3 Concluding summary

Our results are consistent with the prevailing consensus that bone density increases with greater skeletal muscle mass. We found that skeletal muscle mass accounts for up to 31% of total variation in BMD at the hip, 18% at the spine, and 38% of total body BMD in high-performing male

cricketers. Changes in body composition throughout the season were not evident, other than in females who showed a significant reduction in skeletal muscle mass. Lean mass and BMD were significantly greater in dominant arms of both males and females, a finding that lends itself to the theory that greater BMD results from increased muscle mass.

Similar studies in a larger sample of cricket players are warranted taking into account the limitations of the current study. Furthermore it seems logical to examine the efficacy of a resistance-based training program aimed at increasing muscle mass in high-performing cricketers of all ages, in an attempt to improve bone health and potentially minimise the risk of stress injuries.

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Appendices

Appendix A: *Athlete diet index (ADI)*

* 1. **Please enter your unique participant code:**

Fruit and Vegetables:

* 2. **How often do you usually eat fruit (include fresh, frozen and / or canned fruit; do not include juice or dried fruit)?**

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 3. **How many servings of fruit do you usually eat in the timeframe selected above? (include fresh, frozen and / or canned fruit; do not include fruit juice or dried fruit)?**

For example if you selected WEEKLY in the question above and you have 2 apples on a Monday, 1 banana on Tuesday, Wednesday and Thursday and 1 kiwifruit on a Friday you would select that you had 6 serves of fruit in the timeframe selected.

Examples of what a serving may include:

- 1 medium apple, pear, banana or orange
- 2 small apricots or plums
- ½ cup of fresh fruit salad
- ½ cup stewed fruit (fresh, frozen, or canned)

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of Fruit	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Fruit and Vegetables:

* 7. How often do you usually eat starchy vegetables?

Examples could include potato, kumara, taewa (Māori potato), parsnip, yam (Pacific or NZ), taro or cassava

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 8. How many servings of starchy vegetables do you usually eat in the timeframe selected above?

Examples of a serving may include:

- 1 medium or ½ cup of potato, kumara, taewa (Māori potato), parsnip, yam (Pacific or NZ), taro or cassava
- 1 medium sized green banana

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of starchy vegetables	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Fruit and Vegetables:

* 9. **How often do you usually eat non-starchy vegetables? (include fresh, frozen and / or canned)**

Examples could include: pūhā, watercress, silver beet, spinach, kamokamo (squash), carrot, broccoli, bok choy, cabbage, taro leaves, peas, corn, salad or mixed vegetables, tomato

- ○ Never
- ○ Yearly
- ○ Monthly
- ○ Weekly
- ○ Daily

* 10. How many servings of non-starchy vegetables do you usually eat in the timeframe selected above? (include fresh, frozen and / or canned)

Examples of a serving may include:

• ½ cup of cooked vegetables (e.g. pūhā, watercress, silver beet, spinach, kamokamo (squash), carrot, broccoli, bok choy, cabbage, peas, corn, mixed vegetables)
• ½ cup salad
• 1 tomato or ½ cup of canned tomatoes

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of non-starchy vegetables	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Breads and cereals:

* 12. **How often do you usually eat breads and cereals?**

Examples could include bread, cereal, oats, pasta, noodles, quinoa, rice, cassava, muffins, scones, crackers, pancakes, pikelets, muesli bars, cereal bars

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 13. **How many servings of breads and cereals do you usually eat in the timeframe selected above?**

Examples of a serving may include:

- 2 breakfast wheat biscuits
- 1 wholegrain bread roll
- 1 sandwich slice rēwena bread
- 1 sandwich slice wholegrain bread
- ½ cup muesli
- ½ cup of cooked porridge
- 1 cup of cooked pasta, noodles, quinoa or rice
- 1 cup cooked rice
- 2 crackers or plain sweet biscuits
- 1 scone or wholemeal muffin
- 1 cup of cornflakes
- 1 pancake or 2 pikelets
- 1 muesli bar or cereal bar

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of breads and cereals	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

* 14. **How often do you choose whole grain breads and cereals**(e.g. whole grain or multigrain breads, porridge or oats, oatmeal, oat flakes, bran based breakfast cereals, brown rice, wholemeal pasta, quinoa, buckwheat, food made with wholegrain, whole wheat or rye flour; food made from wheat flakes, whole barley, bulgur wheat) rather than more refined breads and cereals (e.g. white breads, cornflakes, rice bubbles, white rice, white pasta, food made with white flour)?

- ☐ Never
- ☐ Rarely (1/4 of the time)
- ☐ Sometimes (1/2 of the time)
- ☐ Mostly (3/4 of the time)
- ☐ Always
- ◯ Not applicable – I don't eat breads and cereals

Milk or milk alternatives:

* 15. How often do you usually eat or drink milk or milk alternatives?

Examples could include milk (cow's goats, sheep, flavoured), plant based milks (soy, rice, nut), yoghurt, dairy food, cheese, milk based dishes such as custard, ice cream

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 16. How many servings of milk or milk alternatives do you usually eat in the timeframe selected above?

Examples of a serving may include:

- 1 large glass of milk (250ml)
- 1 small pottle of yoghurt
- 2 slices of cheese (40g)or ½ cup grated cheese
- 1 cup of ice cream or custard

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of dairy or dairy alternatives	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

* 17. **How often do you choose low fat or reduced fat milk or milk alternatives**(eg. lite, trim, super trim) **over standard or regular milk alternatives** (eg. whole or full cream)**?**

- ◯ Never
- ◯ Rarely (1/4 of the time)
- ◯ Sometimes (1/2 of the time)
- ◯ Mostly (3/4 of the time)
- ◯ Always
- ◯ Not applicable – I don't drink or eat milk or milk alternatives

Meat/Meat alternatives:

* 18. How often do you usually eat red meat (eg. beef, lamb, pork, venison, veal, corned beef or silverside) (do not include sausages, frankfurters, luncheon, ham, bacon, pastrami, salami, canned corned beef)?

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 19. How many servings of red meat do you usually eat in the timeframe selected above?

Examples of a serving may include:

- 2 slices of cooked meat (approximately100g) (e.g. roast beef, lamb or pork)
- 1 medium fillet of steak (100-120g)
- ¾ cup of mince or casserole (195g)

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of red meat	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Meat/Meat alternatives:

* 20. How often do you usually eat chicken (do not include processed chicken such as chicken nuggets)?

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 21. How many servings of chicken do you usually eat in the timeframe selected above?

Examples of a serving may include:

• 2 chicken drumsticks or 1 chicken leg

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
Serves of chicken	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Meat/Meat alternatives:

* 23. How often do you usually eat kaimoana* (fish and other seafood) (do not include fish cakes or fish fingers)?

*Kaimoana includes all fish and seafood including salmon, tuna, mackerel, sardines, kuku (mussels), paua, eel

- ◯ Never
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 24. How many servings of kaimoana (fish or seafood) do you usually eat in the timeframe selected above?

Examples of a serving may include:

- 1 medium fillet of cooked fish (100g)
- 1 medium paua or kina (100-120g)
- 95g tin of fish

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
serves of kaimoana	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Meat/Meat alternatives:

* 25. How often do you eat processed meats such as sausages, frankfurters, ham, luncheon, bacon, pastrami, salami, canned corned beef, chicken nuggets, fish cakes or fish fingers?

- ◯ Never
- ◯ Yearly
- ◯ Monthly
- ◯ Weekly
- ◯ Daily

* 26. How many times have you had processed meats in the timeframe selected above?

	N/A	1	2	3	4	5	6	7	8	10	11	12	13	14+
Times you have had processed meat	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

Meat/Meat alternatives:

* 27. How often do you usually eat meat alternatives?

Examples include eggs, tofu, legumes*, nuts and seeds

* Legumes includes cooked dried beans (baked beans), split peas (dahl), lentils, chickpeas (hummus)

- ○ Never
- ○ Yearly
- ○ Monthly
- ○ Weekly
- ○ Daily

* 28. How many servings of meat alternatives do you usually eat in the timeframe selected above?

Examples of a serving may include:

- 1 egg
- ¾ cup of cooked dried beans, peas or lentils
- ¾ cup of tofu
- 1/3 cup of nuts or seeds

	N/A	1	2	3	4	5	6	7	8	9	10	11	12	13	14+
serves of meat alternatives	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Fluids:

* 29. How often do you USUALLY have the following drinks? (PLEASE provide an answer for all fluids listed)

For example if you have 2 glasses of milk a week please select WEEKLY from the Timeframe drop down menu and 2 from the Serves drop down menu.

1 cup (250mls) = 1 serve

	Timeframe	Serves
Flavoured water / sports water		
Coconut water		
Water		
Milk		
Fruit juice		
Soft drinks / fizzy drinks / carbonated drinks		
Cordial / powdered fruit drinks		
Herbal tea		
Tea		
Drinking chocolate, milo,		
cocoa		
Coffee		
Sports drink		

Appendix B: *Milk and dairy questions from Food Frequency Questionnaire (FFQ)*

2. Dairy Product

The following questions are related to Dairy product consumption.

Please select the desired quantity consumed and frequency from the drop-down menu.

* 1. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Flavoured milk (e.g. milkshake, smoothies, iced coffee, Primo, Nesquik)		

4+ times per DAY user, please state number of times

* 2. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Milk as a drink (e.g. hot drinks made with mainly milk (e.g. Latte), milk in protein shakes, milk added to breakfast cereals)		

4+ times per DAY user, please state number of times

* 3. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Milk added to hot drinks made with water (e.g. coffee, tea)		

4+ times per DAY user, please state number of times

* 4. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Cream, sour cream or cream cheese		

4+ times per DAY user, please state number of times

* 5. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Ice cream		

4+ times per DAY user, please state number of times

* 6. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Custard, dairy food or milk puddings (e.g. instant)		

4+ times per DAY user, please state number of times

* 7. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Yoghurt, plain or flavoured (including fromage frais)		

4+ times per DAY user, please state number of times

* 8. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Cheese (e.g. tasty, mild, gouda, edam, mozzarella, feta, camembert, brie, blue or other specialty cheese)		

4+ times per DAY user, please state number of times

* 9. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Cottage or ricotta cheese		

4+ times per DAY user, please state number of times

* 10. How often in the past 3 months have you eaten the following?

	Quantity	Frequency
Breakfast drinks (e.g. Up and Go)		

4+ times per DAY user, please state number of time

Appendix C: *Calcium content of foods using foodworks 8*

FFQ question number	Name of product in *foodworks*	Calcium content per 100g
1	Flavoured milk, chocolate, other	108.5mg
2	Milk, cow, ready to drink, other	112.9mg
3	Milk, cow, ready to drink, other	112.9mg
4	Sour cream, regular fat	50.0mg
5	Ice cream, from container, vanilla flavour, regular fat	93.0mg
6	Custard, commercial, regular fat, vanilla	120mg
7	Yoghurt, commercial, greek, regular fat – 5%	185mg
8	Cheese, cheddar, natural, plain, regular fat	763mg
9	Cheese, ricotta, regular fat	232mg
10	Sanitarium Up & Go liquid breakfast, choc ice	148mg

Appendix D: *Lifestyle and Health Questionnaire*

Participant ID number:.....

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Lifestyle and health questionnaire

Section 1: Demographics and lifestyle

1.1 What is your date of birth? _____

1.2 Gender

Male ☐
Female ☐

1.3 Which ethnic group do you belong to? Tick whichever applies to you (you may tick more than one box).

☐ New Zealand European
☐ Maori
☐ Samoan
☐ Cook Island Maori
☐ Tongan
☐ Niuean
☐ Chinese
☐ Indian
☐ Other *Please state which ethnicity*_____

1.4 Which country were you born in?

_____

1.5 If you live in New Zealand but were not born here, when did you first arrive to live in New Zealand?

Month (e.g. February)_____ Year (e.g.2000) _____

1.6 How would you describe your eating pattern?

Eat a variety of all foods, including animal products ☐

Eat eggs, dairy, fish and chicken but avoid other meats ☐

Eat eggs and dairy products but avoid all meats and fish ☐

Eat eggs but avoid dairy products, all meats and fish ☐

Eat dairy but avoid eggs, all meats and fish ☐

Vegan – do not eat any animal products whatsoever ☐

Other ☐

Please specify _____

1.7 Do you have any food allergies, food intolerances or digestive disorders?

Yes ☐
No ☐
Unsure ☐

If yes, please specify_____

1.8 Are you following any of the diets listed below? (Please select all that apply)

I don't follow any specific diet ☐

Fat modified

High fat ☐

Low fat ☐
Low cholesterol ☐

Carbohydrate modified

High carbohydrate ☐
Low carbohydrate ☐
High fibre ☐

Protein modified

High protein ☐
Low protein ☐

Energy modified

Low calorie/kilojoule ☐
High calorie/kilojoule ☐

Diet for allergies or intolerances

Gluten free ☐
Low gluten ☐
Wheat free ☐
Low wheat ☐
Dairy free ☐
Low dairy ☐
Lactose free ☐
Low lactose ☐
FODMAP free ☐
Low FODMAP ☐
Peanut free ☐
Nut free ☐
Fish/shellfish free ☐
Egg free ☐

Other allergy (please specify) _____

Other

Clean eating ☐
Paleo ☐

Other (please specify) _____

1.9 How often do you currently smoke tobacco?
(If you have <u>never smoked</u>, please go to question 1.13)

Never ☐
Monthly ☐
Weekly ☐
Daily ☐

1.10 On average, how many cigarettes would you smoke per day?

(Circle one) 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18+

1.11 If you no longer smoke, have you previously smoked for an extended period (1 year or more)

Yes ☐ **No** ☐

If so, how many years did you continuously smoke for?

(Circle one) 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+

1.12 On average, how many cigarettes did you smoke per day during this time?

(Circle one) 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18+

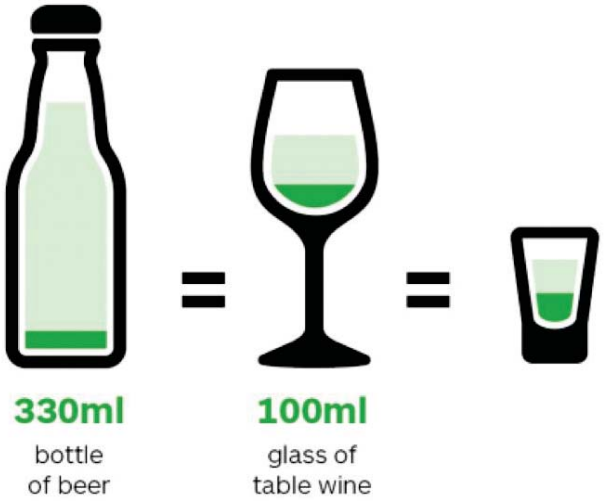
How long ago did you quit smoking?

_____

1.13 How often do you usually drink alcohol?
(If you do not drink alcohol, please go to section 2)

Never ☐
Monthly ☐
Weekly ☐
Daily ☐

1.14 How many standard drinks of alcohol do you usually drink in the timeframe selected above? *If you don't drink, please leave this question blank*
A standard drink is 1 can of beer (330ml), 1 glass of wine (100ml), 1 Ready to Drink (RTDs), 1 shot/nip of spirits (30ml) (see picture below)



(Circle one) 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+

1.15 On any one drinking occasion, what is the maximum number of standard drinks you would have?

(Circle one) 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+

1.16 How many alcohol free days do you have per week?

(Circle one) 0 1 2 3 4 5 6 7

Section 2: Training information

2.1 Please select one of the following, which *best* describes the position do you play?

Batsman ☐
Bowler;
Spin ☐
Pace ☐
All rounder ☐
Wicket keeper ☐

2.2 At what age did you begin training regularly for your current sport?

.....

2.2 Please describe your current training schedule?

	Details of type of training		**Time**
example	*Skills training + weight training, Net session (bowling or batting)*	*Location*	2 hours 30 minutes
Monday			
Tuesday			
Wednesday			
Thursday			
Friday			

Saturday			
Sunday			

Section 3: Health

3.1 Please complete this question if you are female (otherwise go to question 3.2)

Please comment on your menstrual status

Are you menstruating? **Yes** ☐ **No** ☐

If you answered yes, is your menstruation regular? **Yes** ☐ **No** ☐

If you answered no, when was your last menstrual period?

_____

_____

Are you currently using birth control contraception? **Yes** ☐ **No** ☐

If you answered yes, please explain further: the type and or name of the contraception that you are using (eg. oral birth control pills, injectable contraception, intrauterine contraception) and for how long have you used it?

_____

_____

If you have used injectable contraception in the past, please note the duration of time for which you used.

_____

_____

3.2 Have you ever been diagnosed with low Vitamin D levels, or vitamin D deficiency?

Yes ☐ **No** ☐

(Details on diagnosis, including when and by whom, and any treatment received. Also state the current status of this diagnosis)

_____

_____

_____

_____

3.3 Have you ever been treated for a stress fracture?

Yes ☐ **No** ☐

(Details on diagnosis including when and by whom, severity and any treatment received. Also include the length of time you were sidelined by this injury)

_____

_____

_____

_____

3.4 Does anyone in your immediate family (that is, blood relatives) have osteoporosis that you are aware of?

Yes ☐ **No** ☐

(If yes, please tell us the gender of the person, and the age at which they were diagnosed and their relationship to you)

_____

_____

3.5 Do you currently have any illnesses or chronic conditions?

Yes ☐ **No** ☐

If yes, please select (Please select all that apply)

Asthma	☐
Low bone density (osteopenia)	☐
Insulin dependent diabetes mellitus (type 1)	☐
Non-insulin dependent diabetes mellitus (type 2)	☐
High cholesterol or high lipids	☐
Hypertension	☐
Iron deficiency	☐
Vitamin B12 deficiency	☐
Folate deficiency	☐
Inflammatory bowel conditions (eg. Crohn or ulcerative colitis)	☐
Cardiac condition	☐
Kidney condition	☐
Liver condition	☐
Other (please specify)	☐

_____

Section 4: Supplements

4.1 Have you taken any vitamin and/or mineral capsules/tablets at any time during the past year?

Yes ☐ **No** ☐

If yes, please list the brand name of the supplement, the type of supplement, the number taken, the frequency of intake and the dose (including units) and the reason for taking?

Eg; Healtheries Iron & vitamin C, 1 taken every 2nd day, ferrous gluconate (170mg) providing elemental iron (20mg) and vitamin C (40mg), taken because I was feeling tired

If you can't remember the details of the supplements, please email us at S.M.McDonald1@massey.ac.nz *with the brand, type and dose so we can record these on your file.*

_____

_____

_____

_____

4.2 Have you taken any sports supplements at any time during the past year (including sports drinks, sports gels, sports bars, liquid meal supplements, protein supplements, herbal supplements)?

Yes ☐ **No** ☐

If yes, please list the brand name / type of sports supplement, the frequency of intake and the dose (including units), and the reason for taking.

eg. Powerade (750ml) taken every day during evening training (5x/week) for the past 3 years

_____

_____

_____

_____

4.3 Have you taken any other dietary supplements during the past year? (For example, omega-3 tablets, evening primrose oil, performance enhancers)

Yes ☐ **No** ☐

If yes, please list the brand name of the supplement, the type of supplement, the number taken and the frequency of intake and the dose (including units)?

eg. Omega 3 supplements, 1 capsule taken per day for the past 3 months, contains 180mg eicosapentanoic acid & 120mg docosahexaenoic acid 1000mg, took for aching joints

_____

_____

Appendix E: *Injury questionnaire*

Participant ID number:.....

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Participant injury questionnaire

In order to keep track of any injuries over the course of the season, we have designed this short questionnaire to be completed at the end of every month. We will send you a reminder via email to remind you of when to complete it, and we ask that you try to provide the following details to the best of your knowledge and understanding. Please note, all answers you provide in this questionnaire will be used for the purposes of this study only, and will be strictly confidential. We thank you for taking the time to complete this questionnaire and also for your participation in this study.

1.1 Have you suffered *any* injury at any time over the last month?

Please note: If you have not sustained an injury over the last month, please select 'No' and leave the rest of the questions blank.

Yes ☐
No ☐

1.2 Please provide accurate details regarding the type, severity, and location of your injury. If possible, please attach a copy of any medical diagnosis records you received from your doctor.

_____

_____

_____

1.3 How long is this injury expected to keep you from returning to competition?

_____

1.4 How is the injury being treated? Please include details on oral medications including pain relief and anti-inflammatory drugs.

_____

_____

1.5 How did you sustain this injury? Please be as specific as possible. i.e. *I sprained my right ankle after landing on it awkwardly during a delivery in a match.*

_____

_____

_____

_____

1.6 On what date did the injury occur?

_____

Standard Operating Procedure – Bioelectrical Impedance Analysis (BIA)

Setting up before the subject arrives
Check that the USB of the printer is plugged into the back of the BIA machine and turn the printer on (if using the print option).

Turn the BIA machine on – it will self-calibrate, taking about 15 seconds.

Conducting a BIA assessment
For accurate analysis, the following is recommended:

- Measure with an empty stomach (at least 2hrs without eating and drinking)
- Measure after urination and excretion
- Do not exercise or take a shower before measurement
- Measure after standing for at least 5 minutes
- Do not measure if taking a diuretic
- Ensure that the body is warm before measuring (in winter)
- Keep room temperature at 20 - 25°C
- Weight capacity: 10 – 250kg
- Height range: 85 – 220cm
- Age range: 3 – 99 years

The subject's height should be known prior to the test as this is required for the measurement.

The subject should remove accessories, heavy clothing and bandages from the hands and feet. Make sure that the subject's clothing is not interfering with the electrodes (i.e. no long pants or long sleeves that drag over the electrodes) but not compression tights).

If the subject's soles and/or palms are too dry, use a wet tissue to wipe their hands/feet before beginning.

Bare feet must be in contact with the foot electrodes and the end of their heels should align with the end of the heel electrodes.
Once the participant steps on the BIA machine, the weight will automatically be measured and appear on the screen.

Have the participant remain standing on the BIA machine.

Once the weight has been measured, it will transfer into the 'Weight' box. The red cursor will then appear at 'ID'. Ask the participant to enter their:

- ID code (then press 'Enter')
- Age
- Height (round to nearest cm)
- Gender – M or F (then press 'Enter' to begin measurement)

The hand bars should be positioned so that the participant's arms are not in contact with the trunk of their body.

Make sure the participant is holding the hand electrodes with the thumbs on the top side and fingers on the underside (there is no need to grip too tightly)

The participant should remain still and quiet during the measurement.

The measurement takes about 30 seconds. When the measurement is complete, the 'COMPLETED' message appears on the screen. The participant can step off once the screen shows the message 'PRINTING' or 'COMPLETED'. The data will be cleared from the screen once the participant steps off (or after printing, if print option is being used).

The results will automatically print if a printer is connected to the BIA machine.

Once the participant steps off the machine, the electrodes should be cleaned with wet wipes, ready for the next participant.

Appendix G: *Standard Operating Procedure – DXA*

PROTOCOL FOR OBTAINING A DXA SCAN (LUMBAR SPINE, HIP AND WHOLE BODY)

Set Up and DXA QC

Turn on the heater to prepare the room for participant (if necessary).

QC must be performed prior to scanning on every day that the DXA is used, and at least 3 times per week.

1. Turn on the computer, and click QDR on the user menu. The DXA software will automatically load.
2. Click on the flashing QC icon and follow the instructions using the phantom spine.
3. QC should pass. Click on 'Review analysis' and take note of the total BMD value. This should be recorded on the DXA QC spreadsheet (check with the lab staff).
    a. If QC fails, repeat the procedure, that is:
        - Reposition the phantom
        - Check all scanning parameters
        - Check all physical requirements
        - Make sure there is nothing else on the table
        - Rescan
    b. If necessary, reboot the computer.
4. The Radiographic Uniformity test automatically follows every few QCs. Again, follow the prompts. This test involves the bed moving very close to the door, so make sure the door remains shut throughout this procedure. This test should also pass, and if not, the QC procedure must be repeated from the beginning. If it fails a second time, follow the procedures above.
5. If QC and/or Radiographic Uniformity tests repeatedly fail, the DXA should not be used for scanning. Contact Tom Roberts from ISL Medical & Scientific: tom.roberts@islnz.com.

Prior to Scanning

Check with the participant:

- About possible pregnancy (if appropriate)
    - If there is any doubt regarding possible pregnancy, the scan should not be performed.
- Whether they have recently:
    - Had any nuclear medicine studies or been administered any radiographic contrast agents (incl. barium studies, renograms, some CTs)
        - These must be eliminated from body before the participant is scanned, as they can cause an error in the BMD measurement. For doses of oral or rectal barium, waiting a week before scanning should be safe. For radio-

isotopes, the length of time it takes for this to occur depends on the half life. Technetium, a radiopharmaceutical commonly used in cardiac and bone scans, should be eliminated within 48 hours, while other isotopes require longer waiting periods.

- Whether they have any internal surgical devices e.g.
    - Hip or knee prostheses
    - Surgical pins
    - Breast implants
    - Pacemakers
        - If this is the case, the affected areas should be excluded from analysis where possible, or a note should be made of their presence.
- About any previous hip or spine fractures, illnesses or procedures, as these could alter the BMD, e.g.
    - Spinal fusion
    - Laminectomy
    - Previous osteomyelitis

Preparing the Participant for the Scan

Ask the participant if they have had a DXA scan before. Explain the procedure to the participant, letting them know that you are measuring BMD, and that it is a painless, non-invasive procedure that takes only a few minutes for each scan.

Clothing and artefacts

The participant should be provided with a gown to change into. They should leave underpants/knickers on but remove everything else, including pantyhose and socks.
They should also remove all potential artefacts prior to the scan, such as:

- Jewellery
- Belt buckles
- Buttons and zippers
- Coins and keys
- Bra clips and underwires
- Safety pins
- Hair ties with metal parts

The presence of these artefacts will alter the bone mass measurement.

- If removal is not possible (often the case with piercings or wedding rings), the same artefact should be worn in the same place in any subsequent scans.
- The presence of such artefacts should be noted on the report.
- If possible, exclude the artefact from reported regions.

Welcoming/Entering the Participant's Details

- Have the participant sit near the middle of the bed and swing their legs up onto the table. They should lie face-up with their head at the end below the window.
- Click Perform Exam on the screen, then New Patient.
- Enter participant details: first/last names, study ID, DOB, height (cm) and weight (kg).
- Click OK, then OK again on the next screen.

Let the participant know what sites you will be scanning, and select the relevant option from the list (e.g. AP lumbar spine, left hip, whole body).

- Uncheck 'use default scanning mode' and click 'next'.
- Choose 'array' and click OK

On the screen, you should now see pictures of the correct positioning for the scan mode you have chosen. You can use this as a guide while positioning the participant (described below).

AP Lumbar Spine

Positioning the participant

- Ensure the participant is lying straight and is within the black lines on the bed.
    - Stand at the 'head end' and use the markings as a guide. Ensure hips and shoulders are square.
    - For patients with scoliosis, it may be necessary to move the shoulders out of line with the hips to ensure the lumbar spine is straight. In this case, check the belly button and sternum are in line with each other.
- Raise the feet and legs up onto the cushioned cube, creating an angle of 60-90° between the table top and the participant's thighs. This reduces the curve in the spine and separates the vertebral bodies.
    - The front edge of the positioning block should be directly under the bend of the knees.
- The arms should be by the sides and palms flat on the scan bed.

Positioning the scanner arm

The scan should begin at L5 and scan up the body, finishing at T12.

- Press the 'laser' button on the scanner control pad.
- Use the 'arm' and 'table' buttons to move the laser to the start point for the scan.
    - Identify the participant's iliac crests or belly button, asking the participant to indicate these points if necessary.
    - Position the laser 3-5cm below this point.
    - Ensure the laser is centred by lining it up with the sternum.
- Once the scanning arm is positioned, ask the participant to remain still and breathe normally while the scan is in progress.
- Click 'start scan'.

Adjusting the scan

- Watch the screen for the appearance of the spine image, which should span mid L5 to mid T12. You should be able to see both iliac crests, but not below this.
- Ensure the spine is centred and straight.
- If you have started the scan too low or too high, click 'reposition' and click and drag the scanned image until it is in the correct position. Make sure the participant has not moved, and click restart scan.
- If the spine is positioned incorrectly because the participant is not lying straight, abort the scan, reposition them and start again.

Completing the scan

- The scan will finish automatically.
- Remove the cushion from beneath the participant's legs.
- If you want to do another type of scan immediately, click 'new scan' and select the type of scan you want to do (e.g. hip). Otherwise you can choose to analyse the scan.

Hip

The hip is a more difficult region to perform a DXA scan than the spine as small positional changes result in large BMD changes. It is easier to scan the left hip due to the layout of the machine, however, the right hip can be scanned if necessary.
If you have not already done so, click 'new scan' (or 'perform exam' from the main screen) and select 'left hip'. As for the lumbar spine:

- Uncheck 'use default scanning mode' and click 'next'.
- Choose 'array' and click OK

On the screen, you should now see pictures of the correct positioning for the scan mode you have chosen. You can use this as a guide while positioning the participant (described below).

Positioning the participant

- Ensure the participant is lying within the black lines on the bed.
- Check they are lying straight on the table – stand at the 'head end' and use the markings as a guide. Ensure hips and shoulders are square.
- Show the participant the hip positioning fixture, place it on the table and ask them to put their feet on top of the plastic on either side.
- Slide the positioning fixture horizontally so that the left leg (if measuring the left hip) is straight (i.e. parallel to the black line).
- Asking the participant to relax their leg, gently pick up the knee and rotate it medially, approximately 15-20°. The knee should be slightly facing inwards (this might not be

possible in everyone). Hold the leg in this position by strapping the foot to the positioning fixture. Check that the participant is comfortable.

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Positioning the scanner arm

The scan should scan up the body, and begin approximately 7-8cm below the greater trochanter and 2.5cm medial to the shaft of the femur.

- A practical way to identify this position is to align the arm with the base of the symphysis pubis, then move the table laterally so the laser is in the middle of the thigh.
- Once the scanning arm is positioned, ask the participant to remain still and breathe normally while the scan is in progress. Then begin the scan.

Adjusting the scan

- Watch the screen for the appearance of the femoral shaft, which should be straight.
- You should then see the lesser trochanter (which should be minimised due to the hip rotation).
- If necessary, click 'reposition', click and drag the image into the right position and click 'restart scan'.

Completing the scan

- When you have reached a couple of centimetres above the hip joint (into the ileum), you can stop the scan.
- Remove the hip positioning fixture.
- If you want to do another type of scan immediately, click 'new scan'. Otherwise you can choose to analyse the scan.

<u>Whole Body (Body Composition)</u>

This is a straightforward scan that covers the entire length of the participant's body and requires no extra equipment. It begins at the top of the head and moves downwards towards the feet, completing three scans of the body.

Positioning the participant

- Ensure the participant is lying within the black lines on the bed. Their head should be directly below the horizontal line at the top of the scan table.
- Arms should be apart from the trunk and palms down on the scan table.
    - Obese participants may have to place their hands in a vertical position to be within the scan lines. If they are still outside the lines in this position, they can cross their arms over their body. This will invalidate regional body composition results but total body composition results will still be valid. Record any non-standard positions used so they can be duplicated in follow-up scans.

    - If the participant is very tall and cannot fit within the lines when they lie flat, their knees may be slightly bent.
- Feet should be in 'pigeon-toed' position – heels wide apart and tips of big toe together.

Scanning the participant

- Select 'whole body' (this will default to the array setting without you changing anything)
- Ensure the scan width and length values are correct for the person you are about to scan (they should be by default, unless the person is very long/very wide.
- Ask the participant to lie still, breathe normally and relax, then begin the scan.

If the person moves, abort the scan and restart.