THE QUANTIFICATION AND DEVELOPMENT OF AN OSTEOGENIC JUMP-LANDING PROGRAMME AND ITS CHRONIC EFFECTS ON BONE HEALTH IN PREMENOPAUSAL WOMEN

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ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

This thesis fulfills the Auckland University of Technology Doctor of Philosophy guidelines by constructively critiquing previous literature pertinent to the use of strongman implements in strength and conditioning practice. This thesis provides a broad experimental application to this growing body of knowledge.

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PUBLICATIONS AND PRESENTATIONS

The publications listed below are a result of the research conducted in fulfillment of the degree of Doctor of Philosophy.

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The student was the primary contributor (80%) of the research in this thesis and the subsequent analysis and interpretation of the research results. The student was also the main contributor (80%) to the writing of research ethics applications, progress reports and papers, as well as being the main presenter of the research results at conferences. All co-authors have approved the inclusion of the joint work in this thesis.

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ABSTRACT

A review into the effects of impact forces as a bone stimulus found that mineralisation can be achieved in areas where the stress is applied, however specific exercise protocols are currently lacking. It was also apparent that very little research had investigated the factors that influence jump-landing ground reaction forces (GRF's) in premenopausal women, and no study had investigated the use of reactive jump-landings to optimise the osteogenic stimulus for jump-landings when performed by premenopausal women. In addition, no study had attempted to develop a quantified 12-month periodised osteogenic jump-landing programme to be specifically utilised by premenopausal women to improve bone health, nor investigated the chronic effects of such a programme on functional performance parameters, body composition and bone remodelling at clinically relevant sites. Therefore, addressing these gaps and limitations from the reviews has set the framework for this thesis.

The first three studies sought to quantify the full spectrum of ground reaction forces (GRF's) associated with a variety of jumps in this population. Study's 1 to 3 essentially involved one data collection however, they are 3 separate studies (represented as Chapters 3, 4 and 5 in the PhD thesis) given the magnitude of the data collected and the very different kinetic characteristics of the jumps. Study's 1 and 2 investigated the main jumping and jump-landing factors deemed important in achieving greater GRFs included the cueing of participants to; (i) use a vigorous arm swing in a "countermovement" style; and, (ii) 'land stiffly' and 'immediately jump again for maximal height' (reactive jump). With these instructions provided, GRF's for all bilateral vertical and multiplanar jump-landings for magnitude (3.9 to 5.5 Body Weights - BW's) and rate of strain (192 to 359 $BW \cdot s^{-1}$), easily exceeded the previously defined vertical osteogenic thresholds (>3 BW's and 43 $BW \cdot s^{-1}$), shown to improve bone mass at clinically relevant sites for premenopausal women.

Although vertical landing forces were similar for the bilateral multiplanar jumps, substantially different medio-lateral GRF's (↑85% to ↑466%, for star jump) and anterio-posterior (↑103% to ↑316%, for stride jump), were observed between the jumps. The multidirectional nature of these jumps presented an opportunity to maintain and enhance mechanical bone stimulation after the bone becomes saturated to vertical loading cycles, however this was poorly understood for unilateral jump-landings. Therefore, in Study 3 unilateral multiplanar jumps, including the vertical, forward and lateral hop were investigated. Unlike the bilateral jumps, the unilateral hops did not utilise a reactive component, however a vigorous countermovement arm swing was used and participants were cued to land "stiffly". The magnitudes (4.2 to 5.1, BW's) and rates of strain (239 to 334 BW·s^{-1}) for the jump-landings, performed on an AMTI force plate, exceeded osteogenic thresholds previously determined using bilateral jump-landings. Furthermore, significant differences were detected for GRF's for unilateral jumps landings across all planes of motion (19% to 93%) suggesting that each landing type provided a novel force application to potentially optimise bone stimulation.

In Study 4 the kinetic data previously quantified in the aforementioned studies, in combination with a review of current and relevant evidence-based literature was utilised to develop a 12-month periodised osteogenic jump-landing programme for premenopausal women. The data was organised into a bone-specific 'stress stimulus rating' based on GRF magnitude (>3BW), GRF rate (>43 BW·s^{-1}), and technical difficulty (i.e. vertical bilateral to multiplanar unilateral) in a progressive manner over a 12-month period. The 12-month periodised osteogenic jump-landing programme was defined by; a limited number of ground contacts per session (< 50 per session), rest intervals inserted between each jump (15 seconds), and adequate recovery between daily (3 - 5 times per week) sessions (at least 24 hours).

The final study (Study 6), utilised a longitudinal controlled trial to determine the effects of the quantified jump-landing programme, on parameters of bone health in premenopausal women for a period of 12 months. Performance testing and dual energy x-ray absorptiometry (DEXA) was performed at baseline, 3, 6, 9 and 12 months. The excellent test-retest reliability demonstrated for BMD, BMC, bone geometry and body composition in Study 5 provided the ability to determine that the changes we detected over time were statistically and clinically significant. Significant ($p \leq 0.01$) group main effects (↑0.41 - ↑3.72%) in favour of the jump group were observed for bone mineral density (BMD) and bone mineral content (BMC) at the femoral neck, total hip and lumbar spine. Significant ($p \leq 0.01$) group main effects (↑2.78 - ↑3.84%) for cross-sectional area, cortical thickness and section modulus at the femoral narrow neck were also in favour of the jump group. For ground contact time, improvements in the jump group over the control group were apparent (↑21.9% vs ↓8.86%) with significant ($p \leq 0.01$) group and time effects being observed. Group main effects that approached significance (↑7.54% vs ↓0.24%) were towards the jump group for vertical jump performance. Our findings have shown that a brief (2 - 3 minute) jump programme, with a specific focus on the jump-landing technique has provided the required stimulus to improve bone strength at clinically relevant sites associated with osteoporosis in premenopausal women.

In summary, this thesis provides an original and vital contribution to preventative health care management that in the long term has the potential to reduce the direct and indirect costs of osteoporosis to the health sector. Evidence from this research has the potential to inform future exercise recommendations used to improve bone health during the critical premenopausal period, and to both reduce and delay the incidence of osteoporotic fracture in the years post menopause.

CHAPTER 1. PREFACE

1.1 Thesis Rationale and Significance

Jumping and hopping exercises have been researched for their role in the achievement of optimal peak bone mass in young people and for minimising age-related bone loss in females (Bailey & Brooke-Wavell, 2009, 2010b; Bassey, Littlewood, & Taylor, 1997; Bassey & Ramsdale, 1994b; Bassey, Rothwell, Littlewood, & Pye, 1998; Stiles, Griew, & Rowlands, 2013; Weeks & Beck, 2008). Authors of recent meta-analyses reported exercise modalities which involve impact forces as having the greatest 'osteogenic potential', suggesting hypothetical gains in bone mineral density (BMD) of 3 - 5% for premenopausal women during a time when normal bone loss is 0.5% per year (Babatunde, Forsyth, & Gidlow, 2012; Martyn-St James & Carroll, 2010). However, researchers have predominantly focused on "high risk" postmenopausal women and as a consequence, exercise regimes for minimising bone loss in adults are generic and lack specific recommendations for women before they experience accelerated bone losses during and post menopause (Gómez-Cabello, Ara, González-Agüero, Casajüs, & Vicente-Rodríguez, 2012; Guadalupe-Grau, Fuentes, Guerra, & Calbet, 2009). Thus, preventative interventions that target premenopausal women represent a "window of opportunity" to prevent or delay the time before the fracture threshold is surpassed in the postmenopausal years. Activities such as jumping and hopping have been proposed to achieve the desired unusual or atypical strain distributions on the skeleton for women who are habitually inactive and not involved in high-impact sports, however specific protocols to optimise bone health are currently lacking (Bailey & Brooke-Wavell, 2010b; Bassey et al., 1998; Tucker, Strong, LeCheminant, & Bailey, 2014).

The quantification of impact forces for jumps including the countermovement jump and drop jump have been documented by several research groups, however methodological differences have been identified which influence the ability to compare findings between studies: 1) use and non-use of arms when jumping (Lees, Vanrenterghem, & De Clercq, 2004; Richter, Räpple, Kurz, & Schwameder, 2011); 2) landing mechanics in terms of coaching a "hard" or "soft" landing (Bobbert, Mackay, Schinkelshoek, Huijing, & van Ingen Schenau, 1986; Lees, 1981; McNitt-

Gray, 1993); 3) the purpose and timing of instructions provided for jump-landings (Young, Pryor, & Wilson, 1995); 4) the use of specific footwear or barefooted condition (Bassey et al., 1997; Bassey & Ramsdale, 1994b); 5) the use of different calculations to determine the rate of strain (Bassey & Ramsdale, 1995; Hansen, Cronin, & Newton, 2011); and, 6) the use of single versus double jump-landings. Researchers have suggested that the technique utilised when jumping and landing, influences impact and force absorption, therefore the jumping characteristics selected need to reflect the context of the task of interest (Bobbert et al., 1986; Lees, 1981; Richter et al., 2011). Given the limitations identified in the literature reviewed for the quantification of impact forces for jumps, there is a clear need to conduct research using standardised jumping techniques and jump-landing instructions designed to stimulate bone osteogenesis.

Whilst previous studies have investigated the vertical landing forces for jumping exercises including the countermovement jump (Bassey & Ramsdale, 1994a; Heinonen et al., 1996; Niu et al., 2010; Tucker et al., 2014), there is a need to quantify the full spectrum of GRF's (anterio-posterior, medio-lateral and resultant) associated with a variety of commonly performed jumps, as research conducted using animal models has showed that the direction forces are applied to the skeleton is an important osteogenic consideration (Turner, 1999; Turner & Robling, 2003). Thus, osteogenic thresholds which define the minimum magnitude and rates of ground reaction forces required to achieve gains in bone mineral density in premenopausal women, currently represent vertical ground reaction forces only.

Although several studies have analysed the effect of different landings on the magnitude of jump-landing forces, previous studies concerned with bone health, irrespective of life-stage, have focussed primarily on single jump-landings. However, previous biomechanical studies have demonstrated that repeated jumps, which are more ballistic in nature, and can produce greater GRF's (when compared to single jump-landings), as they prevent subjects from "softening" the landing due to the short time period available between jumps. It is therefore of interest to determine whether repeated jump-landings can offer a better osteogenic stimulus than the single jump landings used by previous researchers (Babatunde et al., 2012; Bassey et al., 1998; Niu et al., 2010; Tucker et al., 2014).

As bone health research has predominantly focused on minimising bone losses in "high risk" postmenopausal women, exercise recommendations to improve bone health in adults are generic and lack specific recommendations for women before they experience the accelerated bone losses at menopause (Gómez-Cabello, Ara, González-Agüero, Casajüs, & Vicente-Rodríguez, 2012; Guadalupe-Grau, Fuentes, Guerra, & Calbet, 2009). Thus, future research is required to develop a longitudinal periodised osteogenic jump-landing programme specifically for pre-menopausal women using a resource of quantified jump-landing exercises (bilateral and unilateral), with consideration for different loading activity variables (including; strain magnitude, strain rate and strain direction) whilst integrating current bone health guidelines, research and concepts of best practice strength and conditioning.

Authors of meta-analyses proposed that jump-landing programmes that; utilised brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), are 4 - 18 months duration, and present loading magnitudes of between 2 - 6 BW, can result in significant gains in femoral neck BMD of 0.5 - 3% in premenopausal women during a time when normal bone loss is 0.5% - 1% per year. However, limitations exist for these jumping protocols, in terms of jump-landing technique, monitoring of the daily and weekly loading and adherence to best practice musculoskeletal programme design. In addition, the focus on jump-landing technique and utilising a reactive jump component within a 12-month periodised osteogenic training programme has not been previously presented. Furthermore, research is required to describe the geometry of bone in response to osteogenic exercise protocols, as limitations exist for using a two-dimensional imaging technique (DEXA) to assess a three-dimensional structure and describe the overall strength and fracture resistance of bone in response to the jump-landing intervention.

1.2 Research Question and Aims

Currently, there appears to be a paucity of scientific study on the use of exercise as a stimulus for bone development, specifically as a preventative osteoporosis green prescription for premenopausal women. This thesis provides original academic research on the use of specific jump-landings integrated into a periodised osteogenic jump-landing programme, as an effective way to improve bone health and contribute to the field of preventative health care. In addition, this specific programming for premenopausal women will inform clinicians, primary health workers and strength and conditioning practitioners by providing an experimental application to this body of knowledge. Therefore, this thesis will provide an original and vital contribution to preventative health care management that in the long term has the potential to reduce the direct and indirect costs of osteoporosis to the health sector. It is envisaged that the evidence from these studies will provide a unique approach for the management of bone health and the development of safe and effective exercise protocols, as existing exercise recommendations for this population are not consistent with the current evidence base. The goal is therefore to provide an effective osteogenic exercise intervention that can be used to improve bone health, body composition and performance parameters during the critical premenopausal period, to reduce and delay the incidence of osteoporotic fracture in the years post menopause.

This thesis sought to answer the overarching research question “can a periodised osteogenic jump-landing programme improve bone health, body composition and performance parameters in premenopausal women”? Six separate but related studies were used to investigate the chronic effects of a quantified periodised osteogenic jump-landing programme for premenopausal women. The specific aims of these studies were:

Study’s 1, 2 and 3) To determine whether bilateral vertical and multidirectional jumps with reactive jump-landings and unilateral multidirectional jump-landings can achieve previously determined osteogenic thresholds with and with instruction withdrawn in premenopausal women?

Study 4) To develop a periodised osteogenic jump-landing programme specifically for premenopausal women based on quantified jump-landings.

Study 5) To determine the intra-rater reliability of the Hologic Discovery DEXA machine for assessing clinically relevant bone and body composition variables in premenopausal women.

Study 6) To determine the chronic effects of a periodised osteogenic jump-landing programme on bone health, body composition and performance parameters in premenopausal women.

1.3 Originality of the Thesis

Currently, very little evidence exists in the scientific literature on the effect of exercise on bone health in premenopausal women:

- No study has quantified the full spectrum of ground reaction forces associated with jump-landings for a selection of bilateral and unilateral vertical and multidirectional jumps in premenopausal women.

- No study has investigated the use of reactive jump-landings to optimise the osteogenic stimulus for jump-landings when performed by premenopausal women.

- No study has attempted to develop a quantified 12-month periodised osteogenic jump-landing programme to be specifically utilised by premenopausal women to improve bone health.

- No study has investigated the intra-rater test-retest reliability of a Hologic DEXA (including hip geometry variables and body composition) to assess clinically relevant bone and body composition variables in premenopausal women, by providing measures of absolute (CV) and relative consistency (ICC).

- No study has investigated the chronic effects of a 12-month periodised osteogenic jump-landing programme on functional performance parameters, body composition and bone remodelling at clinically relevant sites in premenopausal women.

1.4 Thesis Organisation

This thesis is composed of four inter-linked sections and consists of nine chapters (Figure 1.1). The first section contains a comprehensive review of the literature that explores the physiology of bone, osteoporosis and current literature on the role of exercise on bone health in premenopausal women (Chapter two). The second section consists of a series of cross-sectional studies (Study's 1, 2 and 3), to determine whether bilateral vertical and multidirectional jumps with reactive jump-landings and unilateral multidirectional jump-landings (hops) can achieve osteogenic thresholds with, and with instruction withdrawn, in premenopausal women (Chapters three, four and five). An exploratory descriptive study design was used to review current and relevant evidence-based literature for Study 4, and uses the quantified data gained from the previous three chapters, to develop a periodised osteogenic jump-landing programme for premenopausal women based on quantified jump-landings (Chapter six). A test-retest reliability study design was utilised in Study 5, to determine the intra-rater reliability of a Hologic DEXA machine for assessing the dependant variable measures (bone mineral density, bone mineral content, bone geometry and body composition), to be used in the longitudinal training study (Chapter seven). A longitudinal quasi-randomised controlled trial experimental design was utilised for Study 6, to determine if differences existed between the jump-landing and control groups over a period of 12-months. This study, which utilises the results and information gained from the previous five studies, sought to investigate the chronic effects of a quantified jump-landing programme on bone health variables, body composition and performance parameters in a cohort of premenopausal women (Chapter eight).

The studies are presented in the format of the journal for which they were written, with the exception that each study is preceded by an explanatory prelude rather than an abstract. The final chapter consists of general conclusions and recommendations for clinicians, primary health workers, strength and conditioning practitioners and premenopausal women. An overall reference list from the entire thesis has been collated at the end of the final chapter in APA (6th ed.) format. An abbreviations and glossary section have been included after the reference list to help guide the reader if required. The appendices present all the relevant material from the studies including the abstracts from the scientific studies, ethics approval, participant information sheets, questionnaires, informed consent forms, and additional data. The literature review was written to summarise the research pertinent to each of the six scientific papers presented in this thesis. The review clearly demonstrates the deficiencies in our current knowledge about the role specific types of exercise for bone health for premenopausal women and establishes the significance of the scientific studies presented in chapters' three to nine. Please note that there is some repetition between the literature reviews and the introductory material of the experimental chapters, owing to the format in which the overall thesis is presented.

The data gained from the three quantification studies (Study's 1, 2 and 3; Chapters three, four and five) were used in combination with a review of relevant literature, to determine how the jumps and hops could be best utilised to develop a 12-month periodised osteogenic exercise programme (Study 4; Chapter six) specifically designed for premenopausal women to help optimise the impact stimulus required to promote bone formation. A 12-month training study (Study 6; Chapter eight) was used to measure the effects of a periodised osteogenic jump-landing programme on bone health, body composition and performance parameters in a cohort of premenopausal women. Prior to the implementation of the 12-month training study a reliability study was undertaken (Study 5; Chapter seven) with the DEXA and to determine the intra-rater reliability for assessing clinically relevant bone and body composition variables in premenopausal women.

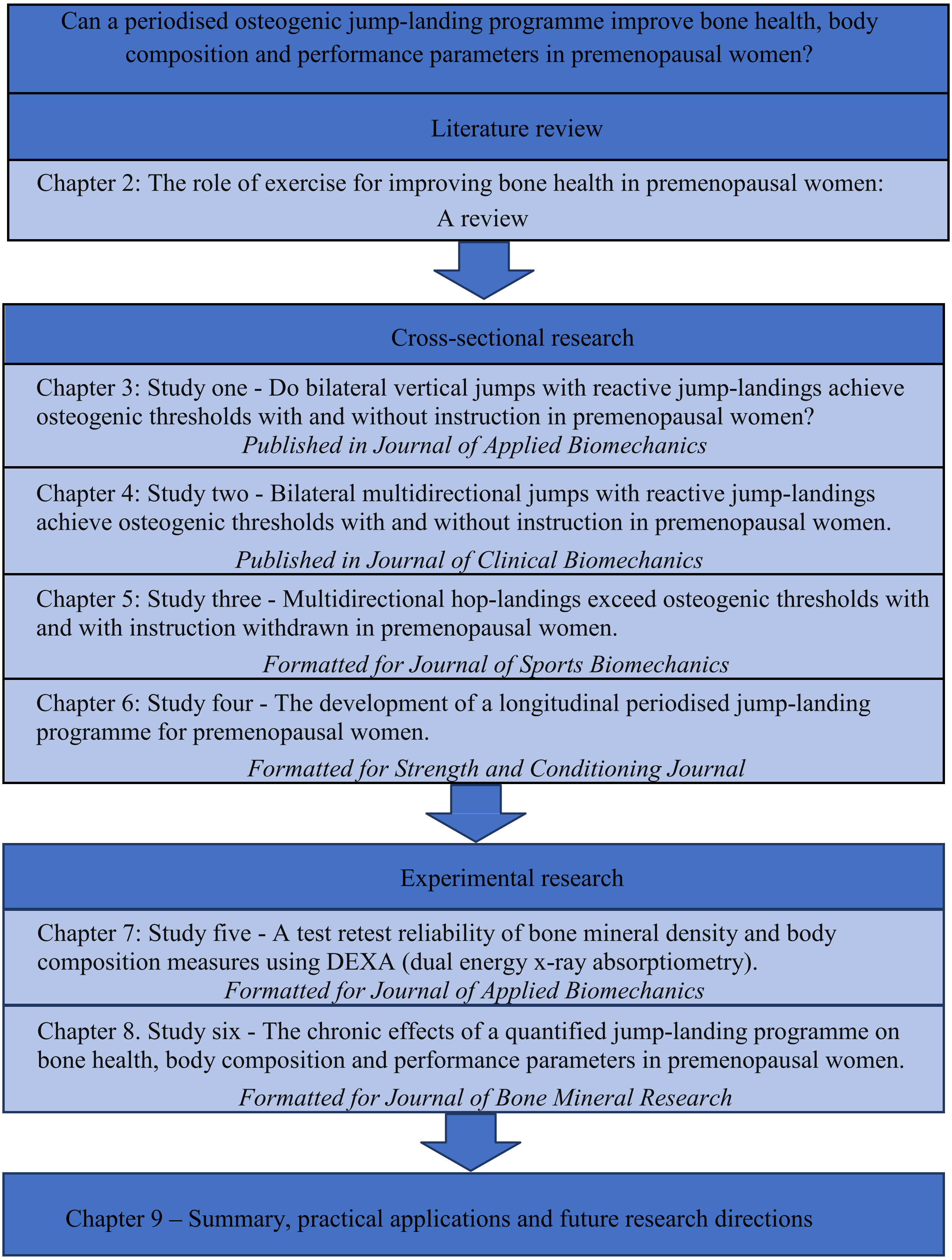


Figure 1. Thesis flowchart

CHAPTER 2. THE ROLE OF EXERCISE FOR IMPROVING BONE HEALTH IN PREMENOPAUSAL WOMEN: A REVIEW

> *"Hip fracture is all too often the final destination of a 30-year journey fuelled by decreasing bone strength and increasing falls risk" (Black et al., 2007).*

2.1 Prelude

Introduction to the problem: Osteoporosis

Osteoporosis is a condition where bone density and bone strength is reduced, and consequently there is a significantly increased risk of bone fracture (Kanis, Adachi, et al., 2013). This disease is recognised as a major public health issue in New Zealand and the developed world. Previous United Nations Secretary General, Mr Ban Ki-Moon described slowly progressing chronic diseases including osteoporosis as 'a global public health emergency in slow motion'(Ban, 2009). In New Zealand and globally, it affects more than half of women and one third of men over the age of 60 years, with 59% of women and 29% of men suffering a fracture from this age (Lippuner, Johansson, Kanis, & Rizzoli, 2009; Osteoporosis New Zealand, 2018). Approximately 52 million women and men have osteoporosis or osteopenia (low bone mass) in the United States and this will increase to more than 61 million by 2020 if additional efforts are not made to address this disease (International Osteoporosis Foundation, 2015).

The economic burden on the public health and social care system as a result of treatment and management of osteoporotic fractures is difficult to determine as often not diagnosed until a fragility fracture occurs (Ebeling, Daly, Kerr, & Kimlim, 2013). Hip fracture has been described as "the final destination of a 30-year journey fuelled by decreasing bone strength and increasing falls risk" (Black et al., 2007). A recent study in Australia estimated the direct economic cost of osteoporosis in 2017 to be AUD$3.4 billion, which is three times higher than in 2007 (Tatangelo et al., 2019). In the United Kingdom the direct costs of osteoporosis treatment exceeded 4.5 billion pounds in 2017 with over half a million people hospitalised because of a fragility fracture (D. A. Turner et al., 2018). The total direct cost of osteoporosis was $NZ330 million for the treatment and management of the 70,631 people diagnosed with osteoporosis in New Zealand in 2007, with hip fracture care alone costing NZ$105 million (Brown, McNeill, Leung, Radwan, & Willingale, 2011). These researchers also suggested that of the more than 84,000 osteoporosis-related fractures occurring that year, almost two-thirds of the fractures were women. Osteoporosis New Zealand estimated the total cost of the disease at a staggering $1 billion each year, with this figure predicted to increase rapidly as New Zealand's 1 million baby boomers began to retire in 2011.

In a recent publication 'Bone 2020', Osteoporosis New Zealand identified the need for a coordinated nationwide strategy to manage the increasing numbers of ageing New Zealanders at risk of fragility fractures. They planned to work with the Ministry of Health to coordinate a strategy which included the aim to "make a determined effort to prevent as many hip fractures as possible" (Osteoporosis New Zealand, 2013). Osteoporosis Australia, who produced the white paper document 'Building healthy bones throughout life', had also admitted "a lack of an accepted strategy for osteoporosis prevention in Australia" (Ebeling et al., 2013). They published an evidence-informed prevention strategy which identified three important and affordable preventative actions which had the potential to reduce the significant personal and economic burden of osteoporosis throughout the life cycle. These interventions focused upon ensuring life-stage specific achievement of adequate calcium and vitamin intake, and appropriate physical activity. An estimated reduction of $432 million in the direct costs of osteoporosis in Australia had been suggested if just the calcium intake and vitamin D levels were addressed (International Osteoporosis Federation; Osteoporosis Australia, 2007).

Osteoporosis Risk Factors

Osteoporosis risk factors considered non-modifiable include; being female, menopause, age, race (Caucasians especially), and genetic predisposition, however the risk of osteoporosis can be changed significantly by focusing on the readily modifiable risk factors (Table 2.1). The main factors identified with potential to have the greatest influence on reducing risk factors for osteoporosis and associated fracture risk include; 1) regular weight-bearing and muscle strengthening exercise (although guidelines for achieving this are generic and do not reflect the current evidence-base); 2) achieving a recommended daily intake of calcium (1000mg, however not more than 500mg in supplemental form); and, 3) achieving the recommended intake of vitamin D (through adequate exposure to UVB rays, or taking supplements if deficient) (Osteoporosis New Zealand, 2018). Other factors such as high protein diets, alcohol consumption, and regular use of corticosteroid medication are also considered to have a negative influence on bone health.

Although some guidelines for the management and prevention of osteoporosis have focussed on exercise and nutrition lifestyle modifications, this has mainly targeted "high risk" postmenopausal women, and as a result appeared to have had minimal effect on the global prevalence of osteoporosis (Brown et al., 2011). Researchers have predominantly focussed on increasing postmenopausal bone mineral density (BMD) and reducing incidence of fragility fractures, and as a consequence, exercise regimes for minimising bone loss in adults are generic and lack specific recommendations for the premenopausal age group. Thus, bone health promotion and preventative interventions for premenopausal women that address these modifiable risk factors represent a "window of opportunity" to prevent or delay the time before the fracture threshold is surpassed in the postmenopausal years, during a period of lowered fracture risk.

Table 2.1 Modifiable risk factors for osteoporosis (adapted from Gallagher & Tella, 2013)

Modifiable Risk Factors for Osteoporosis	**Recommendations:**
Lack of weight-bearing exercise	Regular weight-bearing and muscle-strengthening reduce the risk of falls and fractures by improving agility, strength, posture, and balance, as well as general health benefit.
Poor calcium intake (<RDI)*	A daily intake of 1200 mg of calcium is recommended for all women with osteoporosis. Natural sources of calcium instead of supplements if possible. For optimal absorption, a single dose of calcium supplement should contain about 500 mg of elemental calcium usually given as citrate or carbonate.

Vitamin D deficiency (<AI or inadequate exposure to sunlight)*	Recommend 800 IU per day of vitamin D3, including supplements if necessary, to adults over the age of 50. The goal of treatment is to maintain a serum 25-hydroxyvitamin D level greater than 20 ng per mL (50 nmol per L).
Body weight above or below recommended BMI*	Keep your body weight within a healthy range (BMI 20 - 24.9).
Poor protein intake (<AI)*	Recommend an adequate intake of dietary protein (1 g/kg/day).
Other nutritional factors	Adapt a more alkaline-forming diet. Increased intake of potassium (fruit and vegetables). Reduce intake of sodium (added salt and processed foods).
Cigarette smoking	Tobacco products are detrimental to the skeleton as well as to overall health.
Excess alcohol consumption (> 3 units/day)	Intake of 3 or more units (5oz wine, 1.5oz spirits, 12oz beer) per day is detrimental to bone health and increases the risk of falling.
Long-term use of corticosteroids or anti-convulsants	Leads to decreased calcium and vitamin D absorption.
Increased risk of falling	Falls prevention is the first line of treatment for those at high risk for falling. Consider a falls prevention programme, and physical therapy.

Key: * RDI Recommended dietary intake, AI Adequate intake, BMI Body mass index

It is well recognised that the ageing process is complex and is associated with a progressive degeneration of physical, physiological and cognitive function. This loss of musculoskeletal mass and function has been described as a normal attribute associated with ageing, which is reinforced by an unhealthy lifestyle (Nedergaard, Henriksen, Karsdal, & Christiansen, 2013). However, public health interventions targeting improvements in lifestyle factors like diet and exercise, have had limited success at a population level. Unfortunately, poor compliance to interventions promoting lifestyle modification had prompted suggestions that the primary prevention modality in the future will need to be pharmacological. Nedergaard et al. (2013), argued that pharmacological interventions like hormone replacement therapy

(HRT) would be more effective as a means to slow or prevent the age-related loss in BMD, rather than being used to treat women already diagnosed with osteoporosis. However, consideration is also needed for the different ways bone strength is represented, as studies that showed large increases in BMD and bone mineral content (BMC) resulting from pharmacologic therapy resulted in very small increases in fracture resistance (Kohrt, Barry, & Schwartz, 2009).

Babatunde (2013) proposed a paradigm shift based on the prevention model of Leavell and Clark (1965), which identified the need to consider life stage specificity for promoting preventative measures to reduce risk factors for osteoporosis. In the four-level model (Table 2.2.), primordial, primary, secondary and tertiary levels of prevention for osteoporosis were proposed. Secondary and tertiary levels of prevention represent primarily pharmacology therapy and are potentially more expensive and less effective than the primary and primordial prevention stages (Babatunde, 2013). If post-menopausal BMD is a consequence of peak BMD (achieved at skeletal maturity), menopause and the rate of bone loss as women age, then the period of growth during the pre-pubertal years is the optimal time to focus on positive interventions for maximising bone health. A theoretical analysis by researchers predicted a 13-year delay in the development of osteoporosis and 50% reduction in fracture risk with the attainment of 10% higher peak bone mass during adolescence (Hernandez, Beaupré, & Carter, 2003). Researchers also suggested hypothetical gains of 3 - 5% in bone mass during the premenopausal years, using appropriate lifestyle exercise as a primary prevention strategy (Babatunde, Forsyth, & Gidlow, 2012). However, these guidelines and specific exercise recommendations for premenopausal women, do not currently exist.

Table 2.2 Level of prevention for osteoporosis (adapted from Babatunde, 2013)

Prevention levels for osteoporosis	**Goal**	**Life Stage**	**Potential Intervention**
Primordial	Maximise peak bone mass.	Neonates to adolescence. < 18 years	Impact exercise physical education curriculum.
Primary	Modify or alter the course of risk exposure (enhance bone health before rapid onset of bone loss).	Premenopausal women. 30-50 years	Modify lifestyle factors (appropriate exercise and nutrition).
Secondary	Identification of “at risk” individuals.	Postmenopausal women	BMD testing > 50yr
Tertiary	Management of osteoporosis	Postmenopausal women Over 60 years.	Pharmacology therapy

2.1.1 Physiology of Bone

It is deemed important to have a thorough understanding about the physiology of the different types of bone, bone turnover cycles and various techniques available to assess bone. This knowledge is vital for the critique of existing bone health literature with respect to the research methodology and the age-related time course of bone change.

Types of bone

The skeleton is made up of two types of bone which are both functionally and structurally different; cortical (or compact) and trabecular (or cancellous) (Vanputte, Regan, & Russo, 2013). In the adult skeleton about 80% of bone is cortical, and the clinically relevant sites of the femoral neck and lumbar vertebrae are comprised of 75% and 66% cortical bone, respectively (Dempster & Reeve, 2006). The cortical bone is found on the outer surface of bone, and has a compact mostly solid matrix and cells, whereas the trabecular bone consists of a delicate interlaced network of marrow-filled spaces (Vanputte et al., 2013). There are two main types of bone cells involved with the turnover of bone cells with different functions within bone tissue including; osteoblasts (or bone-forming cells) which are involved with the development of the skeleton, and the repair and remodelling of bone, and osteoclasts (bone-breaking cells) which also contribute to bone repair and remodelling (Vanputte et al., 2013).

The processes of bone modelling and remodelling

Bone modelling describes the process of skeletal growth and development, whereas the purpose of bone remodelling is to repair and replace old and damaged bone and plays a key role in maintaining the mechanical strength of bone (Langdahl, Ferrari, & Dempster, 2016). Bone modelling during growth is a result of coordinated activity of the two types of bone cells, in favour of the bone forming osteoblasts. Although bone modelling is primarily completed by skeletal maturity (or peak bone mass), modelling can still occur in response to mechanical loading (i.e. jump-landings) in adulthood (Burr, 2015; Frost, 1987). Bone remodelling is also a normal process that depends on the balance between bone formation and bone resorption determined by the osteoclasts (bone resorption) and osteoblast (bone formation), and takes place within a basic multicellular unit (BMU) (Kenkre & Bassett, 2018). Constant bone turnover involves old poor quality bone being replaced by new bone matrix and is then rapidly mineralised (Clarke, 2008; Duque, 2013). One remodelling cycle takes 120-200 days (cortical and trabecular bone, respectively), and involves five highly regulated phases including the: activation phase (initiation signal to start remodelling); resorption phase (dissolving the bone mineral); reversal phase (bone resorption switches to formation); formation phase (new bone mineralisation); and, termination (mineralisation complete) as shown in Table 2.3 (Kenkre & Bassett, 2018). The adult skeleton is being constantly remodelled and renewed by this process of bone remodelling throughout life, allowing around 10% of the skeleton being replaced each year, with a new skeleton renewed every 10 years (Langdahl et al., 2016).

Table 2.3 The bone remodelling cycle (adapted from Gallagher & Tella, 2013 and Kenke, 2017)

Phase	**Process**	**Duration (Approximate)**
1. Activation	Osteoclasts recruited to the surface of the bone	Days
2. Resorption	An acidic microenvironment between the cell and the surface of the bone (dissolving or resorbing the bone mineral content), is generated by the osteoclasts.	2 weeks
3. Reversal	Osteoclasts undergo apoptosis (programmed cell death) and recruit osteoblasts to the bone surface.	4 - 5 weeks

4. Formation	Collagen is synthesised and secreted by the osteoblasts and hydroxyapatite crystals are deposited to form new bone (mineralisation).	4 months
5. Termination	Osteoblasts differentiate into osteocytes (mature bone cells), which signals the end of the remodelling cycle.	One remodelling cycle takes 120 - 200 days (cortical and trabecular bone, respectively)

Peak bone mass is normally achieved in the third decade of life (Figure 2.1), however for the spine and hip is reached in the mid-twenties and bones such as the radius will reach a peak at around 40 years (Gallagher & Tella, 2013). After the third decade of life there is an increase in bone remodelling causing an imbalance between bone formation and bone resorption, with the predominance of osteoclastic activity resulting in a normal age-related bone loss of about 0.5% a year (Geusens, Dequeker, Verstraeten, & Nijs, 1986). Osteoporosis is the most common metabolic bone disorder and is a result of the uncoupling between bone resorption and bone formation. This condition is thought to be a consequence of not achieving normal peak bone mass during growth, and an increase in bone resorption and decrease in bone formation post peak mass attainment (Babatunde, 2013). The most common type of osteoporosis is termed primary osteoporosis, and includes both postmenopausal and age-related osteoporosis, which involves structural deterioration of bone and increased porosity leading to increased fragility (Kenkre & Bassett, 2018). The progressive bone loss and increased porosity is thought to predominantly affect the trabecular bone as a result of its greater surface area, however the cortical bone is also affected (Kenkre & Bassett, 2018). It should be noted however, that osteoporotic fractures are not necessarily directly related to this steady age-related loss of bone, as many other factors including; genetics (non-modifiable), nutrition and physical activity (modifiable), are also strongly related to an increased fracture risk.

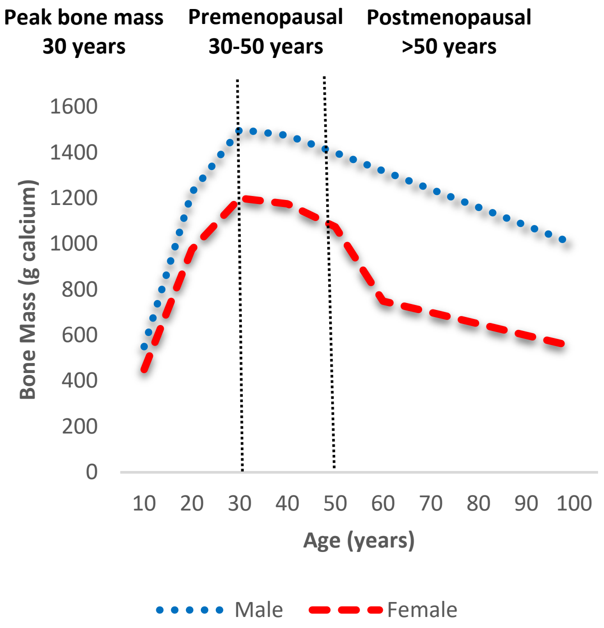


Figure 2. A typical pattern depicting age-related changes in bone mass in males and females.

The effect of age and oestrogen on bone

It is well accepted that women have less total bone mass than men and experience rapid bone loss during menopause. Generally women experience bone losses of approximately 1% per year after the fourth decade of life, however annual losses of 3 - 5% can be experienced during early post-menopause ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993). The SWAN study (2011) observed a rapid acceleration of bone loss starting the year before menopause and continuing for another three years, with the rate of bone loss still significantly high in the 4 - 8 years post menopause (Santoro, Taylor, & Sutton-Tyrrell, 2011). The National Osteoporosis Foundation of America estimated up to 20% of BMD can be lost in the 5 - 7 years after menopause, with lifetime bone losses estimated to be 30 - 40% and 20 - 30% of peak bone mass, for women and men respectively ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993; Sipila & Poutamo, 2003).

Although the exact role of oestrogen on the accelerated decay in bone health has not been completely clarified, a relationship exists between bone mineral density and endogenous oestrogen levels suggesting it is an important sex steroid linked to osteoporosis in women (Compston, 2001). Premature menopause (surgical or non-surgical and including exercise-associated amenorrhoea), which induces a state of oestrogen deficiency, has been linked to reduction in peak bone mass and BMD (De Souza et al., 2008; Scheid et al., 2011). This means that if the average age of menopause in New Zealand is 51 years, then early menopause will have a major effect on ageing the bone at a more rapid rate than normal (Lawton, Rose, Cormack, Stanley, & Dowell, 2008). Although a specific biological marker for menopause has not been identified, lowered BMD and subsequently increased risk of osteoporotic fracture has been observed when serum oestradiol is < 5pg/ml (Rapuri, Gallagher, & Haynatzki, 2004), and < 11pg/ml (Garnero, Sornay-Rendu, Claustrat, & Delmas, 2000). Rapuri and colleagues (2004), reported a significant increase in BMD when serum oestradiol was > 15pg/ml. Another research group reported oestradiol levels < 30pg/ml to generally represent menopausal status in women without ovarian or breast cancer (Winters-Stone et al., 2013).

Oestrogen receptors have been revealed on muscle and bone cells suggesting a relationship between hormone concentration, muscle and bone adaptation (Dahlman-Wright et al., 2006; Heldring et al., 2007). The role of oestrogen in a normal bone remodelling cycle involves inhibiting bone resorption by decreasing osteoclast numbers and activity and having an anabolic effect on osteoblasts, however the oestrogen deficiency experienced at menopause disrupts this process (Clarke, 2008; Gallagher & Tella, 2013; Krassas & Papadopoulou, 2001; Zofková, 2008). Bone remodelling is accelerated during menopause as oestrogen deficiency impairs the normal bone remodelling process. This process described as ‘uncoupling’, results in a net loss of bone due to an increase in osteoclastic bone resorbing activity without a corresponding increase in osteoblastic bone formation activity (Lanyon, 1996).

The mechanism and cellular effects of this menopausal oestrogen deficiency are linked to increased bone resorption induced by elevated levels of proresorptive cytokines including; Tumour necrosis factor (TNF-α) and Interleukin 1 and 6 (IL-1 & 6) in the bone marrow and up regulation of Receptor activator of nuclear factor B ligand (RANKL) production on bone marrow cells (Khosla, 2010). These research groups have identified RANKL as the uncoupling factor, which is produced and secreted by the osteoblasts, and binds to a receptor on the osteoclasts to increase bone resorption.

The key factor in the groups findings is the identification of a natural antagonist to RANKL called osteoprotegerin (OPG), which is stimulated by oestrogen. Therefore, in the reduced oestrogen environment experienced during menopause, the RANKL produced by the osteoblast binds to its receptor RANK on the osteoclasts to increase bone resorption in the absence of OPG (Gallagher & Tella, 2013).

Hormone Replacement Therapy (HRT)

Hormone replacement therapy (HRT) has been used for many years in an attempt to offset oestrogen deficiency and manage the symptoms of menopause. Postmenopausal women treated with exogenous oestrogen have shown reversal of the decrease in bone mass and increase in bone turnover, thus supporting the bone protective effect of oestrogen (Copeland, Chu, & Tremblay, 2004; Duque, 2013; Horstman, Dillon, Urban, & Sheffield-Moore, 2012; Johnson et al., 1997; Kenny & Prestwood, 2000; Khosla, 2010). Thus, some researchers recommended that postmenopausal women might be at increased risk of osteoporosis and related fractures without the use of hormone replacement therapy (Johnson et al., 1997; C. H. Turner, 1999).

Findings from the Women’s Health Initiative study however, showed that the risks of HRT to cardiovascular health may outweigh the benefits’ and alternative options may be warranted (Writing Group for the Women's Health Initiative, 2002). This study reported a significant relationship between the use of combined oestrogen and progestin therapy with increased risk of breast cancer, coronary heart disease and stroke in postmenopausal women. As a result, the U.S. Preventative Services Task Force (USPSTF), and several other professional groups, issued recommendations against using HRT (oestrogen plus progestin and oestrogen alone), to prevent chronic conditions such as cardiovascular disease, dementia and osteoporosis ("Hormone Therapy for the Prevention of Chronic Conditions in Postmenopausal Women: Recommendations from the U.S. Preventive Services Task Force," 2005; "Postmenopausal Hormone Replacement Therapy for Primary Prevention of Chronic Conditions: Recommendations and Rationale," 2002). A systematic review to update the 2005 USPSTF recommendations concluded that the benefits of HRT to chronic disease prevention benefits, including fracture reduction, did not outweigh the harms in postmenopausal women (Moyer, 2013; Nelson, Walker, Zakher, & Mitchell, 2012).

2.1.2 Measurement of Bone

Bone mineral density (BMD) and hip structural analysis (HSA)

The measurement of bone mineral density (BMD), using bone densitometry, is well accepted as a major determinant when defining the risk of osteoporotic fracture (Kanis, 2002; Kanis, Adachi, et al., 2013; Kanis & Kanis, 1994). Currently the tool considered the 'gold standard' in the diagnosis and management of osteoporosis is DEXA (Dual Energy X-Ray Absorptiometry) due to the strong correlation with fracture risk using World Health Organisation (WHO) T-score criteria (Kanis & Kanis, 1994). The World Health Organisation (WHO) originally defined a threshold in the distribution of BMD represented by a T-score (2.5 standard deviations below the young normal mean) for which osteoporosis could be designated. They also identified a second threshold, describing low bone mass or osteopenia (1 - 2.5 standard deviations below the young normal mean) ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993; Kanis & Kanis, 1994). This definition describes the young normal mean as the ideal or peak BMD of a healthy 30-year old adult. Researchers (Drake, Clarke, & Lewiecki, 2015) have demonstrated that the hip and lumbar spine are fracture sites most frequently associated with postmenopausal osteoporosis, which are primarily a consequence of trabecular bone losses due to oestrogen deficiency, however the hip is considered the most severe osteoporosis complication (Kanis, 2002).

Osteoporosis is characterised by decreased bone strength leading to an increased risk of fracture, however bone density is only one of the contributors to bone strength (Hart et al., 2017). Put simply, bone strength can be described as a combination of both bone mineral density and bone quality. Several factors have been identified to describe bone quality including; bone micro and macro architecture, bone material properties and bone remodelling levels (Asikainen, Kukkonen-Harjula, & Miilunpalo, 2004; Chopin et al., 2012; Hart et al., 2017). This suggests that the accelerated bone loss experienced at menopause that is related to an increased fracture risk may not be exclusively described by BMD. In what has been described as a "prevention paradox", more than 50% of women and 70% of men who presented with fragility fractures in a large scale study in the US, did not have BMD in the osteoporosis range (T score < 2.5) (Siris, Miller, Barrett-Connor, & et al., 2001). Furthermore, studies have shown 75 year old women to have four to seven times greater fracture risk than 45 year old women with the same BMD (Burr, 2003). Interestingly, a study showing a 9 - 15% increase in BMD and BMC resulting from pharmacologic therapy only resulted in a 7 - 21% increase in fracture resistance (Kohrt et al., 2009). In comparison, studies which utilised mechanical loading achieved smaller gains in BMD and BMC (5 - 7%), however this potentially translated to very large increases in bone strength and resistance to fracture (64 - 94%) (C. H. Turner & Robling, 2003).

Although BMD represents an important but not exclusive dimension of bone strength (describes 50 - 70% of the strength of bone) (Ammann & Rizzoli, 2003; Cheng et al., 1997; Kanis, 2002), with geometric properties relating to the complex three-dimensional nature of bone also playing an important role in determining the strength of bone and predicting fracture risk (Kaptoge et al., 2008). Due to limitations resulting from the two-dimensional analysis provided by DEXA to determine BMD, a complex biomechanical indice was derived based on hip structural analysis (HSA) (T. J. Beck, Ruff, Warden, Scott, & Rao, 1990). This programme not only measured BMD of the hip area, but also estimated the geometrical and mechanical properties using cross-sections traversing the proximal femur at sites of clinical significance. Geometric properties relating to the complex three-dimensional nature of bone such as; bone girth (cross-sectional area), cortical bone thickness and section modulus (geometric index of bone bending strength), have been shown to play an important role in determining the strength of bone and predicting fracture risk (Kaptoge et al., 2008).

Although limitations exist for using a two-dimensional imaging technique to assess a three-dimensional structure, the HSA programme provides an opportunity to assess variables used to describe the overall strength and fracture resistance of bone. When comparing HSA, computed tomography (CT) and quantified computed tomography (QCT), researchers suggested that the geometry of the proximal femur was well described by DEXA (Ohnaru et al., 2013; Prevrhal et al., 2008). For example, data from these studies using postmenopausal women used both CT and DEXA (using HSA), to scan the proximal hip, and reported a favourable comparison for these scanning techniques ($r^2 = 0.67$ and $r^2 = 0.60 – 0.90$, $p \leq 0.001$ for femoral neck BMD), supporting the validity of using HSA for deriving geometric properties (Ohnaru et al., 2013; Prevrhal et al., 2008).

Bone turnover markers (BTM's)

Although BMD measurements can offer useful information, it has been argued that due to the length of the bone remodelling cycle, DEXA measurement may not be sensitive enough to detect the short-term bone turnover response to exercise interventions. A period of 1 or 2 years has been suggested necessary to detect significant change in BMD in response to therapy, whereas a rapid and large bone turnover response can be detected after only 2 - 3 months (Dreyer & Viera, 2010). Bone turnover markers (BTM) can reflect the dynamic nature of bone not assessed by BMD or clinical risk factors using the FRAX tool (Fracture Risk Assessment Tool), and reflect the metabolic activity of bone (Dreyer & Viera, 2010).

Many bone diseases (including osteoporosis), display an imbalance in the coupling of bone turnover where resorption markers are higher than formation markers leading to increased bone turnover, which indicates the value of utilising this technology (S. Vasikaran, Cooper, et al., 2011). Markers of bone turnover are categorised as either markers of formation or resorption and can be used to monitor acute changes in bone and are measured in the blood or urine to reflect the metabolic activity of bone (Dreyer & Viera, 2010). A systematic review of bone turnover markers by the International Osteoporosis Federation (IOF)/International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) Bone Marker Standards Working Group recommended that serum Procollagen Type I N-Propeptide (P1NP) and Type I Collagen C-Telopeptide (CTx) should be used as reference markers of bone formation and resorption, respectively (S. Vasikaran, Eastell, et al., 2011). P1NP is secreted by the osteoblast during bone formation and reflects type I collagen synthesis as an important precursor component of the bone matrix, and CTx is a degradation product of type I collagen released into the circulation during resorption of bone (S. Vasikaran, Cooper, et al., 2011).

The measurement of biochemical BTMs has been described as an easy and non-invasive way to assess skeletal turnover, however more work needs to be done in this area for changes in bone metabolism to be used in the assessment of treatment effects and to predict fragility fracture risk (S. Vasikaran, Eastell, et al., 2011). Their use in clinical practice for osteoporosis management has potential due to ability to achieve rapid and large responses to therapies which can be detected at early time points (S. D. Vasikaran, 2008). In postmenopausal women it has been suggested that high levels of BTMs may predict fracture risk independently from BMD, but although they have been used for this purpose for many years, there is a need for adopting international reference standards (S. Vasikaran, Cooper, et al., 2011).

BTMs have been used for use in monitoring the response of individuals to anti-resorptive treatments, as the markers have potential to show larger and faster changes than BMD. For example, after only 8 weeks of treatment with anti-resorption agent alendronate, the mean change in bone resorption marker CTx was a decrease of 75% as compared to baseline. In comparison, a 4% change in BMD was determined after 12 months of treatment with alendronate (S. Vasikaran, Eastell, et al., 2011). The authors of reviews assessing BTMs have suggested that the magnitude of change in bone turnover is similar to that shown by bone histomorphometry, and that fracture risk reduction using BTMs can explain between 28 - 77%, compared to 0 - 28% for change in BMD (Eastell, Jacques, & Naylor, 2012). This suggests that improved bone microarchitecture resulting in increased bone strength, as a result of a specific osteoporosis treatment, may be detected by measuring BTMs but not BMD alone.

Although studies have shown that the use of BTMs to determine the effect of osteoporosis treatments to prediction of bone loss and fracture risk reduction are promising, it is important to consider the pre-analytical and analytical variability of BTMs for use in clinical studies. As BTMs are dynamic variables, they can be affected by many factors leading to high variability. Several uncontrollable factors include; age, gender, climate and country, which justifies the need for age and gender-related reference intervals for identified BTMs in specific populations. These have recently been developed in the Australian population for the BTMs recommended by the IOF/IFCC (Jenkins et al., 2013). The controllable factors which affect variability in BTM assessment are listed below:

1. **Time of day:** Diurnal variation has been described, with a greater influence of circadian rhythm for bone resorption than for bone formation markers. For CTx this marked circadian variation is well understood showing a range between ± 30% and ± 35%, with the most dramatic rate of change during the morning (Chubb,

2012; Qvist, Christgau, Pedersen, Schlemmer, & Christiansen, 2002). It appears that use of carefully timed morning samples, or early afternoon may reduce this impact and standardise sampling protocol for CTx.

2. **Food intake:** It is accepted that fasting reduces the intra-individual biological variability. One study of post-menopausal women showed a variation between patients who were fasting compared with non-fasting of ± 8.8% vs ± 35% for serum CTx (Christgau et al., 2000). A study assessing short-term jump activity on bone metabolism failed to detect any changes in bone resorption turnover markers, however stated that this was due to the lack of fasting and variability in time of day for blood draws (Kishimoto, Lynch, Reiger, & Yingling, 2012). The authors concluded that lack of control of nutritional status prior to blood draw was most impacting on CTx levels, and that CTx values may be reduced by 50% following feeding. In contrast, P1NP has the practical advantage of being very stable and little affected by food intake, thus fasting is not necessary (Dreyer & Viera, 2010).

3. **Physical activity over the past 24 hours:** To reduce biological variability, it has been suggested that sampling should be performed in individuals who have abstained from exercise in the previous 24 hours. However, recreational exercise is unlikely to affect CTx or P1NP levels (Chubb, 2012).

4. **Serum vitamin D:** Changes in vitamin D levels can acutely influence bone turnover and consequently levels of BTMs. Thus, clinical trials need to account for serum vitamin D for standardisation of sample collection (Jenkins et al., 2013).

5. **Lifestyle factors:** Smoking habits, alcohol consumption and body mass index (BMI), have been shown to affect the pre-analytical variability of BTMs (Glover, Garnero, Naylor, Rogers, & Eastell, 2008).

6. **Sample storage temperature**: To preserve BTM stability it is recommended to store samples within 4 hours of collecting. The immediate storage of CTx and P1NP serum samples at -80°C has been shown to be stable for several

months, and if freeze-thawing cycles are avoided, this can be extended to 1 - 3 years (Stokes, Ivanov, Bailey, & Fraser, 2011).

7. **Method of automated assay:** Fully automated assays can be utilised to rapidly and precisely determine BTMs resulting in improvement in the variability of measurements (Chubb, 2012).

8. **Oral contraceptive use:** This is associated with reduced CTx concentrations in users compared with non-users (de Papp et al., 2007; Stokes et al., 2011).

9. **The phase of the menstrual cycle**: This can also have a mild influence on CTx concentrations, with higher concentrations of approximately 9.5% shown in the follicular phase (Clowes et al., 2002; Gass, Kagan, Kohles, & Martens, 2008; Glover et al., 2008). Authors of reviews stated that generally an increase of 10 - 20% in bone resorption and bone formation markers occurs in the follicular and luteal phases respectively, and suggest sample collection during the first 3 - 7 days of the menstrual cycle (Garnero et al., 2000; Hlaing & Compston, 2014).

10. **Previous fracture:** BTM concentrations are known to be significantly elevated in the first 4-weeks post-operation and will gradually decline over the following 12-months. It has been suggested that BTM samples should not be collected for 3 - 6 months following a fracture, when analysing osteoporosis treatments (Moghaddam et al., 2011).

11. **Seasonal variation (circannual variation):** Longer term biological variation has been suggested as evidenced from several studies that have shown variations in CTx levels coinciding with seasonal changes in 25-hydroxyvitamin D concentrations. A recent Australian study detected lower CTx levels in autumn compared to higher levels in spring, however this seasonal variation was not shown in the bone formation marker P1NP (Jenkins et al., 2013). They proposed this observation of increased bone turnover, leading to a net increase in bone resorption, during the winter to be partly explained by a combination of decreased physical outdoor activities and subclinical vitamin D deficiency.

12. **Corticosteroid use:** The use of corticosteroids (prednisone 5mg or equivalent), can acutely inhibit bone formation markers, including P1NP. Higher doses of corticosteroids (prednisone 7.5mg or more exceeding three months), will also cause an increase in bone resorption markers (Ton, Gunawardene, Lee, & Neer, 2005).

13. **Country and ethnic origin:** The literature shows that amongst Caucasian women in different countries, P1NP values are very similar however CTx values can show marked variation (Jenkins et al., 2013). However, the difference in CTx reference intervals shown between studies may reflect failure to standardise for many of the controllable factors already described. Thus, population and ethnic specific reference intervals should be used to as standards for bone turnover interpretation.

Note: Due to the high variability, error and cost associated with BTM's, bone marker analysis (personal communication, Professor Mary Jane De Souza 4th April, 2016), this method was not be utilised in the proposed training study. However, the information gained from BTM literature has provided a greater understanding of the factors to be considered in the design and interpretation of bone health research.

2.2 Jump-Landings that Supersede Bone Health Threshold Requirements for Premenopausal Women

2.2.1 Introduction

Osteoporosis is a disease characterised by a reduction in the density and quality of bone leading to a weakness of the skeleton and associated increased risk of fracture (Kanis, Adachi, et al., 2013). This disease is recognised as a major public health issue in New Zealand and globally, affecting more than half of women and one third of men over the age of 60 years (Lippuner et al., 2009; Osteoporosis New Zealand, 2018). Osteoporosis is largely preventable, with specific types of exercise being widely recognised as the leading green prescription. Exercise has been shown to reduce risk factors for lifestyle-related diseases such as obesity, cardiovascular and metabolic disease (McArdle, Katch, & Katch, 2006; Tipton & Medicine, 2006) however, not all exercise provides the stimulus required to be osteogenic (B. R. Beck, Daly, Singh, & Taaffe, 2017; C. H. Turner & Robling, 2003).

It has been suggested that jumping can produce an osteogenic response using low repetition, rapid-onset, high-intensity protocols (Bailey & Brooke-Wavell, 2008, 2010b), as researchers using animals studies have shown the relationship between impact forces and the influence of this type of loading on bone strength, mass and geometry (Lanyon, 1996). Although the optimal dose of exercise is yet to be determined for premenopausal women, researchers have established several criteria deemed necessary to stimulate bone in this population, including: a force magnitude of greater than 3-body weights (BW); a rate of force development exceeding 43-body weights per second ($BW{\cdot}s^{-1}$); and, an unfamiliar or diverse direction of force application (Bassey, Rothwell, Littlewood, & Pye, 1998; Robling, Burr, & Turner, 2001; C. H. Turner & Robling, 2003). However, an in depth understanding of the magnitude and rate of these impact forces in relation to various jump types is unknown. In addition, information about the osteogenic potential and bone-loading forces of different types of exercise would be beneficial to the development of exercise regimes to promote bone formation in premenopausal women. Therefore, the purpose of this literature review is to: determine those jumps and conditions that meet osteogenic threshold requirements for premenopausal women; identify the limitations in the research thus far; and, detail future research directions in this area for this specific population.

2.2.2 Literature Search Methods

The aim of the search strategy was to find articles that quantified the magnitude and rate of loading from jump-landing GRFs in premenopausal women. The databases searched were Academic Search Premier, SPORT Discus, PubMed, MEDLINE, and CINAHL. Literature searches were undertaken using several key words including; 'osteogenic exercise', 'strength and conditioning', 'resistance training', 'premenopausal', 'impact exercise', 'jumping', 'jump-landing', 'ground reaction forces', 'osteogenic threshold', 'bone mineral density', 'bone geometry', 'jumping technique', 'jump-landing technique, hard-landing', soft-landing', 'ballistic jump', 'reactive jump', 'plyometrics', and 'bone health'. Only English language articles published in peer-reviewed journals were considered. Relevant literature was also sourced from searches of related articles and books arising from the reference list of those obtained from the database searches. Five studies (Table 1) were found that met the inclusion criteria which included; being female; between 30-51 years; the measurement of GRF's for jump-landings using force plate technology (magnitude and rate), a bone health focus, and mean data presented for a sample size of at least 10 participants.

2.2.3 Summary of the Research

Participants

A total of 163 participants were involved in the studies outlined in Table 1. All five studies used healthy adult female participants classified as premenopausal, with an average age of 36.7 years. The premenopausal stage is defined as representing the time after the attainment of peak bone mass (around 30 years) and before the onset of hormonal changes associated with menopause (around 51 years) (Gallagher & Tella, 2013).

Table 2.4 Quantification studies for ground reaction forces for jump-landings for premenopausal women

Authors	Participants	Type of Jump Arm Swing	GRF Magnitude	GRF Rate	Jump Height (cm) and Direction
(Bassey & Ramsdale, 1994)	n = 14 females, 32.0 ± 1.2yr	Submaximal CMJ Continuous Arm Swing	>3 BW	>43 BW·s^{-1}	8cm Vertical only
(Bassey et al., 1998)	n = 20 females, 38.4 ± 7.4yr	Submaximal CMJ Continuous Arm Swing	>3 BW	>43 BW·s^{-1}	8cm Vertical only
(Bailey & Brooke-Wavell, 2009)	n = 45 females 32.9 ± 2.4yr	Submaximal Hops Continuous No Arm Swing	2.5 - 2.8 BW	Not stated	10-12cm Multidirectional
(Stiles, Griew, & Rowlands, 2013)	n = 47 females 39.2 ± 6yr	Low CMJ High CMJ Box jump Continuous No Arm Swing	2.4 BW 3.0 BW 3.4 BW	50 BW·s^{-1} 100 BW·s^{-1} 175 BW·s^{-1}	<5cm >5cm 20cm Vertical only
(Tucker, Strong, LeCheminant, & Bailey, 2014)	n = 37 females 41.1 ± 4.4yr	Maximal CMJ Singular Arm Swing	3.8 - 4.1 BW	217 - 243 BW·s^{-1}	38cm Vertical only

Key: GRF Ground reaction force; BW Body weight; BW·s^{-1} Body weights per second; CMJ Countermovement jump

2.2.4 Discussion

It is well accepted that bone responds optimally to the net effect of different loading activity variables (including; strain magnitude, strain rate and strain direction), and these loading variables collectively contribute to the overall osteogenic effect of mechanical loading and are as such interlinked and interdependent (Hart et al., 2017). Therefore, the jump-landing strategy utilised and a variety of other factors including; type of jump-landing instruction, use of arms and type of footwear, can have a significant effect on landing forces, and therefore need to be considered for determining appropriate exercise which can benefit bone. A discussion of the factors identified in this review to be considered when selecting exercises, and the instructions provided for jump-landings, with potential to optimally stimulate an adaptive bone response are presented. Please note that findings from the studies reviewed were combined with relevant longitudinal research where appropriate, which have investigated osteogenic loading in premenopausal women:

2.2.4.1 Load magnitude

From Wolff's Law we understand that bone has the ability to adapt to mechanical loading, suggesting that mechanically-induced strain is a key factor which affects bone formation. A graded dose-response relationship exists for load magnitude and change in bone mass, with an upper 'minimum effective strain' threshold described where damage to bone can occur with excessive loading (Lanyon, 1987). Studies using rat tibia and ulnar determined a linear relationship between the magnitude of an externally applied load and bone strain magnitude (Hsieh, Wang, & Turner, 1999). This has justified the measurement of GRF, represented as body weight (BW) to be used to estimate the influence of this loading on bone. Bassey and colleagues (1998), previously defined a vertical osteogenic threshold for GRF magnitude (>3 BW) which they developed after they achieved significant gains in femoral BMD using a bilateral jump-landing intervention with premenopausal women (Bassey et al., 1998). However, GRFs of 2 - 6 BW have been previously shown to stimulate bone and result in bone formation (Babatunde et al., 2012; Bassey et al., 1998; Zhao, Zhao, & Zhang, 2014). A variety of jumps were quantified in this review, however most of the studies (80%) used a vertical or countermovement jump (CMJ). Although these studies utilised the same type of jump, the GRF magnitudes ranged from 2.4 to 4.1 BW, which may reflect the different CMJ techniques utilised in the different studies. For example, one research group reported GRF's for vertical hops performed maximally which did not achieve (2.5 - 2.8 BW) the accepted osteogenic threshold, however they speculated that the single-leg landing forces may be equivalent to a total landing force of 5 - 6 BW's due to forces being transmitted through one leg only, and therefore easily exceeded the bone stimulation threshold for GRF magnitude.

Effect of Jump-landing Instruction

As can be observed from studies in this review, there is a great deal of variability (2.4 - 4.1 BW) associated with the measurement of peak vertical GRF during jump-landings, highlighting the need to identify the factors that affect this variability. Lees

(1981) reported significant variation in the magnitude of peak GRF's occurring during the first 150-200 ms of landing, which was described as the 'impact absorption phase' (Lees, 1981). In the absence of specific jump-landing instruction, some subjects will bend their knees considerably after landing, whereas others will make only a small downward movement and land "stiffly" (Bobbert, Huijing, & Van Ingen Schenau, 1987). Lees (1981), described a jump with increased knee flexion as a "soft" landing as the absorption of impact energy by the leg musculature over a longer time resulted in reduced peak GRFs.

Four of the studies in this review used submaximal continuous jumps (either sets of 10 or 20) and reported peak landing vertical forces which corresponded to 3 BW's, with instructions provided for participants to land with flexion of the ankles, knees, and hips, followed by a heel strike (Bassey & Ramsdale, 1994; Bassey et al., 1998; Stiles et al., 2013). One study utilised the same landing instructions, however the subjects performed a single maximal jump and rested for 30 seconds between repetitions, and reported greater peak landing forces of 3.8 to 4 BW (Tucker et al., 2014). It would seem from these results that the instruction provided for landing ("soft" or "stiff") affects the landing GRFs, and therefore needs to be considered carefully in programming for osteogenesis.

Effect of Arms

Researchers attempting to determine the influence of arm swing during jumping have reported that an inconsistent arm swing whilst jumping increased variability between trials, and have suggested that efficient use of arm swing can increase jump height by 10 - 20% (Lees, Vanrenterghem, & De Clercq, 2004; Richter, Räpple, Kurz, & Schwameder, 2011). Bassey and colleagues (1998), stated that jump heights for their premenopausal participants were only 8.9 ± 5 cm (3 BW) using a countermovement arm swing, whereas the Tucker et al. (2014) study cued a vigorous arm swing but also instructed participants to jump as high as they could, which resulted in baseline vertical jump heights of 34 ± 11 cm (4 BW). Interestingly, the osteogenic threshold for GRF magnitude (> 3BW) was achieved for jump-landings for both studies, despite the large variability in jump heights (i.e. 8 cm vs 34 cm). Three things are apparent from these findings: 1) what a subject does in the landing phase would seem more important than the propulsive phase in terms of stimulating bone; 2) if all else was equal in terms of instruction regarding landing, then the GRFs of those who jump higher would be greater; and, 3) since arm action can increase jump height substantially then there is the potential to also increase landing forces and therefore the osteogenic stimulus substantially.

Effect of Footwear

All five studies stated that the jumps were performed barefooted. Bassey et al. (1998), instructed participants to remain in working clothes to perform the 10-minute jumping routine (inclusive of gentle warm-up and mobilisation exercises), and stated that all jumps were in the barefooted condition. Early research by Bassey and Ramsdale (1994) compared jumping activities with subjects 'wearing' and 'not wearing shoes' to determine the effect on GRF's. They concluded that the natural elastic components of the body provided a greater protective effect than artificial footwear against excessive load during voluntary exercise. In addition, consideration is needed for the attenuation of forces that can be attributed to the cushioning influence of shoes. Thus, footwear is a factor to be considered and clarified when: assessing the magnitude of forces generated in bone; prescribing jump-landing programmes; and, informing future research in this area.

2.2.4.2 Load rate

Although GRF magnitude is considered an important factor in bone adaptation, the load rate (rate of force development) is considered as equally important (Lanyon, 1987; Robling, Castillo, & Turner, 2006; C. H. Turner & Robling, 2003). Lanyon (1996) modified the original 'minimum effective strain' theory to include other osteogenic factors such as the rate of strain (minimum effective strain-stimulus theory), proposing that the rate a bone was exposed to load was more important than the magnitude of the load on influencing the adaptive response (Robling et al., 2001; C. H. Turner & Robling, 2003). This concept suggested that the mechanisms identified for providing the greatest influence for stimulating bone formation are a function of both peak GRF and peak rate of force production (O'Connor, Lanyon, & MacFie, 1982), implying if peak rate of force production is sufficiently high, then bone adaptation can be stimulated without using high force magnitudes (Lanyon, 1987; O'Connor et al., 1982; C. H. Turner & Robling, 2003).Thus, both peak magnitude and loading rate are considered an appropriate way to represent osteogenic thresholds.

Bassey and colleagues (1998), previously defined a vertical osteogenic threshold for load rate (>43 BW·s^{-1}) which they developed using a bilateral jump-landings intervention that achieved significant femoral BMD gains in premenopausal women (Bassey et al., 1998). As can be observed from the studies reviewed in Table 1, there is a great deal of variability (43 - 243 BW·s^{-1}) associated with the measurement of peak rate of force development during jump-landings, highlighting the need to identify the factors that affect variability.

Effect of Jump-landing Instruction

The rate of force development values reported in this review ranged from 43 - 243 BW·s^{-1} for vertical and CMJ's. Tucker and colleagues (2014) described an average rate of strain for vertical jump-landings of 243 BW·s^{-1}, which far exceeded the previously defined osteogenic threshold (43 BW·s^{-1}), and the load rates reported by the other studies in this review (43 - 100 BW·s^{-1}). The rate of force development landing forces was 400-600% greater for the participants in the Tucker study than those reported by the other studies in the review, interestingly this 400-600% increase is similar to the greater jump heights observed in the participants in this study. Although the big difference in the participants jump heights did not seem to influence GRF magnitude, as described previously, it appears to have affected GRF rate dramatically. Another factor to be considered is the instructions given regarding continuous versus discontinuous jumping. Tucker and colleagues (2014), were the only researchers who cued their participants to jump maximally, rest (30 seconds) and then jump again, whereas all of the other studies in the review utilised submaximal sets of ten jumps or hops, with rest interspersed between each set. Thus, it could be hypothesised that maximal jumps performed singularly may have a greater effect on landing load rate than load magnitude, however this requires further investigation.

Researchers have indicated that repeated jump-landings had potential to heighten bone stimulation (Bobbert et al., 1987; Bobbert, Mackay, Schinkelshoek, Huijing, & van Ingen Schenau, 1986; Lees, 1981; Lees et al., 2004). Repeated jumps, were shown to be more ballistic in nature and prevented subjects from "softening" the landing due to the short time period available between jumps (McNitt-Gray, 1993). With repeated jumps (i.e. jump immediately after the initial jump-landing), participants were instructed to push off quickly after landing and potentially utilise the elastic energy absorbed during the brief landing during the subsequent take-off (McNitt-Gray, 1993). It is therefore of interest for future research to investigate the effect of utilising a reactive or repeated (but not continuous) jump landing whilst cueing for maximal jump height to gain a better understanding of how the repeated jump technique can influence GRF's with respect to the rate of force development. Furthermore, the measurement of GRF's for jump-landings with instructions provided for the jump-landing phase (cueing participants to land 'stiffly' and to utilise a flat-footed ground contact), as well as the propulsive jumping phase (utilise a vigorous arm swing and jump maximally), to compare with osteogenic thresholds previously shown to increase bone mass in premenopausal women is warranted.

Effect of Arms:

The studies in this review provided a variety of different instructions for arm position during jumping or no specific cueing about the use of arms. Three studies out of five, stated the use of an arm swing during jumping, whereas the remaining two studies either provided no instructions or placed no restrictions on arm movement throughout the jumping activities. Although Bassey and colleagues (1994, 1998), used a countermovement arm swing for the CMJ, they stated that the jumps were submaximal and could not be described as athletic. Tucker et al. (2014), on the other hand described the countermovement swing they utilised as vigorous to compliment a maximal CMJ. Interestingly, the landing load rate range for participants employing a vigorous arm swing was 200 - 250% greater than for the study which reported CMJ's (>15 cm), performed without using an arm swing. Therefore, arm swing may be a factor to be considered in future research, with potential to influence the rate of force development for jump-landings in premenopausal women.

Effect of Footwear:

All of the studies in this review performed the jump-landings without shoes, whilst utilising a firm surface. As a wide range of values for GRF loading rates were reported across the five studies, further research is needed to understand the influence of footwear on the resulting landing GRF's when performing jumps.

2.2.4.3 Load direction

All studies in this review involved jumping in the vertical plane, however one study used unilateral multiplanar jumps (Bailey & Brooke-Wavell, 2010b). Researchers have stated that bone adaptation is blunted by habitual patterns of loading (e.g. walking and running), so novel or diverse loading patterns are required to stimulate an adaptive bone response (Lanyon, 1996; C. H. Turner & Robling, 2003). Thus, exercises such as jumping and hopping, which are considered to provide 'unusual' or 'unfamiliar' patterns of loading have been shown to have a greater osteogenic effect than landing force magnitude alone, with bone adaptation being observed at much lower GRF's when these non-habitual strains are applied (Lanyon, 1987; C. H. Turner & Robling, 2003). Furthermore the 'error strain distribution hypothesis' suggests that unusual or novel directions of force application may have a greater osteogenic effect than magnitude and is therefore vital to osteogenesis (Lanyon, 1987, 1996). Although one study in this review included multidirectional jump-landings, it should be highlighted that all of the studies reported GRF's in the vertical direction only. As osteogenic thresholds, and all available GRF jump-landing data is represented in the vertical direction only, research is required for quantifying multiplanar jump-landings (i.e. star jumps, stride jumps, multi-directional hops), across all planes of motion (i.e. anterio-posterior, medio-lateral and resultant). In addition, research to determine the contribution of each GRF vector to the overall osteogenic stimulus for bone is warranted.

Effect of Jump-landing Instruction

As only one study in the review has included multiplanar jump-landings performed by premenopausal women, there is clearly a need for further research in this area. Although Bailey and Brooke-Wavell (2010), instructed their participants to precede the hop with slight knee flexion (countermovement), they provided no specific instruction for jump-landings. Thus, future research is required to explore the effect of cueing participants to land 'stiffly' and to utilise a flat-footed ground contact for multidirectional jump-landings. In addition, the ability to interpret unilateral and multiplanar jump-landing forces with respect to osteogenic thresholds (magnitude and rate) previously established using bilateral vertical jump-landings is needed.

Effect of Arms

It may be speculated that aggressive arm movements in the anterior posterior direction would increase jump distance and landing forces in this plane of motion, similar to the effects of upward arm movement on vertical GRF. However, no description or standardisation for use of arms was provided for the study utilising multiplanar jump-landings. Thus, further research is needed to understand the influence of arm swing on the resulting landing GRF's when performing multidirectional jumps.

Effect of Footwear

Although only one study in this review investigated multiplanar jump-landings, the participants performed the jump-landings in the unshod condition. Thus, further research is needed to understand the influence of footwear on the resulting landing GRF's when premenopausal women perform multiplanar jumps.

2.2.5 Conclusion

Although the authors of the studies in this review stated that to confer the greatest benefit to bone you need to subject the skeleton to large magnitude forces at rapid loading rates, none provided the instructions or specific cueing for the jump-landing phase to optimise bone stimulation for premenopausal women. Therefore, further research is warranted to investigate the effect of specific cueing (i.e. think of the ground as a hot plate and try to land 'stiffly') on jump-landing GRF's in premenopausal women. In addition, the effects of repeated or reactive jump-landing need to be investigated, as it appears that this technique has potential to influence impact and force absorption, and therefore the osteogenic effectiveness of selected jumps. Furthermore, factors such as jump effort, arm swing and footwear also require additional research focus to be able to clarify the influence of these variables on jump-landing GRF's.

Currently GRF data is limited for different jumping movements and has been presented in the vertical plane only. Thus, future studies are needed to quantify landing forces for a variety of jumps (i.e. star and stride jumps) using premenopausal women. In addition, jump-landing GRF's need to be quantified across all planes of motion to gain a better understanding of the contribution of each GRF vector to the overall osteogenic stimulus for bone. Enhanced knowledge about these factors has the potential to influence the osteogenic effectiveness, standardisation and repeatability of jump-landings in this population. Such information could be used to identify what jumps could be best utilised and matched in the development of osteogenic exercise programmes for premenopausal women, to help optimise and create a novel impact stimulus required to promote bone formation.

2.3 Programme Design Considerations for Bone Health in Premenopausal Women

2.3.1 Introduction

Osteoporosis is a disease where bone density and bone quality is reduced, leading to a weakness of the skeleton and a significantly increased risk of bone fracture (Kanis, Adachi, et al., 2013). This disease is recognised as a major public health issue in New Zealand and the developed world, with 59% of women and 29% of men over the age of 60 years suffering a fracture from this age (Lippuner et al., 2009; Osteoporosis New Zealand, 2018). The economic burden on the public health and social care system as a result of treatment and management of osteoporotic fractures is difficult to determine as often not diagnosed until a fragility fracture occurs (Ebeling et al., 2013). An Australian study estimated the direct economic cost of osteoporosis in 2017 to be AUD$3.4 billion, which is three times higher than in 2007 (Tatangelo et al., 2019). Osteoporosis New Zealand estimated the total cost of the disease at a staggering $1 billion each year, with this figure predicted to increase rapidly if additional efforts are not made to address this disease (International Osteoporosis Foundation, 2015).

Generally, women experience bone losses of approximately 1% per year after the fourth decade of life, however annual losses of 3 - 5% bone mineral density (BMD) can be experienced during early post-menopause. The National Osteoporosis Foundation of America estimated that up to 20% of BMD can be lost in the 5 - 7 years after menopause, with lifetime bone losses estimated to be 30 - 40% of peak bone mass ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993; Sipila & Poutamo, 2003). Researchers (Drake et al., 2015) have demonstrated that the hip and lumbar spine are fracture sites most frequently associated with postmenopausal osteoporosis, which are primarily a consequence of trabecular bone losses due to oestrogen deficiency, however the hip is considered the most severe osteoporosis complication (Kanis, 2002).

Recommendations guiding exercise prescription for bone health have suggested moderate weight-bearing exercise, such as walking, as beneficial to these clinically relevant sites, however this intensity of loading is insufficient and no longer consistent with the current evidence base (Ebeling et al., 2013; Martyn-St James & Carroll, 2008; Zhao et al., 2014). It should be noted that although physical activity provides a multitude of health benefits, not all exercise is osteogenic. Therefore, in spite of the benefits aerobic activities such as walking, cycling and swimming may provide to body composition, strength and balance, researchers have shown that these activities may have little or no effect on enhancing bone health (Ma, Wu, & He, 2013; Martyn-St James & Carroll, 2008, 2010; Scofield & Hecht, 2012). Osteoporosis Australia (2013) has published recommendations for physical activity, based on an evidence-informed strategy to prevent osteoporosis. The key message was to optimise bone health throughout all stages of life and that high-impact loading appears to be the most beneficial approach in older women, however the optimal loading prescription was still to be determined (Ebeling et al., 2013; Martyn-St James & Carroll, 2009). More recently, Exercise and Sports Science Australia published a position statement recommending that low risk individuals, defined as healthy adults with normal BMD (T-score above -1.0 SD), need to perform 10 - 50 jumping exercises 4 - 7 times a week for the prevention of osteoporosis (B. R. Beck et al., 2017). However, although the position statement identified the types of jumps to be performed, it lacked specific detail in terms of jump-landing technique, programme design, and monitoring of the daily and weekly loading.

Thus although literature exists to support that specific modes of impact exercise need to be integrated into the lives of healthy adults, and that well designed exercise programmes for enhancing and preserving BMD are required, current recommendations are outdated and need revision (Gómez-Cabello et al., 2012; Guadalupe-Grau et al., 2009; Howe et al., 2011; Ilona, Taina, Mirela, Eugenia, & Mihaela, 2010; Martyn-St James & Carroll, 2009; Polidoulis, Beyene, & Cheung, 2012). In addition, the focus on premenopausal women represents a “window of opportunity” for premenopausal women to prevent or delay the time before the fracture threshold is surpassed in the postmenopausal years. Therefore, the purpose of this literature review is to critique training studies that have examined the effects of jump-landing programmes on bone health parameters in premenopausal women. From this critique those factors thought important for optimising programme design for improved bone health will be identified and discussed.

2.3.2 Literature Search Methods

This review evaluated and interpreted the current evidence base to provide researchers, primary health carers, sport scientists and physical therapists alike, with an understanding of the rationale and application of osteogenic exercise as a preventative approach for osteoporosis and consequently the effects on reducing risk of fracture. The conclusions and practical applications of this review were drawn from peer-reviewed journal publications. The databases searched were Academic Search Premier, SPORT Discus, PubMed, MEDLINE, and CINAHL. Literature searches were undertaken using several key words including 'osteoporosis prevention', 'strength and conditioning', 'resistance training', 'premenopausal', 'impact exercise', 'periodisation', 'exercise frequency', 'exercise loading', 'neural adaptation for exercise', 'exercise duration', 'contraindications to exercise', 'falls prevention', 'muscle reactivity', 'balance', 'body composition', 'jumping', 'ground reaction forces', 'bone mineral density', 'DEXA', 'bone geometry', 'jumping technique', 'plyometrics', and 'bone health'. Only English language articles published in peer-reviewed journals were considered. Relevant literature was also sourced from searches of related articles and books arising from the reference list of those obtained from the database searches. The studies reviewed examined various recommendations from credible national organisations, and 'best practice' strength and conditioning programmes that could be integrated into an osteogenic exercise programme for premenopausal women. Ten studies (Table 2.4) were found that met the inclusion criteria which included; being female, premenopausal (< 51 years), utilising dual energy x-ray absorptiometry (DEXA) technology, and involving a jumping intervention lasting more than 3 months (minimum bone turnover cycle).

2.3.3. Summary of the Research

Participants

A total of 615 female participants subjects were involved in the research and comprised of 329 participants who performed a jump intervention and 286 controls. The average age for all participants was 34.6 years, which represented the premenopausal stage (post the attainment of peak bone mass and pre the hormonal changes associated with menopause) (Gallagher & Tella, 2013). The population of interest was healthy premenopausal women who were not performing regular exercise (no more than 2.5 hours per week), and therefore representative of the general population.

Table 2.5 Randomised controlled trials of jump-landing interventions in premenopausal women.

Authors	**Age (year) (mean ± SD)**	**Sample size (n)**	**Jump-landing Intervention**	**Duration (months)**	**Change in BMD %**
(Bassey & Ramsdale, 1994)	J = 32.0 ± 1.2 C = 29.8 ± 1.8	**n = 14** J = 14 C = 13	50 vertical jumps/ day >2BW	6	FN: J = ↑2.4; C = ↓1.8 LS: J = ↑1.0; C = ↑1.5
(Heinonen et al., 1996)	J = 39.0 ± 3.0 C = 39.0 ± 3.0	**n = 84** J = 39 C = 45	60 min session with 20 min high impact jumping 2.1 - 5.6BW	18	[€]FN: J = ↑1.6; C = ↑0.6 LS: J = ↑2.2; C = ↑0.7
(Bassey et al., 1998)	J = 38.4 ±7.4 C = 36.4 ±7.6	**n = 55** J = 20 C = 35	5 x10 vertical jumps 6x week 3BW	5	[€]FN: J = ↑2.8; C = ↑0.3 [€]LS: J = ↑1.1; C = ↑1.1
(Vainionpää, Korpelainen, Leppäluoto, & Jämsä, 2005)	J = 38.1 ±1.7 C = 38.5 ±1.6	**n = 80** J = 39 C = 41	60 min session with 40 min high impact stamping, jumping & running 3x week	12	[€]FN: J = ↑1.1; C = ↓0.4 *LS: J = ↑2.2; C = ↓0.4 * L1 only
(Kato et al., 2006)	J = 20.5 ±0.6 C = 20.9 ±0.8	**n = 36** J = 18 C = 18	10x maximal vertical jumps 3x week 4.76BW (peak)	6	[€]FN: J = ↑2.6; C = ↓1.1 [€]LS: J = ↑2.4; C = ↓0.6
(Winters-Stone & Snow, 2006)	J1 = 38.3 ± 3.8 J2 = 41.3 ± 3.8 C = 40.5 ± 3.5	**n = 59** J1 = 19, J2 = 16 C = 24	100 jumps + lower only (J1) or upper & lower (J2) body resistance exercises 3x week 4 - 5BW	12	[€]FN: J1 = ↑1.0; J2 = ↑1.0; C = ↑0.1 [€]LS: J1 = ↓0.3; J2 = ↑1.1; C = ↑0.6
(Bailey & Brooke-Wavell, 2010b)	32.9 ± 2.4	**n = 64** J1 = 16, J2 = 13 & J3 = 16 C = 19	5 x 10 multidirectional hops 2, 4, or 7x week 2.5 – 2.8BW	6	[€]FN: J1 = nc; J2 = ↑0.9 and J3 = ↑01.8; C = ↓1.2 * No changes in LS reported
(Niu et al., 2010)	J = 39.7 ±1.2 C = 38.1 ±1.2	**n = 67** J = 34 C = 33	5x 10 vertical jumps in office setting 3x week >3.9g (2 - 3BW)	12	[€]FN: J = ↑0.6; C = ↓0.1 [€]LS: J = ↑0.8; C = ↓0.2
(Babatunde & Forsyth, 2013)	J= 22.8 ±4.0 C= 21.7 ±2.9	**n=96** J= 48 C= 48	10x maximal vertical jumps 3x week 4.56 BW (3.64 - 6.46)	6	FN: J = ↑3.7; C = ↓2.0 * using BUA (proposed to equal to ↑4.0 BMD in J group)
(Tucker et al., 2014)	J1 = 41.0 ±4.4	**n =60**	Jump 10 jumps, 2x day (J1)	4	Hip: J1 = ↑0.3; J2 = ↑0.2; C =↓0.9

	J2 = 39.8 ±4.8 C = 37.6 ±6.4	J1 = 23 J2 = 14 C = 23	Jump 20 jumps, 2x day (J2) (8 hours between sessions) 6x week 3.8 - 4BW		* LS not reported

Key: BMD Bone mineral density, FN Femoral neck, LS Lumbar spine, J Jump group, C Control group, BUA Broadband ultrasound attenuation, BW Body weight € Significant change compared to the control group

2.3.4. Discussion

A discussion of the factors to be considered when designing an exercise programme to optimally stimulate an adaptive bone response are detailed below. Please note that the findings of the training studies reviewed was combined with relevant acute research where appropriate, which has investigated osteogenic loading in pre-menopausal women.

1. **GRF magnitude and rate of force development:** Although the optimal dose of exercise is yet to be determined, it would seem from the research reviewed and other acute data that a ground reaction force (GRF) magnitude of greater than 3-body weights (BW) and a rate of force development exceeding 43-body weights per second (BW·s^{-1}) are needed for stimulating bone (Bassey et al., 1998; Robling et al., 2001; C. H. Turner & Robling, 2003). Bassey and colleagues (1998), previously defined vertical osteogenic thresholds for GRF magnitude and rate (>3 BW and 4 BW·s^{-1}, respectively), which they developed using bilateral jump-landings with premenopausal women (Bassey et al., 1998). The jumps utilised in this review reported GRF's ranging from 2.0 – 6.5 BW, using mostly bilateral jump-landings, which is in agreement with authors of meta-analyses that reported GRF's of 2 - 5 BW as being effective to stimulate bone and result in bone formation (Babatunde et al., 2012; Bassey et al., 1998; Zhao et al., 2014). Interestingly, although Bailey and Brooke-Wavell (2010), reported GRF's for vertical hops performed maximally that did not achieve the previously defined osteogenic threshold (>3BW), they reported femoral BMD gains of nearly 2% for the premenopausal participants. They speculated that the single-leg landing forces may be equivalent to a total landing force of 5 - 6 BW's due to forces being transmitted through one leg only, and therefore easily exceeded the bone stimulation thresholds previously defined. Although GRF magnitude is considered an important factor to influence the adaptation of bone, the rate of loading (rate of force development) is considered as equally important (Lanyon, 1987; Robling et al., 2006; C. H. Turner & Robling, 2003). Researchers have reported that if the peak rate of force production is sufficiently high, then bone adaptation can be stimulated without using high force magnitudes (Lanyon, 1987; O'Connor et al.,

1982; C. H. Turner & Robling, 2003). Thus, both peak magnitude and loading rate are considered important factors in achieving osteogenic thresholds.

2. **Distribution pattern of loading:** Most of the studies included in this review utilised jumps in the vertical plane, and all studies represented GRF's in the vertical direction only. Bone adaptation has been shown to be blunted by habitual patterns of loading (e.g. walking and running), so novel or diverse loading patterns are required to stimulate an adaptive bone response (Lanyon, 1996; C. H. Turner & Robling, 2003). Thus, exercises such as jumping and hopping in different directions, which are considered to provide 'unusual' or 'unfamiliar' patterns of loading have been shown to have a greater osteogenic effect than landing force magnitude alone, with bone adaptation being observed at much lower GRF's when these non-habitual strains are applied (Lanyon, 1987; C. H. Turner & Robling, 2003). Furthermore the 'error strain distribution hypothesis' suggests that unusual or novel directions of force application may have a greater osteogenic effect than magnitude alone, and is therefore vital to osteogenesis (Lanyon, 1987, 1996). Interestingly, the studies which utilised multidirectional jumps in this review (Heinonen et al., 1996; Vainionpää et al., 2005; Winters-Stone & Snow, 2006), reported similar gains in BMD to those that utilised jumps in the vertical direction only. However, these multidirectional studies incorporated up to 200 jumps within a prolonged exercise session (60 minutes), which according to animal studies, may have saturated the optimal impact stimulus and consequently had a negative effect on bone mechanosensitivity (Robling et al., 2001; Umemura, Sogo, & Honda, 2002). In addition, the principle of variation may explain some of the findings in this review, whereby the changes in five months were similar to 18 months, as maybe not enough variation (i.e. multiplanar, unilateral vs bilateral) had been provided as a programming progression. The influence of loading variation is a particularly important consideration for osteogenic jump-landing programmes and for special populations such as older adults unable to tolerate high magnitude and rate of GRF that warrants further investigation. Thus, future research is required to gain an understanding of the contribution of multi-planar GRF's (i.e. medio-lateral and anterio-posterior) in addition to vertical only, on the mechanosensitivity and subsequent adaptation of bone.

3. **Number of loading cycles:** The number of impacts (loading cycles) has been shown to affect the rate of bone formation, with animal studies demonstrating that a range of 5-100 loading cycles can stimulate bone formation and maintain the mechanosensitivity of bone (Lanyon, 1987; Robling et al., 2001; Umemura et al., 2002). Researchers using rats have shown that bone quickly becomes desensitised to impact exercise as the loading bout continues without interruption (Robling et al., 2001; Umemura et al., 2002). These researchers using animal models reported that skeletal tissue becomes desensitised after only 40 - 50 repetitive loading cycles, and furthermore recommended a rest period of 24 hours as sufficient to restore bone mechanosensitivity (Robling et al., 2001). Interestingly, as few as 10 maximal vertical jumps (4.6BW), achieved femoral neck gains equivalent to 4% (determined using broadband ultrasound attenuation), and thus fewer jump-landing repetitions (achieving osteogenic thresholds for magnitude and rate) may optimise the adaptive response of bone whilst reducing the risk of injury relating to fatigue. Studies which utilised longer duration exercise sessions (i.e. 60 minutes), including more jump-landing repetitions and additional resistance exercise (Vainionpää et al., 2005; Winters-Stone & Snow, 2006), achieved similar (or lesser) increases in femoral BMD than studies lasting less than 5 minutes (Kato et al., 2006) (↑1.0 compared to ↑2.6%). This finding further supports the concept that GRF magnitudes exceeding >3BW are essential to bone adaptation. Although the optimal number of loading cycles for humans has not been determined, it appears from the current review that a similar, and potentially greater, osteogenic effect occurred for the shorter exercise sessions (< 50 loading cycles), as compared to the longer exercise sessions (100 - 200 loading cycles). Thus, a shorter exercise session (< 10 minutes), would potentially be more beneficial to bone, and more likely to positively influence exercise adherence, than exercise programmes of extended duration.

4. **Study duration:** The jump-landing studies in this review ranged from 4 - 18 months, with an average intervention duration of 8.7 months. As one bone remodelling cycle (the complete cycle of activation, resorption, and formation of bone), is approximately 3 to 4 months, the programme duration needs to be continued through several cycles in order to detect changes in BMD using DEXA (Kenkre & Bassett, 2018). Thus, a longer study duration (at least 12 months) has

been suggested as providing a more valid representation of bone changes (B. R. Beck et al., 2017; Hart et al., 2017; Zhao et al., 2014). It appears that significant increases in femoral BMD (↑0.3 – ↑2.8%), have been achieved with jump-landing programmes of only 4 - 5 months in duration, using vertical jumps (10 - 50 each session). Interestingly, studies of at least 12-months report similar benefit to femoral BMD (↑0.6 - ↑1.6%), using similar jump-landing protocols which indicates that longer studies may require loading to be progressively increased (periodised) or varied in some manner, to continue to satisfy bone mechanosensitivity requirements.

5. **Frequency and recovery between loading sessions:** The jump-landing protocols in this review utilised exercise session frequencies ranging from 3 - 7 times per week. One of these studies focused directly on the effect of frequency, reporting greater BMD gains when the jump-landing programme was performed daily, compared to twice or four times (no change, ↑0.9 and ↑1.8%, respectively) (Bailey & Brooke-Wavell, 2010b). These findings indicate that at least three sessions of a jump-landing programme are required to achieve significant increases at the femoral neck, however consideration may be needed for recovery and to reduce injury risk. Although the optimal frequency of loading bouts has not been established in humans, increases in BMD have previously been reported in premenopausal women using jumping interventions performed 3 - 7 times per week, thus further research is required regarding this variable. Interestingly, one study in the review, which used a multidirectional hopping intervention, concluded that hopping exercises need to be performed daily, when compared to other weekly frequencies, to increase femoral neck BMD (Bailey & Brooke-Wavell, 2010b). Furthermore, two unrelated studies using young men and premenopausal women concluded that jumping twice daily (separated by 6 - 8 hours recovery) was more osteogenic than the same number of jumps (40 - 60 jumps/day) carried out in a single session (Erickson & Vukovich, 2010; Tucker et al., 2014). Adequate recovery between loading cycles and jumping sessions has been shown to maintain the mechanosensitivity of bone and optimise the osteogenic response by enhancing the surface area of bone actively forming new bone (Srinivasan, Weimer, Agans, Bain, & Gross, 2002). Researchers using animal models demonstrated that skeletal tissue became desensitised after 40 - 50 repetitive loading cycles, and a rest period

of 24 hours was sufficient to restore bone mechanosensitivity (Robling et al., 2001). Furthermore, rest periods between loading bouts of around 15 seconds and up to 4 hours, have been shown to increase bone formation outcomes by 65% to 100% (Burr, 2003; Robling et al., 2001; Robling et al., 2006; Srinivasan et al., 2002). Less than half of the studies in this review utilised rest intervals between jumps, and after sets of jumps, in spite of the recommendations indicated from these animal studies. Thus, the design of a jump-landing programme needs to consider inserting appropriate rest periods within and between jump-landing sessions to optimise bone adaptation, and reduce the risk of fatigue and bone damage (Burr, 2011, 2015).

6. **Age-specific response to loading:** One study in this review investigated the effect of providing the same vertical jumping intervention in a cohort of premenopausal and postmenopausal women (Bassey et al., 1998). Bassey and colleagues (1998), reported an increased femoral neck BMD gain of 2.8% in the premenopausal group, however failed to achieve a significant difference for the postmenopausal group. This finding indicated that the loading forces required to achieve an osteogenic response in older (> 50 years) women may be higher than for younger women (< 50 years) (Gomez-Cabello, Ara, Gonzalez-Aguero, Casajus, & Vicente-Rodriguez, 2012; Guadalupe-Grau et al., 2009; Lanyon, 1996). If we consider the concept that post-menopausal BMD is a consequence of peak BMD (achieved at skeletal maturity), menopause and the rate of bone loss as the women ages, then the period of bone growth during the pre-pubertal, pubertal and premenopausal years is the optimal time to focus on positive interventions for maximising bone health. In a recent Exercise Sports Science Australia (ESSA) position statement, the key message was to optimise bone health throughout all stages of life, however high-impact loading (i.e. jumping and hopping) appeared to be the most beneficial approach in healthy premenopausal women (Beck et al. 2017).

7. **Bone-site specificity:** Cross-sectional studies have shown that athletes in weight-bearing sports (i.e. gymnastics, tennis, and volleyball) which involve high magnitude and rates of loading and novel or diverse loading patterns, have greater bone mass at loaded skeletal sites compared to non-athletes or athletes in non-weight-bearing or lower-impact sports (Alfredson, Nordstrom, & Lorentzon,

1997; Kontulainen, Sievanen, Kannus, Pasanen, & Vuori, 2003; Snow, Williams, LaRiviere, Fuchs, & Robinson, 2001). These observations indicated that an osteoporosis prevention programme needs to provide an appropriate osteogenic stimulus at clinically relevant bone sites related to osteoporotic fracture (i.e. femoral neck and lumbar spine), as the hip and lumbar spine are fracture sites most frequently associated with postmenopausal osteoporosis, although the hip is considered the most severe osteoporosis complication (Kanis, 2002). Evidence from all the studies in this review have shown that jump-landing exercises can provide osteogenic stimulus to the hip region (i.e. femoral neck), and the majority of studies also achieved significant BMD gains at the lumbar spine. The researchers from one study suggested that jump-landings would not provide an effective stimulus for individuals aiming to improve bone strength at the spine, and recommended upper body resistance exercises as a better option (Winters-Stone & Snow, 2006). These researchers suggested that jump-landing exercises fail to generate sufficient osteogenic stimulus for bone formation at the spine, as the mechanical load is attenuated before being translated to the lumbar area (Vainionpää et al., 2005; Winters-Stone & Snow, 2006). It is therefore of interest to determine whether jump-landings performed whilst utilising a reactive jump-landing, and ‘stiff’ landing mechanics, have the ability to stimulate the lumbar spine, in addition to the femoral region.

8. **Instructions provided:** Researchers have shown that we can successfully employ a specific jumping style after being instructed only once (Bobbert et al., 1987), which implies that once proficient, jumps do not need further coaching and can be performed in the home setting with the knowledge that the appropriate GRF’s and subsequent osteogenic thresholds will be met. The studies in this review documented a variety of different instructions for arm position, effort during jumping and most importantly, the technique utilised when landing. In addition, most of the studies in this review provided supervision during the jump-landing sessions. Therefore, future research is required to determine whether participants can achieve similar or greater jump-landing forces after only one instructed session, using specific cues to land stiffly with minimal knee flexion, due to learning or practice effects. This information would have clinical implications for

osteogenic jump-landing programmes to be effective when performed in a home-based unsupervised setting.

9. **Jump-landing technique:** Biomechanics researchers have indicated that jumping and hopping exercises may only be useful in terms of osteogenic benefit, if the jump-landing technique is elucidated for this purpose. The important aspects of jump-landing include the cueing of participants to land stiffly and to minimise ground contact time, which have been shown to significantly influence this aspect of force attenuation, and therefore are vital to osteogenesis (Bobbert et al., 1987; Bobbert et al., 1986; Lees, 1981; Lees et al., 2004). Researchers from these biomechanical studies showed that the jump-landing technique utilised by participants is a major factor that can influence the osteogenic effectiveness of jumps, and that repeated jump-landings have the potential to heighten bone stimulation. Although the studies included in this review have provided some information about jumping technique, few have focussed on the jump-landing technique. Thus, future research is required to explore the effect of cueing participants to land ‘stiffly’, to utilise a flat-footed ground contact, and to employ a repeated jump-landing for achieving osteogenic thresholds previously shown to increase bone mass in premenopausal women.

10. **Progressive Overload:** In accordance with ‘best practice’ strength and conditioning, and physiotherapeutic programming, the first stage of a jumping or plyometric training programme needs to focus on developing competent movement patterns, general strength and balance (Kritz, Cronin, & Hume, 2009; Mothersole, Cronin, & Harris, 2014; Stone, Pierce, Sands, & Stone, 2006). It is recommended that the successful completion of a progressive weight-bearing programme, including strength and balance, will adequately prepare untrained individuals to tolerate the stresses involved with jump-landings to maximise benefits to bone health and reduce risk of injury (Davies, Riemann, & Manske, 2015; Mansfield, 2006; Mothersole et al., 2014). The studies in this review lacked any description nor provided evidence of providing participants with the opportunity for the musculoskeletal and neural adaptations required prior to participating in a jump-landing programme. It is therefore recommended that before an individual can undertake jump-landing exercises, pre-conditioning

exercise may be needed to tolerate the stresses involved with jump-landing exercises to maximise benefits to bone health and reduce risk of injury. It is recommended that this phase be performed in a supervised capacity, as the ability to provide instruction and demonstrate proper technique is an important process for guiding exercise prescription and progression in a safe manner (Ashley & Weiss, 1994; Wang et al., 2016; Young, Pryor, & Wilson, 1995). In addition, it is essential that participants are loaded and progressed within a jump-landing programme according to several factors including; strength, balance, movement and technical proficiency, fitness level, injury status and comfort, to maximise potential for adaptation and minimise risk of injury (Davies et al., 2015; Mansfield, 2006; Mothersole et al., 2014). It is however evident that the jump-landing programmes in this review are very basic in their design, with most including only one exercise (i.e. vertical jump). In addition, these studies have provided a very basic understanding of the principle of progressive overload, with increased number and/or height of jump described within the first 4 months only. Thus, further research is required to establish jump-landing programmes that can continue to stimulate bone over long periods of time (i.e. greater than 1 year).

11. **Individualisation:** Although the studies reviewed stipulated that participants needed to be healthy and without current musculoskeletal injury to take part in the jump-landing programmes, a limitation of current exercise recommendations for osteoporosis management and prevention, is the lack of consideration for individual difference, existing bone health, movement competency and functional capacity. Therefore, a safe and effective osteogenic jump-landing programme must consider risk factors which may compromise the safety for performing such a programme such as; age, frailty, pre-existing osteoporosis, musculoskeletal pain or injury, osteoarthritis and history of fractures or falls (Gallagher & Tella, 2013). Authors of a recent position statement on exercise prescription for the prevention and management of osteoporosis, recommended that individuals were classified into three levels of risk for fragility fracture (low, moderate and high), using the World Health Organisation (WHO) defined T-scores (B. R. Beck et al., 2017). According to this classification, low risk individuals were defined as having normal BMD (T-score above -1.0 SD), and no clinical risk factors for falls or fracture, and deemed safe to participate in a jump-landing programme. Individuals

classed as moderate and high risk (T-score -1.0 to -2.5 SD and less than -2.5 SD, respectively), were also recommended to perform jump-landings (2 - 3 BW), with an emphasis on conditioning the musculoskeletal system, gradual loading increments, pain-free competency and safety in terms of falls prevention (B. R. Beck et al., 2017).

12. **Mesocycle design and periodisation:** Strength and conditioning training principles imply that a musculoskeletal exercise programme needs to utilise a model of periodisation to ensure that training principles are manipulated safely and effectively to achieve long-term benefit to the individual (Bompa & Haff, 2009; Fleck & Kraemer, 2014; Haff & Triplett, 2015). Thus, a jump-landing programme needs to progress in volume and technical difficulty over a 12-month period, and its development should consider findings from previous studies which have achieved BMD gains in premenopausal women over similar time periods (B. R. Beck et al., 2017; Bompa & Haff, 2009; Fleck & Kraemer, 2014; Haff & Triplett, 2015). However, periodisation and musculoskeletal programming principles, which may influence the long-term effectiveness and safety of these programmes, are not currently reflected in the osteogenic jump-landing programmes reviewed. Variables to be considered in a periodised training programme for bone (adapted from musculoskeletal programming) include a progressively increased; magnitude, rate of strain, number of ground contacts and technical difficulty (i.e. bilateral to unilateral) over at least a 12-month period. In addition, it would be of interest to utilise previously quantified GRF data for premenopausal women performing a variety of different jump-landings (i.e. multiplanar, bilateral and unilateral), to determine the order these exercises should be introduced into an osteogenic jump-landing programme.

2.3.5 Conclusion

The purpose of this review was to present a summary of the variables identified as integral in the development of a longitudinal periodised osteogenic jump-landing programme for premenopausal women. Information regarding optimal jump-landing kinetics was identified whilst integrating current bone health guidelines, research and concepts of best practice strength and conditioning. It was concluded that to provide an adaptive bone response the programme must consider: 1) GRF magnitude and rate of force development; 2) distribution patterns of loading; 3) duration of the programme; 4) number of loading cycles; 5) frequency and recovery between loading sessions; 6) age-specific response to loading; 7) bone-site specificity; 8) instructions provided; and, 9) jump-landing technique. In addition, the programme needs to adhere to best practice strength and conditioning principles such as; 10) progressive overload; 11) individualisation; and, 12) mesocycle design and periodisation.

From this review, it can be concluded that jump-landing protocols that; utilise brief jumping episodes (10 - 100 jumps/day, 3 - 7 days/week), are 4 - 18 months duration, and present loading magnitudes of between 2 - 6 BW and rates of >43 $BW \cdot s^{-1}$, can result in significant gains in femoral neck BMD of 0.6 – 2.8% in premenopausal women. Although these researchers have demonstrated that bone responds optimally to unusual or atypical mechanical forces applied to the skeleton for women who are habitually inactive and are not involved in high-impact sports, the aspects of the programme design deemed important to the osteogenic potential of the exercise have not been clearly identified. In addition, no study has attempted to incorporate all of the osteogenic loading (i.e. GRF magnitude, rate and direction), and programming (frequency, intensity, duration and type) variables, deemed important to musculoskeletal adaptation.

National and International Osteoporosis Organisations are now recommending that exercises, including jumping and hopping, should be utilised in an osteoporosis prevention programme. However, currently the peer-reviewed scientific literature on the use of exercise as a means of preventing osteoporosis is quite limited. While it would appear that jumping and hopping exercises are effective for this purpose, osteogenic programmes specifically designed for premenopausal women are currently lacking (Babatunde et al., 2012; B. R. Beck et al., 2017; Ebeling et al., 2013; Weaver et al., 2016; Zhao et al., 2014). Practitioners need to develop longitudinal periodised osteogenic jump-landing programmes for healthy pre-menopausal women, which utilise quantified jump-landing force data (obtained from premenopausal women), whilst integrating current bone health guidelines, research and concepts of best practice strength and conditioning. These programmes need to utilise a model of periodisation to ensure that training principles are manipulated safely and effectively to achieve long-term benefit to bone whilst adhering to safe programming guidelines.

In addition to participants developing adaptations to both generate and tolerate increased landing forces over time, multidirectional jumping and hopping interventions have potential to achieve improvements in factors relevant to falls prevention, such as muscle strength and balance, in addition to enhanced BMD for premenopausal women at clinically relevant sites for osteoporosis prevention.

No evidence currently exists on the chronic effects of utilising such a programme, with specific emphasis on jump-landings technique, in premenopausal women. Thus, research is required to determine the effects of quantified (GRF) exercises incorporated into jump-landing programmes on functional performance parameters, body composition and bone remodelling at clinically relevant sites in premenopausal women. Such information will provide clinicians, primary carers, strength and conditioning coaches and the general population with a greater understanding of the benefits and limitations of utilising a periodised osteogenic jump-landing programme to improve bone health in this population.

CHAPTER 3. DO BILATERAL VERTICAL JUMPS WITH REACTIVE JUMP-LANDINGS ACHIEVE OSTEOGENIC THRESHOLDS WITH AND WITHOUT INSTRUCTION IN PREMENOPAUSAL WOMEN?

3.1 Prelude

Jumps have been investigated as a stimulus for bone development, however the effects of instruction, jump type and jump-landing techniques need investigation. Although the quantification of bilateral vertical jump impact forces has been documented by several research groups previously, methodological differences influence the validity, reliability and comparability of these studies. For example, the jumps used have differed in terms of the use of arm swing, landing mechanics and the instructions given. In addition, no research has explored the use of a reactive jump (jumping immediately after the initial jump landing), to determine the effect of this jumping and landing technique on enabling participants to consistently achieve the jump-landing forces required to stimulate bone. Therefore, this is the first study to determine whether ground reaction forces (GRF's) for bilateral vertical jumps (Countermovement jump, CMJ and Drop Jump, DJ) with reactive jump-landings can achieve the magnitudes and rates of strain (Osteogenic Thresholds), previously shown to improve bone mass among premenopausal women. It was also of interest to determine whether these Osteogenic Thresholds could still be achieved when the jump-landings were performed one week later in the absence of any further instruction for this specific reactive jump-landing technique, and whether any differences in landing forces exist between countermovement and drop jump-landings. This research could indicate what jumps could be best utilised and matched in the development of osteogenic exercise programmes for premenopausal women (without pre-existing osteoporosis), to help optimise and create a novel impact stimulus required to promote bone formation.

Clissold, T. L., Winwood, P. W., Cronin, J. B. & De Souza, M. J. (2018). Do bilateral vertical jumps with reactive jump landings achieve osteogenic thresholds with and without instruction in premenopausal women? *Journal of Applied Biomechanics.* 2018 Apr 1;34(2):118-126. doi: 10.1123/jab.2017-0114. Epub 2018 Apr 6.

3.2 Introduction

Osteoporosis is a condition where bone density and bone strength is reduced, and there is a significantly increased risk of bone fracture (Kanis, McCloskey, et al., 2013). Osteoporosis is a silent epidemic responsible for fractures in 50% of women and 20% of men worldwide (Lippuner et al., 2009). Approximately 52 million women and men have osteoporosis or osteopenia (low bone mass) in the United States and this will increase to more than 61 million by 2020 if additional efforts are not made to address this disease (International Osteoporosis Foundation, 2015). Osteoporosis is largely preventable, with specific types of exercise being widely recognised as an important element of a larger programme to slow and prevent loss of bone mass (Ebeling et al., 2013; Weaver et al., 2016). This emphasis on exercise, specifically jump-landings, provides the focus of this paper.

Bilateral vertical jumps, including the countermovement (CMJ) and drop jump (DJ), have been shown to be valid and reliable tests for determining explosive leg power (Ashley & Weiss, 1994; Bobbert et al., 1986; Markovic, Dizdar, Jukic, & Cardinale, 2004; Winwood et al., 2015). These jumps have also been utilised extensively by coaches and physical educators when performing plyometric exercises to improve vertical jumping ability (Bobbert et al., 1987; Bobbert et al., 1986). In addition to being commonly described as performance tests for the quantification and training of lower body power, researchers have investigated the use of these jumps as a stimulus for bone development (Babatunde et al., 2012; Bassey, Littlewood, & Taylor, 1997; Bassey et al., 1998; Strong, 2004; Tucker et al., 2014) in adolescent (McKay et al., 2005), premenopausal (Bassey & Ramsdale, 1994; Strong, 2004; Tucker et al., 2014) and postmenopausal populations (Bassey et al., 1998). Jumping and hopping exercises are of special interest given their role in improving peak bone mass in children and adolescents and for minimising age-related bone loss in women (Bailey & Brooke-Wavell, 2009, 2010b; Bassey et al., 1997; Bassey & Ramsdale, 1994; Bassey et al., 1998; Stiles et al., 2013; Weeks & Beck, 2008). The utility of bilateral vertical jumps combined with reactive jumps as potential osteogenic stimuli are of particular interest to these researchers. Note: For the purpose of this study a reactive jump was defined as 'jumping immediately after an initial jump-landing'.

According to Wolff's Law, bone has the ability to adapt to mechanical loads, suggesting that mechanically-induced strain is a key factor which affects bone formation. Frost explored the threshold of strain necessary to achieve skeletal adaptation in the development of his 'minimum effective strain', or 'mechanostat' theory, hypothesising that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation and increase bone mass and bone strength (Frost, 1987, 1992, 2003). Animal studies using rat tibia and ulna have previously determined a linear relationship between the magnitude of an externally applied load and bone strain magnitude (Frost, 1987; Hsieh et al., 1999; Lanyon, 1987; Robling et al., 2001; Umemura et al., 2002). Bassey and colleagues (1998), documented a case study using a person who had an instrumented titanium rod implanted into his proximal femur to demonstrate significant correlations between vertical ground reaction forces (GRFs) and internal forces directly measured for a selection of activities, including the CMJ and DJ. Such research supports the measurement of vertical GRF's, represented as body weight (BW) to be used to estimate the influence of loading on bone.

Bassey and colleagues (1998), reported peak landing vertical forces which corresponded to 3 BW's and mean peak loading rates of 43 body weights per second ($BW \cdot s^{-1}$), using CMJ's (50 jumps at 8.5 cm, 6 days/week), resulted in significant increases in femoral bone mineral density (BMD) of 2.8%. From meta-analyses it can be concluded that jump-landing programmes that; utilise brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), are 4 - 18 months duration, and present loading magnitudes of between 2 - 6 BW, can result in significant gains in femoral neck BMD of 0.5 - 3% in premenopausal women (Babatunde & Forsyth, 2013; Bailey & Brooke-Wavell, 2010b; Bassey & Ramsdale, 1994; Bassey et al., 1998; Heinonen et al., 1996; Kato et al., 2006; Niu et al., 2010; Tucker et al., 2014). From these evidence-based values it might be concluded that a safe and effective osteogenic threshold exists around this range of load magnitude for jumping and hopping exercises, however none of the studies explored the use of repeated jump-landings or the influence of instruction on the GRF and rates of strain.

Several studies comparing elite and recreational athletes have analysed vertical force-loading curves to understand how different landings affect the magnitude of impact forces (Bobbert et al., 1987; Bobbert et al., 1986; Lees, 1981). A jump with increased knee flexion can be described as a “soft” landing as the absorption of impact energy by the leg musculature occurs over a longer time and results in reduced peak GRF’s (Bobbert et al., 1986; Lees, 1981). However, researchers have shown that repeated jumps are more ballistic in nature and produce greater GRF’s as they prevent subjects from “softening” the landing, due to the short time period available between jumps (Bobbert et al., 1987; McNitt-Gray, 1993). The use of repeated jumps requires the participant to push off quickly after landing and potentially utilise the elastic energy absorbed during the brief landing during the subsequent take-off (McNitt-Gray, 1993; van Ingen Schenau, Bobbert, & de Haan, 1997). This demonstrates that jump-landing technique is a major factor that can influence the osteogenic effectiveness of jumps, and suggests that repeated jump-landings could provide enhanced bone stimulation. Interestingly, researchers have shown that participants can successfully employ either jumping style after being instructed (Bobbert et al., 1987), however little research exists that has investigated GRF’s for jump-landings under the conditions of instruction and instruction withdrawn.

Although the quantification of bilateral vertical jump impact forces have been documented by several research groups, methodological differences influenced the validity, reliability and comparability of these studies. For example the jumps used have differed in terms of; arm swing (Lees et al., 2004; Richter et al., 2011), landing mechanics (Bobbert et al., 1986; Ebben, Fauth, Kaufmann, & Petushek, 2010; Lees, 1981; McNitt-Gray, 1993), instructions given (Young et al., 1995), footwear (Bassey et al., 1997; Bassey & Ramsdale, 1994) and calculation of rate of strain (Bassey & Ramsdale, 1995; Hansen, Cronin, & Newton, 2011). Given the variability identified, this study sought to; a) determine whether GRF’s for bilateral vertical jumps (CMJ and DJ) with reactive jump-landings achieve magnitudes and rates of strain previously shown to improve bone mass among premenopausal women; b) determine if differences exist in landing forces between jumps ‘with instruction’ and jumps with ‘instruction withdrawn’; c) determine if differences exist between the two types of landings (i.e. reactive and post-reactive jump); and, d) to determine if differences exist between countermovement and drop jump landings. Due to the scope of the study, several hypotheses were generated; i) GRF's for all jump-landings would achieve and exceed the defined osteogenic thresholds previously shown to improve bone mass at clinically relevant sites for premenopausal women; ii) greater magnitudes and rates of strain would occur in jump-landings performed with 'instruction withdrawn' due to learning and practice effects; iii) greater magnitudes and rates of strain would be observed for first jump-landing (reactive jump) due to a reduction in ground contact time; and, iv) greater landing forces would be associated with the CMJ landings as it was expected that participants would achieve greater jump heights than the standard 20 cm step height used for the DJ.

3.3 Methods

3.3.1 Participants

Twenty-one healthy premenopausal women (31 - 50 y), volunteered to participate in this study (Table 3.1) (Appendix 3). It was calculated using G*Power, that a target sample size of 21 participants will allow for the detection of changes in jump performance ($\alpha = 0.05$, $1-\beta = 0.80$) between jumps with and without instruction. The sample size was comparable to other studies that used a similar design (Babatunde & Forsyth, 2013; Bassey et al., 1998; Niu et al., 2010). All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) (Appendix 4a) and inclusion criteria required participants to be between 30 and 50 years of age, in conjunction with the participants reporting a regular menstrual cycle to determine premenopausal status. Participants were excluded if: any medical problems were reported that compromised their participation or performance in this study, including; having a recent or current musculoskeletal injury, osteoarthritis and any condition of impaired balance or coordination. The methods and procedures used in this study were approved by the Institutional Review Board Committee (R14/17) (Appendix 2).

Table 3.1 Baseline characteristics of the participants (mean ± SD)

	All Participants (n = 21)
Demographics	
Age (yr)	43.3 ± 5.9
Height (cm)	167 ± 5.5
Body mass (kg)	69.4 ± 9.6
BMI ($kg \cdot m^{-2}$)	24.9 ± 3.4
Body fat (%)	27.5 ± 8.7
Maximal Countermovement Jump	
Jump height (Vertec, cm)	35.5 ± 9.3

3.3.2 Experimental Approach to the Problem

A cross-sectional descriptive design was utilised and peak GRF's for the bilateral vertical jumps 'with instruction' and with 'instruction withdrawn' were quantified. Jump-landing forces were collected at 400 Hz using a portable AMTI (Advanced Mechanical Technology Inc., Watertown, Massachusetts) Accupower (ACP) force plate (length 101.6 cm x width 76.2 cm x height 12.4 cm). Data was collected for each participant over two testing sessions separated by one week, with a familiarisation session scheduled at least 3 - days prior to the first testing session (Figure 1). In the first testing session participants were given detailed instruction on how to perform the bilateral vertical jumps and in the second testing session participants were just asked to perform the jumps with instructions withdrawn. All participants refrained from performing any of the jumps between testing sessions and commencement of normal daily activity was undertaken as determined by activity diaries (Appendix 7).

During the familiarisation session participants filled in pre-screening questionnaires (Appendix 4a) and had their height (Appendix 17a), body mass and body composition measured using a bioelectrical impedance machine (InBody230, Biospace) (Appendix 17b). The Vertec Yardstick (Swift Performance Equipment, Australia), a portable device used to measure vertical jump height, was used to determine baseline jumping ability and as a surrogate measure for lower body explosive power (Leard et al., 2007;

Wulf & Dufek, 2009) (Appendix 16). Before jump commencement the participants reach height was determined. They were then encouraged to jump and touch the highest vane of the Vertec device. The authors thought it important to determine maximal baseline vertical jump ability to allow for comparison with previous studies who have utilised this subject demographic. Participants were then given a demonstration of the bilateral vertical jumps (CMJ and DJ) combined with a reactive jump, followed by two to three practice jumps. All jumps in this study were performed barefooted as researchers have suggested the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise (Bassey et al., 1997; Bassey & Ramsdale, 1994).

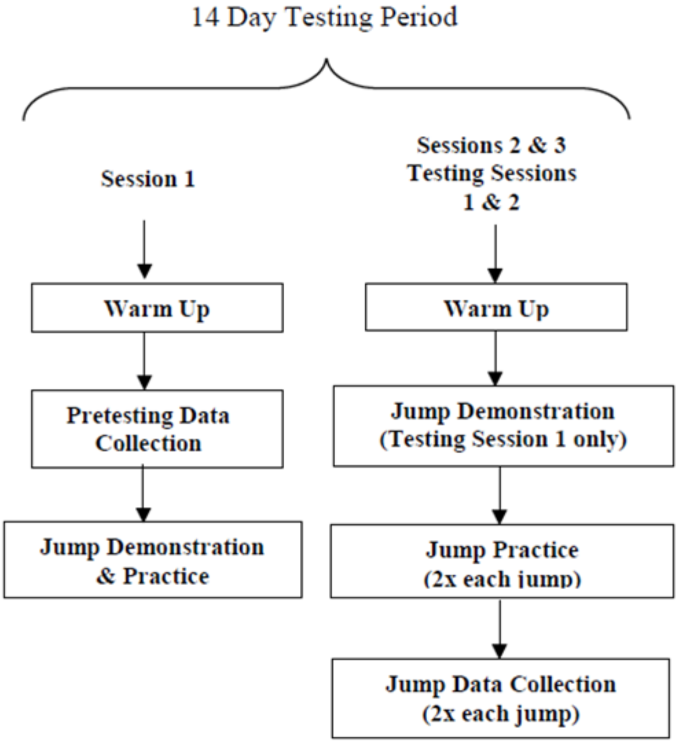


Figure 3.1 Experimental design of the 14 - day testing period

For the first testing session, participants performed a ten-minute standardised warm up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilisation exercises. Testing commenced five minutes after the warm up. Prior to testing, the jumps were demonstrated using proper technique, with all instructions standardised for every participant. For the CMJ combined with a reactive jump, participants were instructed to stand with feet shoulder-width apart with their arms raised above their head. Participants were then instructed to flex the knees and hips with arms “swinging” downwards (during the eccentric phase) and then jump upwards with arms “swinging” in the intended direction of travel (in the concentric phase) to perform a maximal jump for height. Participants were cued to immediately jump again after the initial jump-landing.

For the DJ combined with a reactive jump, participants were instructed to step up and off a 20 cm box and only allow a small downward knee movement after landing, followed quickly by a second maximal jump. All participants were instructed to land as if the force plate was a “hot plate” (first jump-landing; reactive jump), and to immediately jump again for maximal height before landing again (second jump-landing; post-reactive jump). A pictorial representation of the phases of the bilateral vertical jumps utilised in this study can be observed (Figure 3.2).

Participants remained stationary on the force plate for five seconds after the second landing and each jump was separated by a 30 - second rest interval. The participants performed two practice jumps followed by two jumps where force plate output variables were collected. Jumps were performed in a randomised order which was replicated in the second testing session. All participants jump-landings were performed with both feet on the force plate.

Data was analysed as an average of the two jumps. For the second testing session the same protocol was followed, however, no instruction or cueing was given for how the participant was to perform the bilateral vertical jumps. All testing for this study was undertaken at a similar time of day with participants instructed to maintain their normal dietary intake before and after each testing session. Participants completed activity diaries to monitor physical activity to ensure that inter-session physiological status was similar. We did not control for nutrition, or hydration levels but participants were told not to make any changes in the above during the testing period. All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

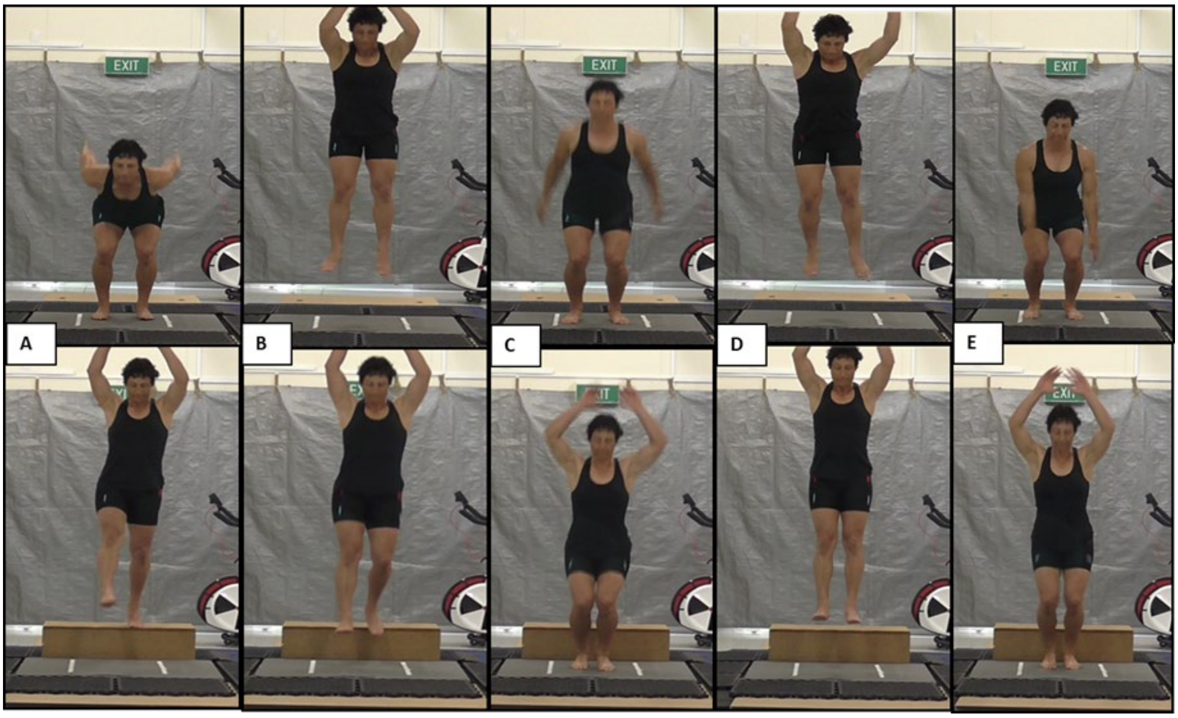
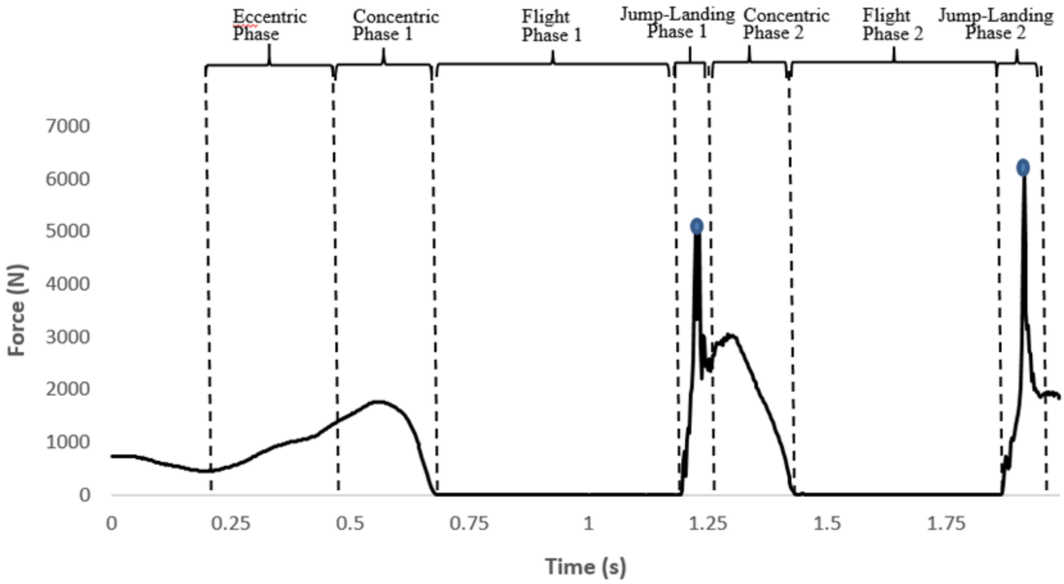


Figure 3.2 Pictorial representation of the phases of the countermovement jump (top row) and drop jump (bottom row) and reactive jump, as described in the study: A) Start of the jump; B) Flight phase 1; C) First impact for jump-landing 1; D) Flight phase 2; E) Second impact for jump-landing 2.

3.3.3 Data Analysis

All force-time data were filtered using a second order low-pass Butterworth filter (cut off frequency 20 Hz) with zero lag. The force-time data was calculated in Microsoft Excel 2013 and presented as peak values. Forces in the X and Y axis were calculated as medial (positive) and lateral (negative), and anterior (propulsive) and posterior (braking), respectively. Peak resultant forces were calculated as the square root of each axes $(X^2 + Y^2 + Z^2)$ and used to calculate the rate of force development over 10 ms taken from the steepest part of the slope between the end of the flight phase and the peak landing force (Bassey & Ramsdale, 1994). A pictorial representation of the force profile of the bilateral vertical jumps utilised in this study are presented (Figure 3.3).



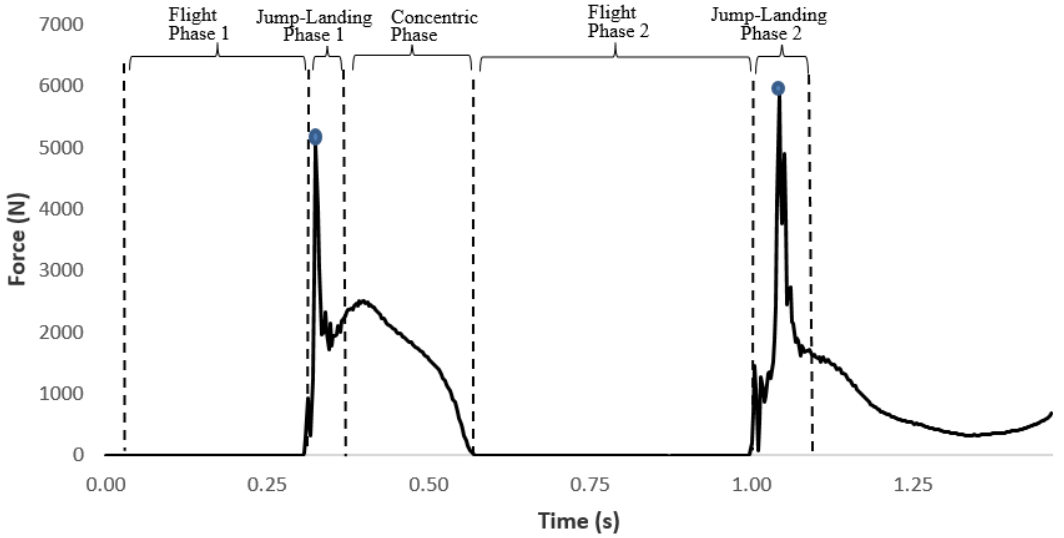


Figure 3.3 A typical vertical force profile of the countermovement jump (top) and drop jump (below) and subsequent reactive jump. Dashed lines represent the various phases of the jumps. Circles indicate peak landing forces for jump-landing 1 and 2, respectively.

3.3.4 Statistical Analyses

Stem and leaf plots were used to ascertain whether there were any outliers in the data for each variable. All values three or more box lengths from upper or lower edges of box were considered extreme outliers and were removed. After extreme outliers were removed descriptive statistics were calculated and reported as mean and standard deviations. A three-way (landing type x jump type x instruction type) ANOVA was used to determine if differences existed between the jump type, landing type and whether instruction was provided. All data was normally distributed and met the assumptions associated with the 3-way ANOVA. To counteract the problem of multiple comparisons and the chance of a false positive, significance was accepted at the $p \leq .01$ level. All statistical analyses were carried out using Data Desk 6.01 for Windows (Data Description Inc., Ithaca, NY, USA). Effect sizes (ES = mean change/standard deviation of the sample scores) were calculated to quantify the magnitude of the effects associated with landings 'with instruction withdrawn' Cohen (Cohen, 1988) applied qualitative descriptors for the effect sizes with ratios of 0.2, 0.5 and 0.8 indicating small, moderate and large changes, respectively.

3.4 Results

The range of magnitudes (4.59 to 5.49 BW's) and rates of strain (264 to 359 $BW{\cdot}s^{-1}$) for the jump landings in this study exceed previously defined osteogenic thresholds (>3 BW's and 43 $BW{\cdot}s^{-1}$) (Bassey et al., 1998) (Table 2).

No significant 'Jump Type' or 'Instruction' effect was found, although there were indications that 'Instruction' may have some effect on vertical and resultant forces measured both in N and BW ($p = .06$). Small increases (ES = 0.22 to 0.42) in peak vertical force (N and BW), peak resultant force (N and BW) and peak rate of force development ($KN{\cdot}s^{-1}$ and $BW{\cdot}s^{-1}$) were observed in the second jump-landing (post-reactive) with 'instruction withdrawn' in the CMJ combined with a reactive jump. In contrast, small decreases (ES = -0.35 and -0.36 respectively) were observed for peak rate of force production in the second jump-landing of the DJ combined with a reactive jump with 'instruction withdrawn'.

The order of landing was found to have a significant main effect, with the 'second jump-landing' (post-reactive jump-landing) consistently higher than the 'first jump-landing' (reactive jump-landing) in all cases except for vertical ground reaction force (N) (Table 3). When the two landings were compared within each jump condition (i.e. with and without instruction) the 'second jump-landing' was found to result in greater landing forces (ES = 0.20 to 0.53) for all variables except for the CMJ 'with instruction' (ES = 0.06 to 0.14). No significant interactions were observed between landing type, jump type and instruction type.

Table 3.2 Ground reaction forces associated with the bilateral vertical jumps and reactive jump-landings with and without instruction

	Countermovement Vertical Jump						20 cm Drop Jump					
Peak Force Parameters	Jump-Landing One			Jump-Landing Two			Jump-Landing One			Jump-Landing Two		
	WI	WO	ES	WI	WO	ES	WI	WO	ES	WI	WO	ES
Vertical												
PVF (N)	3230 ± 1253	3350 ± 1092	0.10	3298 ± 1208	3871 ± 1519	0.42	3189 ± 1147	3313 ± 1089	0.11	3788 ± 1263	3723 ± 1363	0.05
PVF (BW)	4.76 ± 1.72	4.77 ± 1.37	0.01	4.91 ± 1.81	5.42 ± 1.77	0.29	4.72 ± 1.55	4.93 ± 1.55	0.14	5.00 ± 1.68	5.24 ± 1.64	0.15
Resultant												
PRF (N)	3259 ± 1279	3378 ± 1107	0.10	3357 ± 1277	3916 ± 1546	0.40	3200 ± 1159	3329 ± 1103	0.11	3752 ± 1310	3757 ± 1387	0.00
PRF (BW)	4.59 ± 1.49	4.81 ± 1.39	0.15	5.00 ± 1.93	5.49 ± 1.82	0.26	4.74 ± 1.56	4.96 ± 1.57	0.14	5.16 ± 1.55	5.29 ± 1.67	0.08
Rate of Force Development												
PRFD (kN·s^{-1})	194 ± 111	190 ± 109	-0.04	207 ± 118	236 ± 117	0.24	194 ± 121	190 ± 110	-0.03	240 ± 115	205 ± 82	-0.35
PRFD (BW·s^{-1})	263 ± 126	281 ± 163	0.12	307 ± 176	345 ± 163	0.22	283 ± 167	283 ± 161	0.00	359 ± 179	304 ± 126	-0.36

Key: Data expressed as mean ± SD
WI With Instruction; WO Without instruction; ES Effect size; N Newtons, BW Body weight; kN·s^{-1} kilo Newtons per second; BW·s^{-1} Body weight per second; Jump-Landing One (reactive jump-landing); Jump-Landing Two (post reactive jump-landing)

Table 3.3 Results of analysis of variance main effects of jump-landing force variables for the combined bilateral vertical jumps

Force Variables	Jump-Landing 1*	Jump-Landing 2*	df	F-ratio
Mean Peak vertical force (N)	3270	3670	(1,141)	10.4
Peak vertical force (BW)	4.82	5.20	(1,137)	6.2
Peak resultant force (N)	3291	3715	(1,142)	11.0
Peak resultant force (BW)	4.81	5.29	(1,136)	9.8
Peak rate of force development (kN·s^{-1})	1920	2253	(1,139)	9.7
Peak rate of force development (BW·s^{-1})	280.2	334.7	(1,138)	11.8

Key: †Significant main effect $p \leq .01$; *Mean values

3.5 Discussion

This is the first study to quantify the GRF's associated with bilateral vertical jump-landings in premenopausal women 'with instruction' and 'instruction withdrawn' whilst utilising a reactive jump component. The main findings of the current study in relation to the initial hypotheses were: i) GRF's for all jump-landings achieved and exceeded the defined osteogenic thresholds previously shown to improve bone mass at clinically relevant sites for premenopausal women; ii) greater ($p < .05$) magnitudes and rates of GRF occurred in jump-landings performed with 'instruction withdrawn' due to learning and practice effects; iii) in contrast to our hypotheses, significantly greater forces were observed in the second jump-landing (post-reactive jump), for most of the force variables measured; and, iv) the hypothesis that greater landing forces would be associated with the CMJ landings was unsupported as non-significant main effects were observed for jump type.

In this study baseline peak vertical landing forces of 4.6 to 5.5 BW's exceeded the magnitude of force development (>3 BW's), which achieved femoral BMD gains in premenopausal women (Bassey et al., 1998). Bassey et al. (1998), reported peak landing vertical forces that corresponded to 3.0 BW's for continuous vertical jumping bouts, for the CMJ heights (8.9 ± 5 cm) of their premenopausal participants. Interestingly, Tucker et al. (2014), and Kato et al. (2006), utilised jumps for maximal height interspersed with short rest intervals, which resulted in CMJ heights three to four times higher (34 ± 11 cm and 38.1 ± 6 cm, respectively) than the women achieved in the Bassey et al. (1998) study, and consequently higher peak CMJ landing forces (3.8 and 4.8 BW's, respectively). In this study baseline Vertec CMJ heights of 35.5 ± 9 cm were similar to the results of Tucker et al., and Kato et al., and participants were cued to jump for maximal height and utilise a vigorous "countermovement" arm swing, which may have contributed to the greater observed GRF's. Given the existing literature documenting vertical jump-landing impact forces utilises a variety of different instructions for arm position and effort during jumping, the researchers in this study believe cueing participants to use a vigorous arm swing in a "countermovement" maximises jump height and hence impact forces, and consequently the osteogenic potential of the exercise.

The mechanisms identified for providing the greatest influence for stimulating bone formation are a function of peak vertical force magnitude and peak rate of force production (O'Connor et al., 1982), with the suggestion that if peak rate of force production is sufficiently high then bone adaptation can be stimulated without using high forces (Lanyon, 1987; O'Connor et al., 1982; C. H. Turner & Robling, 2003). This suggests that peak rate of force production is an appropriate measurement to be considered when describing 'osteogenic thresholds'. In this study peak GRF's were measured in three axes and used to calculate peak resultant forces for both jump-landings, and the steepest 10 ms for each phase was used to represent the peak rate of force production, as described by Bassey et al. (1998). The mean values for peak rate of force production of both jump-landings (280 and 334 $BW\cdot s^{-1}$, first and second jump-landings, respectively) in this study were substantially higher than the values described by Bassey et al. (1998) (43 $BW\cdot s^{-1}$). It would seem that the jumping and jump-landing techniques utilized in the current study significantly influenced this aspect of force production. Tucker et al. (2014), reported similar rate of force production values for CMJ landing forces (217 to 243 $BW\cdot s^{-1}$), however they determined this value using the slope of force versus time from ground contact to peak landing force. We acknowledge that many different methods can be utilised to calculate rate of force production and thus effect the validity of comparison to selected osteogenic thresholds; therefore, recommend standardisation for methods of analysis wherever possible.

The variability that exists when quantifying peak vertical landing forces (2 to 6 times body weights) for the bilateral vertical jumps in different studies (Bassey et al., 1998;

McKay et al., 2005; Tucker et al., 2014; Weeks & Beck, 2008), highlights the need to explore different aspects of jump technique and the way instruction can influence jump-landing GRFs. Instruction was of interest for two reasons to these researchers: i) quantifying the influence of instruction on the magnitude of the GRFs; and, ii) whether similar or greater GRF's could be achieved if instruction was withdrawn, as this could influence programming considerations. In terms of the influence of instruction on the magnitude of the GRFs, we were unable to establish a significant effect for 'Instruction', however there were indications that 'Instruction' and test-retest effects may have had some influence on vertical and resultant forces with greater

forces measured with 'Instruction withdrawn', in N's and BW's (*p* values = ~ .06). With regards to withdrawal of instruction, small increases (ES = 0.22 to 0.42; $p = .06$) in peak vertical force (N and BW), peak resultant force (N and BW) and peak rate of force production (kNs^{-1} and BW·s^{-1}) were observed for the second jump-landing in the CMJ, indicative that a practice effect had occurred after only one instructed jump-landing session. This may indicate that participants are able to improve their jump-landing ability when practiced over time and thus be able to increase the osteogenic potential of the bilateral vertical jump-landings. It would seem that subjects can still achieve high GRF and rate of force production without instruction, the implications being that once proficient, such jumps do not need further coaching and can be performed in the home setting with the knowledge that the appropriate GRF's and subsequent osteogenic thresholds would be met.

In contrast to our hypothesis, significantly larger peak resultant force, (↑10%; $p = .002$) and peak rate of force production (↑20%; $p < .001$) values (in relation to BW and BW·s^{-1}, respectively) were observed for the second jump-landing. It was initially hypothesised that greater forces would be observed for reactive jump-landings (first jump-landing), due to cueing provided to 'land quickly' and 'immediately jump again for maximal height'. The greater forces associated with the second jump-landing could be attributed to; i) greater height resulting from the reactive jump, and ii) a stiffer second jump-landing as there is no need to produce propulsive forces for another jump. To clarify such mechanisms would require further videography, not utilised in this study. Irrespective of this limitation, greater

GRF's were associated with the second jump-landing and offers a method of increasing the osteogenic training stimulus.

The authors proposed that the CMJ would result in greater landing GRF's than the DJ as study participants achieved baseline maximal vertical jump heights (35.5 ± 9 cm) greater than the 20 cm step selected for the DJ. However, greater rates and magnitudes of GRF's (↑1 to 3%), for jump-landings were observed for the DJ when represented as a total stimulus (both jump landings combined), although the differences were non-significant. A great deal of literature has compared the DJ with the CMJ, however comparisons with the findings of this study are problematic due to; i) most studies are comparing propulsive forces and not landing forces (Bobbert, Gerritsen, Litjens, & Van Soest, 1996; Bobbert et al., 1987; Bobbert et al., 1986), and ii) the analyses are principally videographic and electromyographic (Bobbert et al., 1987; Bobbert et al., 1986). Irrespectively, as no significant main effects were observed for jump type, this suggests that both jumps could be used interchangeably in an osteogenic exercise programme for premenopausal women in the home setting once participants are proficient with jumping technique.

While the GRF's in the X and Y axes were not presented in this study due to the vertical nature of the investigated jumps, resultant forces were used in the analysis to represent the contribution of anterio-positive and medio-lateral jump-landing forces. However, previous research in this area has focused primarily on quantifying vertical GRF's, and subsequent osteogenic thresholds, are represented in the vertical direction only. Future research could utilise methods presented in the current study to quantify the osteogenic potential and bone-loading forces of various types of bilateral multidirectional (i.e. star and stride jumps) and unilateral jumps (vertical, lateral and forward hops) using resultant forces to compare to previously determined osteogenic thresholds. Such research could indicate what jumps could be best utilised and matched in the development of osteogenic exercise programmes for premenopausal women (without pre-existing osteoporosis), to help optimise and create a novel impact stimulus required to promote bone formation. Recommendations and exercise programmes specifically targeting bone health for premenopausal women are currently lacking (Babatunde et al., 2012; Ebeling et al., 2013; Weaver et al., 2016; Zhao et al., 2014).

3.6 Practical Applications

Researchers have suggested that bone responds optimally to unusual or atypical mechanical forces applied to the skeleton for women who are habitually inactive and are not involved in high-impact sports, thus jumping and specifically jump-landings present as an effective bone stimulus for this population. It would seem from our results that the CMJ and DJ combined with reactive jump-landings, performed ‘with instruction’ and with ‘instruction withdrawn’, easily exceeded osteogenic thresholds previously shown to increase bone mass in premenopausal women. Note: Participants seeking to undertake jump-landing exercises, such as those described in the current study, may need to pre-condition themselves to tolerate the stresses involved with jump-landing exercises to maximise benefits to bone health and reduce risk of injury.

CHAPTER 4. BILATERAL MULTIDIRECTIONAL JUMPS WITH REACTIVE JUMP-LANDINGS ACHIEVE OSTEOGENIC THRESHOLDS WITH AND WITHOUT INSTRUCTION IN PREMENOPAUSAL WOMEN.

4.1 Prelude

Currently jump-landing ground reaction forces have only been quantified and described in the vertical direction as a stimulus for bone development, in spite of evidence (using animal studies), that suggests that bone responds optimally to unusual or unfamiliar mechanical forces applied to the skeleton. Therefore, there is a need to quantify moderate to high impact jump-landings which produce GRF's in different directions, in addition to the vertical direction, to determine their osteogenic potential and subsequent use as a stimulus for bone development in premenopausal women. Thus, research is required to quantify jump-landing forces across all planes of motion (medio-lateral, anterio-posterior, resultant and vertical), for commonly performed bilateral multidirectional jumps, such as the star jump and stride jump. The findings from the previous study demonstrated that by utilising a reactive jump-landing (i.e. jumping immediately after initial jump-landing), with bilateral vertical jumps, participants easily achieved and exceeded previously defined vertical osteogenic thresholds (>3BW's and >43BW·s^{-1}) for premenopausal women. It is therefore of interest to investigate jumps with multidirectional landing qualities, to determine whether osteogenic thresholds can be achieved in the vertical direction, whilst collectively contributing multidirectional strain distribution to the overall effectiveness of loading. In addition, there is a need to explore the influence of instruction on the magnitude and rate of the jump-landing ground reaction forces for the full-spectrum of GRF's and to determine if differences exist between the two types of landings (i.e. reactive and post-reactive jump), and between star and stride jump landings.

Clissold, T. L., Cronin, J. B., De Souza, M. J., Wilson D. & Winwood P.W. (2020). Bilateral multidirectional jumps with reactive jump landings achieve osteogenic thresholds with and without instruction in premenopausal women. *Clinical Biomechanics* March 2020 (73) 1-8. doi.org/10.1016/j.clinbiomech.2019.12.025

4.2 Introduction

Researchers have suggested that bone responds optimally to unusual or unfamiliar mechanical forces applied to the skeleton (Lanyon, 1996; C. H. Turner & Robling, 2003). However, research in this area has focused primarily on quantifying vertical ground reaction forces (GRF's), and therefore overlooking the influence of forces applied across the full spectrum (Bassey et al., 1997; McKay et al., 2005; Weeks & Beck, 2008). Current evidence has shown that people participating in weight-bearing sports (i.e. gymnastics, tennis, and volleyball) involving novel or diverse loading patterns with high GRF's and rates of loading, have greater bone mass at loaded skeletal sites compared to participation in non-weight-bearing or lower-impact sports (Alfredson et al., 1997; Kontulainen et al., 2003; Snow et al., 2001). Although low or moderate impact activities, such as walking and jogging, are stated to benefit bone, studies have reported minimal effect of these activities on improving bone health, or for blunting the age-related bone losses in pre or post-menopausal women (B. R. Beck et al., 2017; Ma et al., 2013; Martyn-St James & Carroll, 2008). Therefore, there is a need to understand and quantify different types of moderate to high impact multidirectional jump landings to determine their osteogenic potential, safety, and use as a stimulus for bone development across life stages for at risk populations.

It is well accepted that women have less total bone mass than men and experience rapid bone loss during menopause. Generally, women achieve peak bone mass by the third decade of life, after which experience bone losses of approximately 0.5 - 1% per year, however annual losses of 3 - 5% bone mineral density (BMD) can be experienced during early post-menopause (Greendale et al., 2012). Researchers have suggested hypothetical gains of 3 - 5% in bone mass during the premenopausal years, using appropriate exercise as a primary osteoporosis prevention strategy (Babatunde et al., 2012). Exercises such as jumping and hopping, which are considered to provide 'unusual' or 'novel' patterns of strain in pre and post-menopausal women who are habitually inactive and not involved in high-impact sports, have been shown to have a greater osteogenic effect than magnitude alone, with bone adaptation being observed at much lower GRF's when these non-habitual strains are applied (Lanyon, 1987; C. H. Turner & Robling, 2003). Interestingly, interventions involving multi-directional jump-landings have not only produced increases in BMD for premenopausal women at clinically relevant sites for osteoporosis prevention, but report improvements in other factors that contribute to reduced falls risk, including muscle strength and balance (Bailey & Brooke-Wavell, 2010a, 2010b).

Several studies have analysed vertical force-loading curves to understand how different landings affect the magnitude of impact forces (Bobbert et al., 1987; Bobbert et al., 1986; Lees, 1981). These results show that using repeated jumps, which are more ballistic in nature, produce greater GRF's as they prevent subjects from "softening" the landing due to the short time period available between jumps (Bobbert et al., 1987; McNitt-Gray, 1993). These findings suggest that jump-landing technique, with specific cues provided for jump-landing (i.e. think of the ground as a hot plate), is a major factor that can influence the osteogenic effectiveness and repeatability of jumps, and demonstrate that repeated jump-landings may provide enhanced bone stimulation. In addition, instruction was of interest to these researchers to both quantify the influence of instruction on the magnitude of the GRFs, and to determine whether similar or greater GRF's could be achieved if instruction was withdrawn. Thus, once proficient such jumps would not need further coaching and could be performed in the home setting with the knowledge that the appropriate GRF's and subsequent osteogenic thresholds would be met.

A recent study (Clissold, Winwood, Cronin, & De Souza, 2018) studied peak vertical landing forces for countermovement jumps (flex the knees and hips and then jump upwards to perform a maximal jump) and drop jumps (step off a 20 cm box and only allow a small downward knee movement after landing), with each followed quickly by a second maximal jump (defined as a 'reactive jump'), and utilising arm swing. They reported peak GRF magnitudes (4.6 to 5.5 BW's) and peak rates of force production (280 and 334 $BW \cdot s^{-1}$) for first and second jump-landings respectively, which were substantially higher than the values that previously resulted in significant increases in femoral BMD of 2.8% in premenopausal women (>3BW's and >43$BW \cdot s^{-1}$, magnitude and rate of strain, respectively) (Bassey et al., 1998).

Mechanistically, bone responds to different combinations of strain-related stimuli (i.e. magnitude, rate, direction), which are considered interlinked and interdependent (Hart et al., 2017; Robling et al., 2006; C. H. Turner & Robling, 2003). Therefore, it is of interest to investigate jumps with multidirectional landing qualities, to determine whether osteogenic thresholds can be achieved in the vertical direction, whilst collectively contributing multidirectional strain distribution to the overall effectiveness of loading.

Currently, no studies have quantified the full spectrum of forces involved with multidirectional jump-landings , therefore the current study sought to; a) determine whether GRF's for bilateral multidirectional jumps, (star jump, (SJ) and stride jump, (SDJ)) with reactive jump-landings (defined as 'jumping immediately after an initial jump-landing') achieve magnitudes and rates of strain previously shown to improve bone mass among premenopausal women; b) determine if differences exist in landing forces between jumps 'with instruction' and jumps performed one week later with 'instruction withdrawn'; c) determine if differences exist between the two types of landings (i.e. reactive and post-reactive jump); and, d) to determine if differences exist between star and stride jump landings. Due to the scope of the study, several hypotheses were generated; i) Vertical and resultant GRF's for all jump-landings would achieve and exceed previously defined osteogenic thresholds (>3BW's and >43BW·s^{-1}) for premenopausal women; ii) greater magnitudes and rates of strain would occur in jump-landings performed with 'instruction withdrawn' due to learning and practice effects; iii) greater magnitudes and rates of strain would be observed for the second jump-landing (post-reactive jump) due to a stiffer landing; and, iv) although similar magnitude vertical GRF's would be observed for SJ & SDJ landings, greater medio-lateral landing forces would be associated with the SJ landings; and greater anterio-posterior landing forces would be associated with the SDJ landings.

4.3 Methods

4.3.1 Participants

Twenty-one healthy premenopausal women (31 - 50 yr), volunteered to participate in this study (Table 4.1) (Appendix 3). It was calculated using G*Power, that a target sample size of 21 participants will allow for the detection of changes in jump performance ($\alpha = 0.05$, $1-\beta = 0.80$) between jumps with and without instruction. The sample size was comparable to other studies that used a similar design (Babatunde & Forsyth, 2013; Bassey et al., 1998; Niu et al., 2010). All participants were considered healthy as determined by completing Pre-exercise Participation and Physical Activity Readiness Questionnaires (PAR-Q) (Appendix 4a) and inclusion criteria required participants to be between 30 and 50 years of age, in conjunction with the participants reporting a regular menstrual cycle to determine premenopausal status. Participants were excluded if: any medical problems were reported that compromised their participation or performance in this study, including; having a recent or current musculoskeletal injury, osteoarthritis and any condition of impaired balance or coordination. The methods and procedures used in this study were approved by the Institutional Review Board Committee (R14/17) (Appendix 2).

Table 4.1 Baseline characteristics of the participants (mean ± SD)

	All Participants (n = 21)
Demographics	
Age (yr)	43.3 ± 5.9
Height (cm)	167 ± 5.5
Body mass (kg)	69.4 ± 9.6
BMI ($kg \cdot m^2$)	24.9 ± 3.4
Body fat (%)	27.5 ± 8.7
Maximal Countermovement Jump	
Jump height (cm)	35.5 ± 9.3

4.3.2 Experimental Approach to the Problem

A cross-sectional descriptive design was utilised and peak GRF’s for the bilateral multidirectional jumps ‘with instruction’ and with ‘instruction withdrawn’ were quantified. Jump-landing forces were collected at 400 Hz using a portable AMTI (Advanced Mechanical Technology Inc., Watertown, Massachusetts) Accupower (ACP) force plate (length 101.6 cm x width 76.2 cm x height 12.4 cm). Data was collected for each participant over two testing sessions separated by one week, with a familiarisation session scheduled at least 3 - days prior to the first testing session (Figure 4.1). In the familiarisation and then again in the first testing session, participants were given detailed instruction on how to perform the bilateral multidirectional jumps (SJ and SDJ) and in the second testing session participants were asked to perform the jumps with instructions withdrawn. All participants refrained from performing any of the jumps between testing sessions and commencement of normal daily activity was undertaken as determined by activity diaries (Appendix 7). The study design utilised in this study was similar to previous jump-landing quantification studies (McKay et al., 2005; Weeks & Beck, 2008), however the methodology’s robustness was improved to include specific instructions provided for jump-landing mechanics and an additional testing session (with instruction withdrawn), to assess whether osteogenic jump-landing forces could be achieved in a non-supervised setting. Thus, the study design is similar to that previously utilised by Clissold and colleagues, to quantify a series of vertical bilateral jump-landings in the same population (Clissold et al., 2018).

Familiarisation

During the familiarisation session participants filled in pre-screening questionnaires (Appendix 4a) and had their height (Appendix 17a), body mass and body composition measured using a bioelectrical impedance machine (InBody230, Biospace) (Appendix 17b). The Vertec Yardstick (Swift Performance Equipment, Australia), a portable device used to measure vertical jump height, was used to determine baseline jumping ability and as a surrogate measure for lower body explosive power (Leard et al., 2007; Wulf & Dufek, 2009) (Appendix 16). Before jump commencement the participants reach height was determined. They were then encouraged to jump and touch the highest vane of the Vertec device. The authors thought it important to determine maximal baseline vertical jump ability to allow for comparison with previous studies who have utilised this subject demographic. Participants were then given a demonstration of the bilateral multidirectional jumps (SJ and SDJ) combined with a reactive jump, followed by two to three practice jumps on the force plate. All jumps in this study were performed barefooted as researchers have suggested the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise (Bassey et al., 1997; Bassey & Ramsdale, 1994).

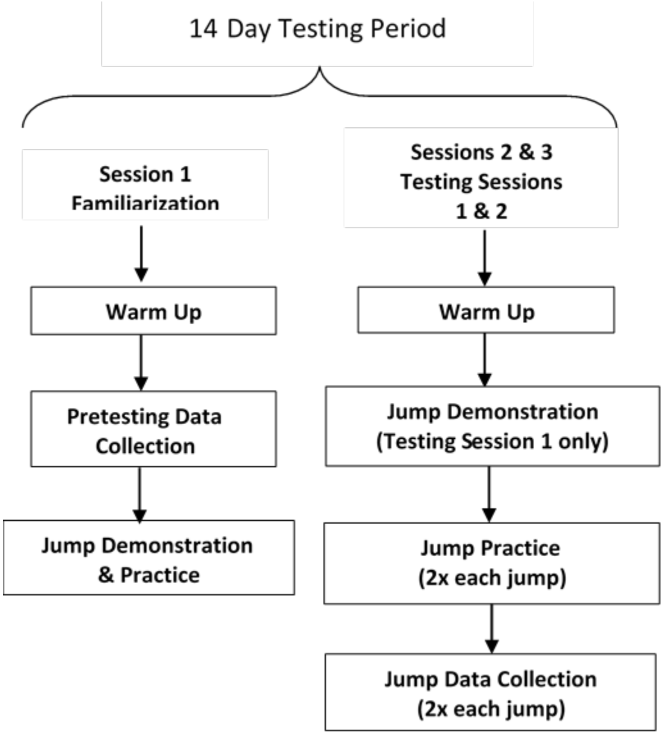


Figure 4.1 Experimental design of the 14 - day testing period

Testing Protocol (Sessions 2 & 3)

For the first testing session, participants performed a ten-minute standardised warm-up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilisation exercises. Testing commenced five minutes after the warm-up. Prior to testing, the jumps were demonstrated using proper technique, with all instructions standardised for every participant, and provided before each jump. For the SJ combined with a reactive jump, participants were instructed to stand with feet together with their arms by their side. Participants were then instructed to flex the knees and hips slightly (during the eccentric phase) then to quickly jump upwards (during the concentric phase) with arms 'swinging' upwards and legs 'swinging' outwards to land in a shortened 'star' position with feet flat on the ground. Participants were cued to immediately jump again after the initial jump-landing (i.e. think of the ground as a hot plate), 'pulling' their arms and legs back to a stiff starting position.

For the SDJ combined with a reactive jump, participants started in a stride position with one leg forward and one leg back with heels flat on the ground. They were taught to bend their knees and hips slightly (during the eccentric phase) to perform a maximal jump for height (during the concentric phase) with legs 'swinging' to land with the opposite foot forward in a shortened position, with feet flat on the ground (first jump-landing; reactive jump). Participants were cued to immediately jump again after the initial jump-landing (i.e. think of the ground as a hot plate), back to a stiff starting position (second jump-landing; post-reactive jump). To combat the rotary actions of the hips, participants were instructed to vigorously move the arms in opposite directions to the legs. A pictorial representation of the phases of the bilateral multidirectional jumps utilised in this study can be observed (Figure 4.2).

Participants remained stationary on the force plate for five seconds after the second landing and each jump was separated by a 30 - second rest interval. The participants performed two practice jumps (for each leg position for the SDJ), followed by two jumps where force plate output variables were collected using AMTI version 1.5 software (Athletic Republic, Fargo, North Dakota). Data was analysed as an average of the two jumps (the two jump-landings for each jump were represented as jump-landing one and jump-landing two), with no additional jumps permitted. Jumps were performed in a randomised order which was replicated in the second testing session. All participants' jump-landings were performed with both feet on the force plate.

For the second testing session the same protocol was followed, however, no instruction or cueing was given (instruction withdrawn) for how the participant was to perform the bilateral multidirectional jumps. All testing for this study was undertaken at a similar time of day with participants instructed to maintain their normal dietary intake before and after each testing session. Participants completed activity diaries between testing sessions to monitor physical activity and ensure that inter-session physiological status was similar. We did not control for nutrition, or hydration levels but participants were told not to make any changes in the above during the testing period. All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

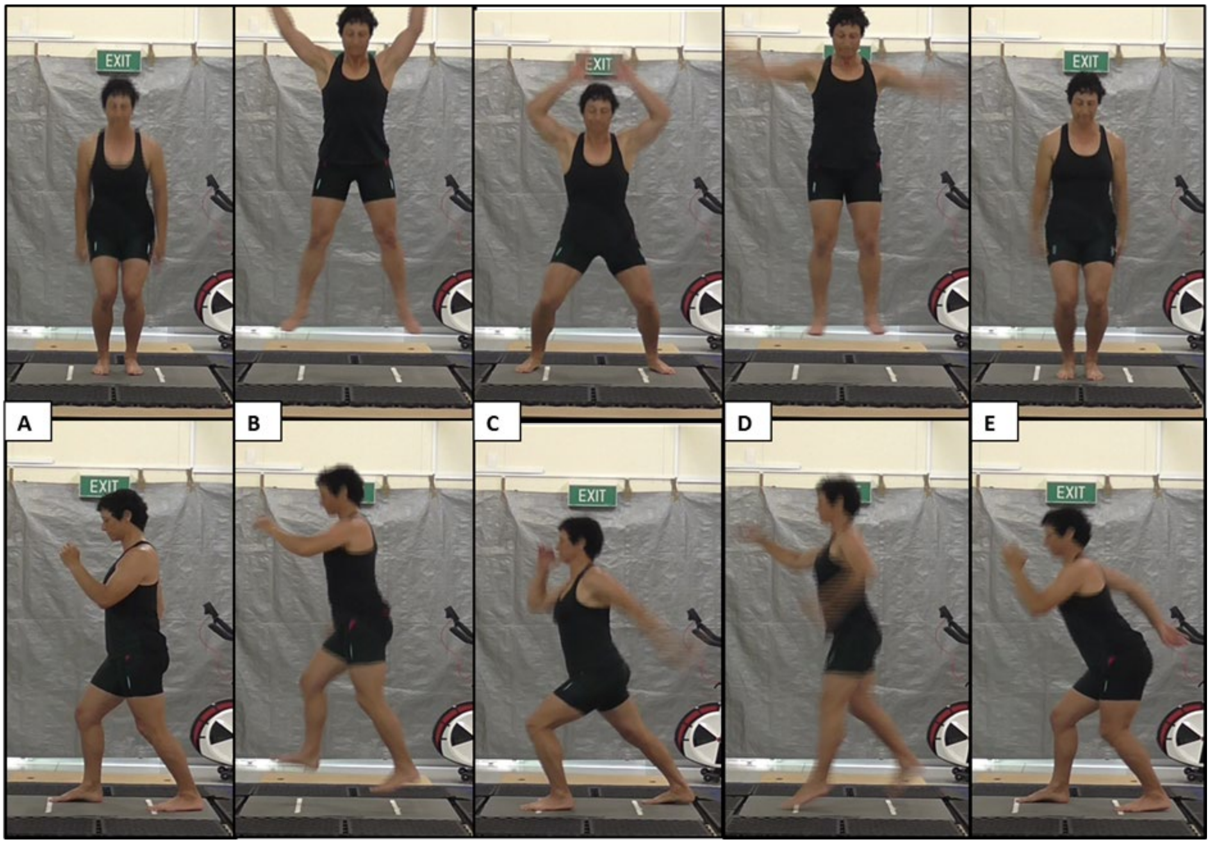


Figure 4.2 Pictorial representation of the phases of the star jump (top row) and stride jump (bottom row) and reactive jump, as described in this study: A) Start of the jump; B) Flight phase1; C) First impact for jump-landing 1; D) Flight phase 2; E) Second impact for jump-landing 2.

4.3.3 Data Analysis

The force-time data was calculated in Microsoft Excel 2013 (v 15.0.5179.1000, Microsoft, California, USA) and presented as peak values. Forces in the x and y axis were calculated as medial (positive) and lateral (negative), and anterior (propulsive) and posterior (braking), respectively. Peak GRF magnitude was presented in respect to body weight (BW), and was calculated as peak GRF, (N)/ body mass, (N). Peak resultant forces were calculated as $\sqrt{x^2 + y^2 + z^2}$ and used to determine the rate of force development ($N \cdot s^{-1}$ * 100/ body mass, N; body weight per second, $BW \cdot s^{-1}$) over 10 ms taken from the steepest part of the slope between the end of the flight phase and the peak landing force (Bassey & Ramsdale, 1994). The representation of GRF's as BW enables comparison with osteogenic thresholds previously used to define cut-points which have achieved gains in BMD at clinically relevant sites for premenopausal women. All force-time data were filtered using a second order low-pass Butterworth filter (cut off frequency 20 Hz) with zero lag. A pictorial representation of the force profile of the bilateral multidirectional jumps utilised in this study are presented (Figure 4.3).

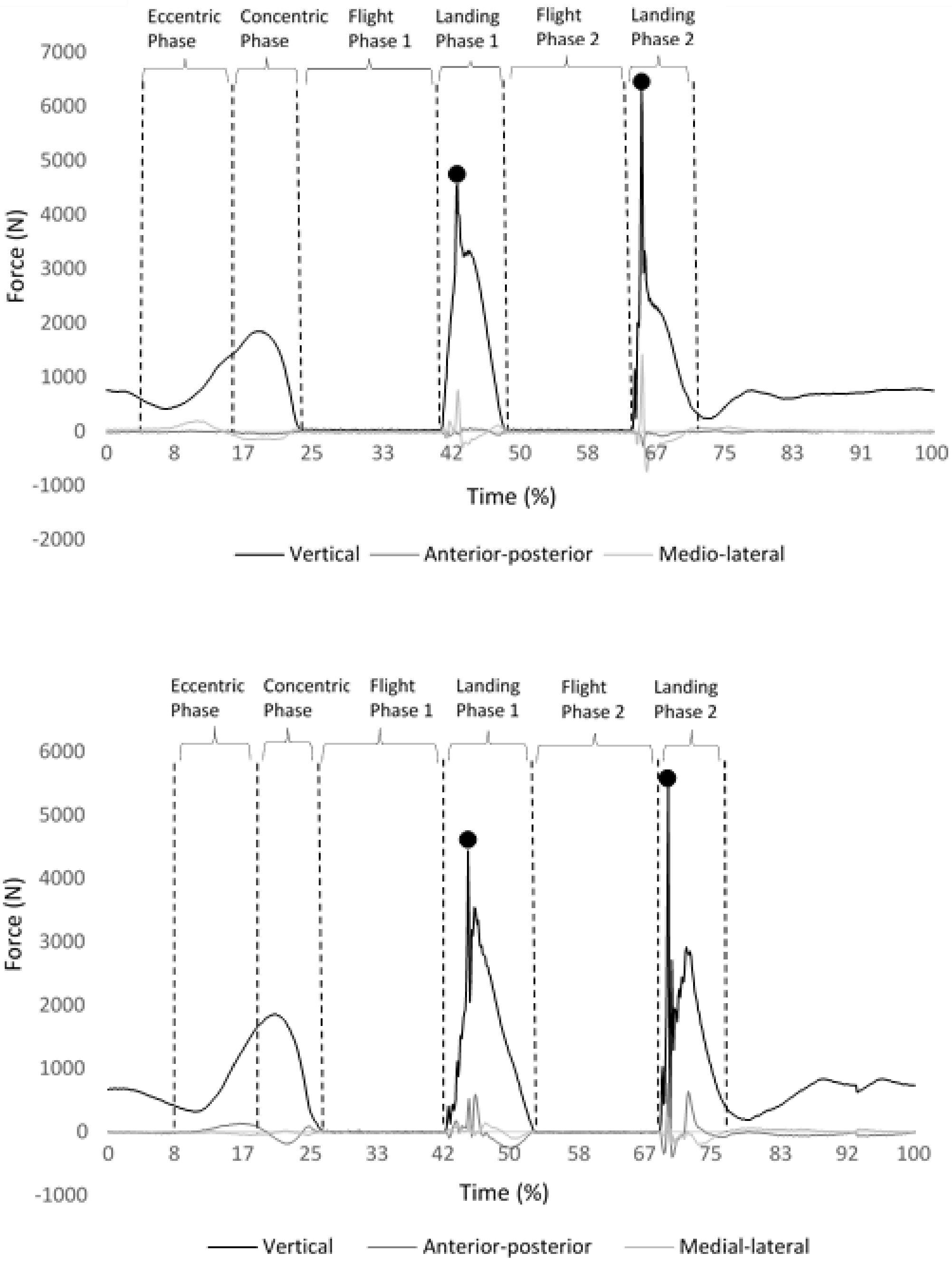


Figure 4.3 A full-spectrum force profile for a representative participant of the star jump (top) and stride jump (below) and subsequent reactive jump. Dashed lines represent the various phases of the jumps. Circles indicate peak landing forces for landing 1 and 2, respectively.

4.3.4 Statistical Analyses

Stem and leaf plots were used to ascertain whether there were any outliers in the data for each variable. All values three or more box lengths from upper or lower edges of box were investigated carefully before being considered extreme outliers and were removed (Kwak & Kim, 2017). After extreme outliers were removed descriptive statistics were calculated and reported as mean and standard deviations. A 3-way (landing type x jump type x instruction type) ANOVA with Bonferroni's post hoc tests was used to determine if significant differences existed between the jump type, landing type and whether instruction was provided. Significance was accepted at the $P \leq .01$ level. A Shapiro-Wilk's test was used to show all data was normally distributed and met the assumptions associated with the 3-way ANOVA. All statistical analyses were carried out using Data Desk 6.01 for Windows (Data Description Inc., Ithaca, NY, USA). Effect sizes (ES = mean change/standard deviation of the sample scores) were calculated to quantify the magnitude of the effects associated with landings 'with instruction withdrawn'. Cohen (Cohen, 1988) applied qualitative descriptors for the effect sizes with ratios of 0.2, 0.5 and 0.8 indicating small, moderate and large changes, respectively.

4.4 Results

The range of magnitudes (3.87 to 5.33 BW's) and rates of strain (192 to 329 BW·s^{-1}) for vertical and resultant forces for the jump landings in this study exceed previously defined osteogenic thresholds (>3 BW's and 43 BW·s^{-1}) (Bassey et al., 1998) (Table 4.2).

No significant interactions were observed between landing type, jump type and instruction type. Significant main effects ($P \leq .01$) were found for 'Instruction', indicating that 'Instruction' had an effect on vertical (N) ($P = .01$) and resultant forces (N) ($P = .004$). Increases in force for all axes (except anterior) were observed in jump-landing one for the stride jump (ES = 0.20 to 0.93) and in jump-landing two for the star jump (ES = 0.22 to 0.61). In contrast, small decreases (ES = -0.30 and -0.31) were observed for posterior and medial peak force production for the stride jump for jump-landing two. Although no significant effects were observed for rate of force development, small effect sizes were observed towards jump-landing one in the stride jump (ES = 0.21 to 0.25, kNs^{-1} & BW·s^{-1}) and jump-landing two in the star jump (ES = 0.37 to 0.38, kNs^{-1} & BW·s^{-1}).

Landing type was found to have a significant main effect ($P \leq .01$), with the 'second jump-landing' (post-reactive jump-landing) consistently higher than the 'first jump-landing' (reactive jump-landing) in all cases except for anterior ground reaction force (N and BW) (Table 4.3). Greater peak landing forces (N and BW, respectively) were observed for resultant (↑11% and ↑12%; $P \leq .0001$), vertical (↑12% and ↑13%; $P \leq .0001$), posterior (↑23%; $P \leq .001$), medial (↑25% and ↑26%; $P \leq .01$) and lateral (↑42% and ↑49%; $P \leq .0001$) forces. Peak rate of force development (↑29%; $P \leq .0001$) also showed a significant effect for landing type.

While no significant 'Jump Type' effect was found, star jump medio-lateral GRF's were substantially greater (↑85% to ↑466%) than the SDJ. Conversely, anterio-posterior GRF's were markedly greater for the SDJ jump-landings (↑103% to ↑316%) when compared with the SJ.

Table 4.2 Ground reaction forces associated with the bilateral multidirectional jumps and reactive jump-landings with and without instruction

	Stride Jump						Star Jump					
Peak Force Parameters	Jump-Landing One			Jump-Landing Two			Jump-Landing One			Jump-Landing Two		
	WI	WO	ES	WI	WO	ES	WI	WO	ES	WI	WO	ES
Vertical												
PVF (N)	2796 (644)	2976 (881)	0.24	2887 (760)	3079 (810)	0.25	2808 (762)	2915 (918)	0.33	3233 (1004)	3554 (1065)	0.31
PVF (BW)	4.11 (1.03)	4.25 (1.14)	0.13	4.35 (1.10)	4.33 (0.96)	-0.02	3.87 (0.63)	3.89 (0.88)	0.03	4.46 (1.13)	5.33 (1.72)	0.61
Anterior												
PAF (N)	312 (86)	320 (119)	0.07	281 (156)	299 (147)	0.12	76 (33)	78 (46)	0.05	57 (30)	80 (60)	0.51
PAF (BW)	0.47 (0.15)	0.45 (0.14)	-0.14	0.38 (0.16)	0.41 (0.17)	0.18	0.11 (0.04)	0.12 (0.07)	0.18	0.08 (0.04)	0.11 (0.07)	0.55
Posterior												
PPF (N)	-140 (56)	-144 (65)	0.07	-231 (96)	-236 (103)	0.05	-107 (72)	-97 (47)	-0.17	-80 (47)	-86 (44)	0.13
PPF (BW)	-0.20 (0.08)	-0.22 (0.10)	0.22	-0.32 (0.12)	-0.29 (0.08)	-0.30	-0.13 (0.07)	-0.14 (0.07)	0.14	-0.11 (0.04)	-0.12 (0.05)	0.22
Medial												
PMF (N)	91 (54)	132 (84)	0.60	83 (49)	82 (43)	-0.02	425 (265)	427 (316)	0.01	519 (268)	630 (314)	0.38
PMF (BW)	0.11 (0.05)	0.18 (0.10)	0.93	0.13 (0.08)	0.11 (0.05)	-0.31	0.63 (0.40)	0.64 (0.48)	0.02	0.78 (0.42)	0.95 (0.49)	0.37
Lateral												
PLF (N)	-104 (38)	-114 (61)	0.20	-143 (54)	-142 (69)	-0.02	-175 (55)	-173 (69)	-0.03	-279 (91)	-305 (123)	0.24
PLF (BW)	-0.16 (0.05)	-0.14 (0.06)	-0.36	-0.20 (0.08)	-0.19 (0.08)	-0.13	-0.26 (0.08)	-0.26 (0.11)	0.00	-0.39 (0.11)	-0.43 (0.15)	0.31
Resultant												
PRF (N)	2811 (647)	3034 (875)	0.29	2893 (762)	3087 (810)	0.25	2832 (778)	2941 (947)	0.13	3261 (1020)	3588 (1080)	0.31
PRF (BW)	4.13 (1.04)	4.34 (1.15)	0.19	4.36 (1.10)	4.34 (0.96)	-0.02	3.90 (0.65)	3.92 (0.90)	0.03	4.50 (1.15)	5.38 (1.74)	0.60
RFD												
PRFD ($kN.s^{-1}$)	1456 (738)	1641 (999)	0.21	1687 (802)	1680 (968)	-0.01	1287 (821)	1313 (975)	0.03	1758 (924)	2175 (1319)	0.37
PRFD ($BW.s^{-1}$)	194 (86.8)	248 (161)	0.25	252 (116)	208 (105)	0.09	192 (128)	195 (148)	0.02	262 (142)	329 (205)	0.38

Key: Data expressed as mean (SD)
WI With Instruction; WO Without instruction; ES Effect size; N Newtons, BW Body weight; $kN.s^{-1}$ kilo Newtons per second; $BW.S^{-1}$ Body weight per second. Jump-Landing One (reactive jump-landing); Jump-Landing Two (post reactive jump-landing). RFD Rate of force development.

Table 4.3 Results of analysis of variance main effects of landing and instruction on force variables

Peak Force Variables	Jump-Landing 1*	Jump-Landing 2*	df	F-ratio	*P*-value
Landing:					
Vertical force (N)	2853	3185	(1,144)	16.9	≤.001[†]
Vertical force (BW)	4.18	4.72	(1,134)	19.8	≤.001[†]
Posterior force (N)	-118	-145	(1,134)	10.5	.002[†]
Posterior force (BW)	-0.18	-0.22	(1,136)	11.8	.001[†]
Medial force (N)	264	329	(1,142)	6.19	.014
Medial force (BW)	0.40	0.50	(1,141)	6.76	.010[†]
Lateral force (N)	-142	-202	(1,142)	50.1	≤.001[†]
Lateral force (BW)	-0.21	-0.31	(1,135)	54.7	≤.001[†]
Resultant force (N)	2883	3203	(1,142)	15.4	.001[†]
Resultant force (BW)	4.22	4.75	(1,134)	18.4	≤.001[†]
Rate of force development (BW.s^{-1})	211	272	(1,141)	18.9	≤.001[†]
Instruction:					
Vertical force (N)	2906	3131	(1,144)	7.70	.010[†]
Vertical force (BW)	4.30	4.60	(1,134)	6.00	.016
Resultant force (N)	2924	3162	(1,142)	8.50	.004[†]
Resultant force (BW)	4.22	4.75	(1,134)	6.70	.011

Key: [†]Significant main effect $P \le .01$; * Mean values

4.5 Discussion

This is the first study to quantify the full spectrum of GRF's associated with bilateral multidirectional jump-landings in premenopausal women 'with instruction' and 'instruction withdrawn' whilst utilising a reactive jump component. The main findings of the current study in relation to the initial hypotheses were: i) GRF's for all jump-landings achieved and exceeded the defined osteogenic thresholds previously shown to improve bone mass at clinically relevant sites for premenopausal women; ii) greater ($P < .01$) magnitudes and rates of GRF occurred in jump-landings performed with 'instruction withdrawn' due to learning and practice effects; iii) significantly greater forces were observed in the second jump-landing (post-reactive jump), for the majority of the force variables measured at all force axes; and, iv) the hypothesis that vertical landing forces would be similar for both bilateral multidirectional jump-landings was supported, however although non-significant main effects were identified for jump type, substantially different medio-lateral and anterio-posterior GRF's were observed.

The current study reported baseline peak vertical landing forces of 3.87 to 5.33 BW's which exceeds the magnitude of force development (>3 BW's), that achieved femoral BMD gains in thirty premenopausal women (Bassey et al., 1998). Bassey et al. (1998), utilised sub-maximal countermovement jumps (average jump height of 8 cm) performed with a 'countermovement arm-swing', to produce peak landing vertical forces that corresponded to 3.0 BW's. Interestingly, the subjects were provided instructions to land by employing flexion at the ankle, knee and hips followed by heel strike on impact. Researchers have suggested that GRF at impact may be attenuated when the knees are flexed upon landing, as the leg musculature will absorb the impact energy over an extended time (Lees, 1981). In comparison, the current study provided cueing to land quickly then jump again to increase the stiffness of landing and potentially enhance the forces transmitted to the bone. The utility of a reactive jump (defined as 'jumping immediately after an initial jump-landing') with bilateral multidirectional jumps was of particular interest in the current study, as recently researchers have demonstrated that jumping and jump-landing techniques significantly influenced peak GRF's using bilateral vertical jumps (Clissold et al., 2018).

Weeks and Beck (2008), investigated a series of jumps with forty healthy young adults [males, 24 (2.9) yr; females, 25 (2.8) yr], and reported similar vertical GRF's for the star jump-landing with comparison to our first star jump-landing (3.8 BW compared to 3.9 BW, respectively). Similar GRF's for the star jump (performed sub-maximally and maximally) were also observed by McKay and colleagues (2005), who conducted a paediatric cross-sectional study (n = 70, 8 - 12yr), that described GRF's for 12 different jumping activities including the star jump. They reported maximal vertical GRF's of 3.4 BW, using a technique involving the subjects starting with legs straddling the sides of the force plate, and coming together onto the force plate repeatedly using a ballistic technique. However, the second jump-landing (performed immediately after the first jump-landing), utilised in the current study, produced substantially greater GRF's (5.3 BW; ↑40%). Interestingly, Weeks and Beck (2008), stated vertical GRF's of only 2.1 BW for the stride jump (no specific instructions given for arm movement), compared to 4.3 BW reported for both jump-landings performed in the current study (utilising a vigorous arm swing). Based on previously defined osteogenic thresholds (>3 BW's) that resulted in femoral neck BMD gains in premenopausal women, star and stride jumps may not be useful in terms of osteogenic benefit, unless aspects of jumping and jump-landing technique are clarified for this purpose. It would seem that cueing participants to jump maximally, minimise ground contact time and employ vigorous arm-swing, as utilised in the current study, significantly influenced this aspect of force production.

Human and animal studies (Bassey et al., 1997; Hsieh et al., 1999; C. H. Turner, 1999; C. H. Turner & Robling, 2003), not only support the measurement of vertical GRF's, represented as body weight (BW) to be used to estimate the influence of loading on bone, but also determined that the rate bone is exposed to strain is more important than magnitude for influencing the adaptive response (Lanyon, 1996; C. H. Turner & Robling, 2003). Bassey and colleagues (1998), determined that mean peak loading rates of 43 body weights per second ($BW \cdot s^{-1}$), using countermovement jumps (50 jumps at 8 cm, 6 days/week), contributed to significant increases in femoral neck BMD. This previously established osteogenic threshold was clearly surpassed in the current study for star (196 and 329 $BW \cdot s^{-1}$) and stride (248 and 252 $BW \cdot s^{-1}$) jumps (jump-landing one and two, respectively). In comparison, Weeks and Beck (2008), quantified much lower rate of force application (determined by time to peak vertical

GRF) values of 52 and 57 BW·s^{-1} (SJ and SDJ, respectively) in healthy young adult males and females. Rate of strain data specified by McKay et al. (2005), for the elementary school students who performed the submaximal and maximal SJ (160 and 211 BW·s^{-1}, respectively), was calculated by identifying the peak value for the slope of the force-time curve (McKay et al., 2005). The current study calculated peak resultant forces for both jump-landings, and the steepest 10 ms for each phase was used to represent the peak rate of force production, as described by Bassey et al. (1998). It would seem that the jump-landing techniques utilised in the current study significantly influenced the rate of force production, however we acknowledge that many different methods can be utilised to calculate rate of force production and thus effect the validity of comparison to selected osteogenic thresholds; therefore, we recommend standardisation for methods of analysis wherever possible.

It was of clinical interest to the researchers to determine whether participants are able to; firstly, achieve similar GRF and rate of force production without further instruction, and secondly, improve their jump-landing ability when practiced over time, thus be able to increase the osteogenic potential of the bilateral multidirectional jump-landings. We observed a significant main effect ($P < .01$) for 'Instruction', as vertical (↑8% and ↑7%) and resultant (↑8% and ↑12%) GRF's N and BW respectively) increased after only one instructed jump-landing session. This indicates a practice effect, as test-retest effects have influenced vertical and resultant forces, with greater forces measured with 'Instruction withdrawn'. Although no significant effects were observed for rate of force development, small effect sizes towards 'without instruction' were observed for jump-landing one in the stride jump (ES = 0.21 to 0.25, kNs^{-1} & BW·s^{-1}) and jump-landing two in the star jump (ES = 0.37 to 0.38, kNs^{-1} & BW·s^{-1}). The findings from the current study have clinical implications for an osteogenic jump-landing programme in the home setting, as once subjects are proficient (in this case after only one instructed session), subjects can achieve and exceed the appropriate magnitude and rate of GRF without further coaching.

It was initially hypothesised that due to cueing provided for the first jump-landing to 'land quickly' and 'immediately jump again for maximal height', greater magnitude and strain rates would be associated with the second jump-landing. The landing type was found to have a significant main effect ($P \leq .01$), with the 'second jump-landing' (post-reactive jump-landing) consistently higher (↑11% to ↑49%) than the 'first jump-landing' (reactive jump-landing) in all force axes except for anterior ground reaction force (N and BW). Peak rate of force development (↑29%; $P \leq .0001$) also showed a significant effect for landing type. The use of a 'reactive jump-landing' was initially investigated by Clissold and colleagues (2018), using bilateral vertical jumps (countermovement and drop jumps). They reported significantly larger peak resultant force, (↑10%; $P = .002$) and peak rate of force production (↑20%; $P < .001$) values (in relation to BW and $\text{BW} \cdot \text{s}^{-1}$, respectively) for the second jump-landings (Clissold et al., 2018). They proposed the utilisation of the stretch shortening cycle to achieve greater jump heights ensuing from the first (reactive) jump-landing enhanced the stiffness of the second (stationary) jump-landing, which increased subsequent GRF's (Clissold et al., 2018).

To the authors knowledge, no jumping studies have reported GRF's in the X and Y axes. Thus, the contribution of anterio-posterior and medio-lateral jump-landing forces to total osteogenic stimuli is poorly understood in the area of bone health. We proposed that similar magnitude vertical GRF's would be observed for SJ & SDJ landings, and that differences in GRF's would be observed based on the directional emphasis of each jump type. Researchers have suggested that bone will not adapt to habitual patterns of loading (e.g. walking and running) and therefore requires novel or diverse loading patterns to stimulate an adaptive bone response (Lanyon, 1996; C. H. Turner & Robling, 2003). In addition, the influence of loading variation may be a particularly important consideration for osteogenic jump-landing programmes and for special populations such as older adults unable to tolerate high magnitude and rate of GRF.

When GRF's for both jump-landings are presented as a total stimulus (with instruction conditions combined), vertical and resultant forces were similar for both bilateral multidirectional jumps, although marginally greater for the SJ (↑7% and ↑3%). Thus, without any significant main effects observed for jump type, we may suggest that both jumps could be used interchangeably (when considering progressive overload and variation) in an osteogenic exercise program for premenopausal women in the home setting once participants are proficient with jumping technique. However, when we represent the full spectrum of GRF's (X, Y and Z) we recognize the directional qualities each type of jump provides. As clinical data reporting force thresholds required to increase BMD are in the vertical direction only, it is therefore unknown whether the same conclusion can be drawn from the resultant, medio-lateral and anterio-posterior forces without clinical support. In spite of this limitation, and in support of the original hypothesis, medio-lateral GRF's were substantially greater (↑85% to ↑466%) for the SJ jump-landings when compared with SDJ jump-landings, and anterio-posterior GRF's were markedly greater for the SDJ jump-landings (↑103% to ↑316%) when compared with the SJ jump-landings. As researchers have suggested that bone responds optimally to the net effect of different loading activity variables (including; strain magnitude, strain rate and strain direction), non-habitual or atypical activities (i.e. multidirectional jumping and specifically jump-landings) for women who are habitually inactive and are not involved in high-impact sports, present as effective modes of exercise to stimulate bone remodelling for this population.

4.6 Conclusion

In conclusion, it would seem from our results that the SJ and SDJ combined with reactive jump-landings, performed 'with instruction' and with 'instruction withdrawn', easily exceeded osteogenic thresholds previously shown to increase bone mass in premenopausal women. Although our results showed high inter-subject variability in most outcome measures (due to a wide range of fitness and movement competencies), all of our participants achieved the predefined osteogenic thresholds for magnitude and rate of strain (3BW and $43BW \cdot s^{-1}$, respectively). Although osteogenic thresholds are useful for describing effective jump-landing intensities, the variability that exists between individuals when determining a safe effective dose of impact exercise requires further investigation. Note: Although our participants were cued to jump maximally and to land stiffly, we recommend that jumping and landing intensities are modified based on factors such as; injury status, fitness level, movement competency and comfort.

Further research could utilise methods presented in the current study to quantify the GRF's of various types of unilateral multidirectional jumps (vertical, lateral and forward hops) and compare them to previously determined osteogenic thresholds. Such research could add value through providing a range of jumping movements which could be utilised in the development of osteogenic exercise programmes for premenopausal women (without pre-existing osteoporosis), whilst collecting BMD data to enable effectiveness over time. While osteogenic programmes are currently lacking (Babatunde et al., 2012; B. R. Beck et al., 2017; Ebeling et al., 2013; Weaver et al., 2016; Zhao et al., 2014), a resource of quantified jump-landing exercises could provide a strong foundation for the development of bone specific programming with consideration to specific training principles i.e. progressive overload, novel stress and technical progression. Such programmes could help to optimise and create a novel impact stimulus required to promote bone formation in healthy premenopausal women. However, before participants seek to undertake jump-landing exercises, such as those described in the current study, pre-conditioning exercise may be needed to tolerate the stresses involved with jump-landing exercises to maximise benefits to bone health and reduce risk of injury.

CHAPTER 5. MULTIPLANAR HOP-LANDINGS EXCEED OSTEOGENIC THRESHOLDS WITH AND WITH INSTRUCTION WITHDRAWN IN PREMENOPAUSAL WOMEN

5.1 Prelude

The focus of quantification studies of landing forces in the literature (and the previous two studies), has been primarily on bilateral jump-landings in premenopausal women, and thus the estimation of landing forces associated with unilateral jumps or hops has been limited. Therefore, research is required to quantify the osteogenic potential and bone-loading forces of various types of unilateral jumps (vertical, lateral and forward hops) across all planes of motion, to compare to previously determined vertical osteogenic thresholds. It is however important that the unilateral jump-landing technique is clarified and standardised with respect to factors such as the landing technique and use of arms, in order to maximise the opportunity for premenopausal women to consistently achieve the rates and magnitudes of GRF's, which have achieved gains in bone strength and mineralisation in other studies. Multidirectional hop-landings can provide unique and variably distributed forces to the femoral neck, and represent opportunity for exercise progressions (i.e. variation and progressive overload) with respect to osteogenic programme design. It is therefore of interest to investigate the differences in landing forces for the different types of hops to satisfy the bones directional loading requirement (in addition to magnitude and rate of strain), and the influence of instruction, utilising the methodology for the previous bilateral studies. This research has implications for including multidirectional hops, in a resource of quantified jump-landing exercises which could provide a strong foundation for the development of bone specific programming for premenopausal women.

Clissold, T. L., Winwood, P. W., Cronin, J. B. & De Souza, M. J. (2019). Multidirectional single leg hop-landings exceed osteogenic thresholds with and without instruction in premenopausal women**.** *Sports Biomechanics (currently under review).*

5.2 Introduction

Osteoporosis is a disease characterised by a reduction in the density and quality of bone leading to a weakness of the skeleton and associated increased risk of fracture (Kanis, Adachi, et al., 2013). This disease is recognised as a major public health issue in the developed world affecting more than half of women and one third of men over the age of 60 years. In the United Kingdom the direct costs of osteoporosis treatment exceeded 4.5 billion pounds in 2017 with over half a million people hospitalised because of a fragility fracture (D. A. Turner et al., 2018). Osteoporosis is largely preventable, with specific types of exercise being widely recognised as the leading green prescription.

Although regular exercise has been shown to reduce risk factors for lifestyle-related diseases such as obesity, cardiovascular and metabolic disease (McArdle et al., 2006; Tipton & Medicine, 2006), not all exercise provides the stimulus required to be osteogenic (B. R. Beck et al., 2017; C. H. Turner & Robling, 2003). Although the optimal dose of exercise is yet to be determined, researchers have established several criteria deemed necessary to stimulate bone including; a force magnitude of greater than 3-body weights (BW), a rate of force development exceeding 43-body weights per second (BW/s) and an unfamiliar or diverse direction of force application (Bassey et al., 1998; Robling et al., 2001; C. H. Turner & Robling, 2003). Evidence from cross-sectional studies describe athletes in weight-bearing sports (i.e. gymnastics, tennis, and volleyball) which involve high magnitude and rates of loading and novel or diverse loading patterns, as having greater bone mass at loaded skeletal sites compared to non-athletes or athletes in non-weight-bearing or lower-impact sports (Alfredson et al., 1997; Kontulainen et al., 2003; Snow et al., 2001). Therefore, there is a need to understand and quantify the landing forces for different types of exercises to determine their osteogenic potential as a stimulus for bone development across the life stages, in addition to identifying at risk populations. Such exercises could help to build a better skeleton, and maintenance of that would decrease the susceptibility to fractures and osteoporosis in later years.

Jumping and hopping exercises are of special interest as have been shown to increase peak bone mass in young people and minimise age-related bone loss in females (Bailey

& Brooke-Wavell, 2009, 2010b; Bassey et al., 1997; Bassey & Ramsdale, 1994; Bassey et al., 1998; Stiles et al., 2013; Weeks & Beck, 2008). From different meta-analyses (Babatunde et al., 2012; Zhao et al., 2014) it can be concluded that brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), of 4 - 18 months duration, and loading magnitudes (between 2 - 6 BW) and rates (> 43 BW/s), can produce significant gains in femoral neck bone mineral density (BMD) of 0.5 - 3% in premenopausal women. These evidence-based values suggest that a safe and effective osteogenic threshold exists around this range of load magnitude and rate for jumping and hopping exercises, however the primary focus has been on bilateral jump-landings. Research conducted by Bailey and Brooke-Wavell (2010) investigated whether hopping (unilateral jump-landings) would have greater osteogenic potential than jumping (bilateral jump-landings) due to total body weight-bearing on one leg only, and providing a greater ‘novelty factor’ for premenopausal women. A strength of their study was the paired design they utilised, which provided a direct comparison between the trained and controlled limb for each participant, during the 6-month exercise intervention, and they reported almost 2% gain in BMD at the femoral neck of the trained limb. However, although this study acknowledged the importance of utilising a selection of hops due to their multidirectional landing qualities, ground reaction force (GRF) magnitudes and rates of loading were presented in the vertical direction only. It is therefore of interest to investigate the forces for all planes of motion associated with multidirectional jump-landings, as understanding such kinetics would assist other practitioners in programme design for osteogenesis.

Jump-landing technique was also of interest to the current study as previous research has described how landing mechanics can affect the magnitude and rate of impact forces, and providing specific cues to land ‘stiffly’ can prevent participants from ‘softening’ the landing and influence its osteogenic effectiveness (Bobbert et al., 1987; Bobbert et al., 1986; Lees, 1981; McNitt-Gray, 1993). Thus, instruction was deemed important to both quantify the magnitude of GRF’s with specific jump-landing instructions provided, and to determine whether similar or greater GRF’s could be achieved after instruction was withdrawn. This would have implications for the hops to be performed in the home setting, once proficient, with the knowledge that the appropriate GRF’s and subsequent osteogenic thresholds would be met. It is therefore important that jump-landing technique is clarified and standardised (with respect to factors such as; instructions provided, arm swing and landing technique), in order to maximise the opportunity for premenopausal women to consistently achieve the rates and magnitudes of GRF's (Bassey et al., 1998), which have achieved gains in bone strength and mineralisation in other studies (Bassey et al., 1998; Heinonen et al., 1996; Kato et al., 2006; Niu et al., 2010; Tucker et al., 2014).

Although jump impact forces have been quantified by several research groups, the focus has been primarily on bilateral jumps in this population (Bassey & Ramsdale, 1994; Clissold et al., 2018; Tucker et al., 2014), and thus the estimation of landing forces associated with unilateral jumps or hops has been limited (Bailey & Brooke-Wavell, 2008). In addition, these studies have presented GRF's in the vertical direction only, therefore neglecting the contribution of landing forces across all planes of motion. Given the limitations identified, this study sought to; a) determine whether GRF's for unilateral multidirectional jump-landings, [forward hop, (FH), lateral hop, (LH) and vertical hop, (VH)] could achieve osteogenic thresholds previously presented for bilateral vertical jumps, which improved bone mass among premenopausal women; b) determine if differences in landing forces exist for the different types of hops to satisfy the bones directional loading requirement (in addition to magnitude and rate of strain); and, c) determine if differences exist in landing forces between the different hops 'with instruction' and then performed one week later with 'instruction withdrawn'. Due to the scope of the study, several hypotheses were generated; i) Vertical and resultant GRF's for all hop-landings would achieve and exceed previously defined vertical only, osteogenic thresholds for magnitude and rate (>3BW's and >43BW/s, respectively); ii) superior vertical GRF's (magnitude and rate), would be observed for the VH landings, greater medio-lateral landing forces would be associated with the LH landings, and greater anterio-posterior landing forces would be associated with the FH landings, representing the multidirectional qualities required to stimulate bone remodelling; and, iii) greater magnitudes and rates of strain would occur for hop-landings performed with 'instruction withdrawn' due to learning and practice effects.

5.3 Methods

5.3.1 Experimental Approach to the Problem

A cross-sectional descriptive design was utilised for this study. Data was collected for each participant over two testing sessions separated by one week, with a familiarisation session scheduled at least 3 - days prior to the first testing session (Figure 5.1). In the familiarisation and first testing session participants were given detailed instruction on how to perform the hops and in the second testing session participants were just asked to perform the hops with instructions withdrawn. All participants refrained from performing any of the hops between testing sessions and commencement of normal daily activity was undertaken as determined by activity diaries (Appendix 7). The study design utilised in this study was previously used to quantify a series of vertical and multidirectional bilateral jump-landings in the same population (Clissold, Cronin, De Souza, Wilson, & Winwood, 2019; Clissold et al., 2018).

Familiarisation (Session 1)

Participants were required to complete pre-screening questionnaires (Appendix 4a) and had their height (Appendix 17a) and body mass recorded, and their body composition measured using a bioelectrical impedance machine (InBody230, Biospace, Seoul, Korea) (Appendix 17b). The Vertec Yardstick (Swift Performance Equipment, Australia) was used to measure vertical jump height and baseline jumping ability, which was used as a surrogate measure for lower body explosive power (Leard et al., 2007; Wulf & Dufek, 2009) (Appendix 17b). Before jump commencement the participants reach height was determined. They were then encouraged to jump and touch the highest vane of the Vertec device. The authors thought it important to determine maximal baseline vertical jump ability to allow for comparison with previous studies who have utilised this subject demographic. Participants were then given a demonstration of the hops (vertical, forward and lateral), followed by two to three practice hops (on each leg) on the force plate. They were taught to bend their knees and hips slightly (during the eccentric phase) to perform a maximal jump for height (during the concentric phase) and to land stiffly, with the foot flat on the ground.

All hops in this study were performed barefooted as researchers have suggested the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise (Bassey et al., 1997; Bassey & Ramsdale, 1994).

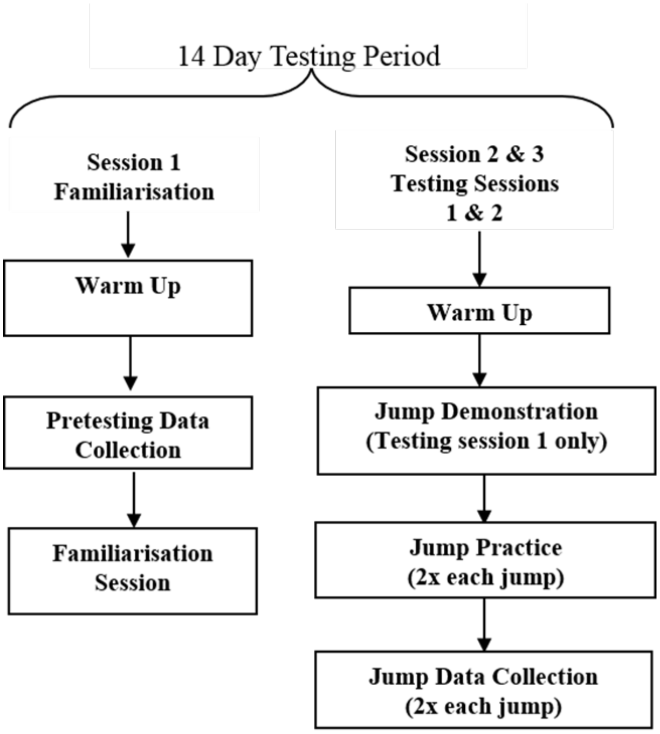


Figure 5.1 Experimental design of the 14 - day testing period

Testing Protocol (Sessions 2 & 3)

For the first testing session, participants performed a ten-minute standardised warm-up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilisation exercises. Testing commenced five minutes after the warm-up. Prior to testing, the hops were demonstrated using proper technique, with all instructions standardised for every participant, and provided before every hop. For the VH, participants were instructed to stand on the force plate with feet shoulder-width apart with their arms by their side. Participants were then instructed to start with arms above their head, then flex the knees and hips (during the eccentric phase) and quickly jump upwards (during the concentric phase) with arms 'swinging' in a countermovement style, to land stiffly on one leg. For the forward and lateral hop participants stood on one side of the force plate with feet shoulder-width apart before leaping forward or sideways, and landing stiffly onto the other side of the force plate on one foot. Participants were cued to land with minimal flexion of the hip and knee, and to utilise a flat-footed ground contact. A pictorial representation of the phases of the hops presented in this study are depicted in Figure 5.2.

Figure 5.2 Pictorial representation of the phases of the vertical hop (top), forward hop (middle) and lateral hop (below), as described in this study: A) Start of eccentric phase; B) Start of concentric phase; C) Flight phase; D) Landing phase

Peak jump-landing forces were collected for the hop-landings ‘with instruction’ and with ‘instruction withdrawn’ at 400 Hz using a portable AMTI (Advanced Mechanical Technology Inc., Watertown, Massachusetts) Accupower (ACP) force plate (length 101.6 cm x width 76.2 cm x height 12.4 cm). Participants remained stationary on the force plate for five seconds after landing and each hop was separated by a 30 - second rest interval. The participants performed two practice hops (on each leg), followed by two hops (on each leg) where they were cued to jump maximally in the vertical direction for each hop type, and force plate data was collected using AMTI version 1.5 software (Athletic Republic, Fargo, North Dakota). Hops were performed in a randomised order which was replicated in the second testing session. Data was analysed as an average of the two hops (for each leg).

For the second testing session the same protocol was followed, however, no instruction or cueing was given (instruction withdrawn) for how the participant was to perform the hops. All testing for this study was undertaken at a similar time of day with participants instructed to maintain their normal dietary intake before and after each testing session. Participants completed activity diaries to monitor physical activity to ensure that inter-session physiological status was similar. We did not control for nutrition, or hydration levels but participants were told not to make any changes in the above during the testing period. All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

5.3.2 Participants

Twenty-one healthy premenopausal women (31 - 50 yr), volunteered to participate in this study (Appendix 3). It was calculated using G*Power, that a target sample size of 21 participants will allow for the detection of changes in jump performance (α= 0.05, 1-β= 0.80) between jumps with and without instruction. A summary of the participant characteristics is presented in Table 5.1. All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) and a Pre-exercise questionnaire (Appendix 4a), and inclusion criteria required participants to be between 30 and 50 years of age, in conjunction with the participants reporting a regular menstrual cycle to determine premenopausal status. Participants were excluded if any medical problems were reported that compromised their participation or performance in this study, including; having a recent or current musculoskeletal injury, osteoarthritis and any condition of impaired balance or coordination. The methods and procedures used in this study were approved by the Institutional Review Board Committee (R14/17) (Appendix 2).

Table 5.1 Baseline characteristics of the participants (mean ± SD)

	All Participants (n = 21)
Demographics	
Age (yr)	43.3 ± 5.9
Height (cm)	167 ± 5.5
Body mass (kg)	69.4 ± 9.6
BMI (kg·m^{-2})	24.9 ± 3.4
Body fat (%)	27.5 ± 8.7
Maximal Countermovement Jump	
Jump height (cm)	35.5 ± 9.3

5.3.3 Data Analysis

The force-time data was calculated in Microsoft Excel 2013 (v 15.0.5179.1000, Microsoft, California, USA) and presented as peak values. Forces in the x and y axis were calculated as medial (positive) and lateral (negative), and anterior (propulsive) and posterior (braking), respectively. Peak GRF magnitude was presented in respect to body weight (BW), and was calculated as peak GRF, (N)/ body mass, (N). Peak resultant forces were calculated as $\sqrt{x^2 + y^2 + z^2}$ and used to determine the rate of force development (N·s^{-1} * 100/ body mass, N; body weight per second, BW/s) over 10 ms taken from the steepest part of the slope between the end of the flight phase and the peak landing force (Bassey & Ramsdale, 1994). All force-time data were filtered using a second order low-pass Butterworth filter (cut off frequency 20 Hz) with zero lag. A pictorial representation of the force profile of the hops utilised in this study are presented in Figure 5.3.

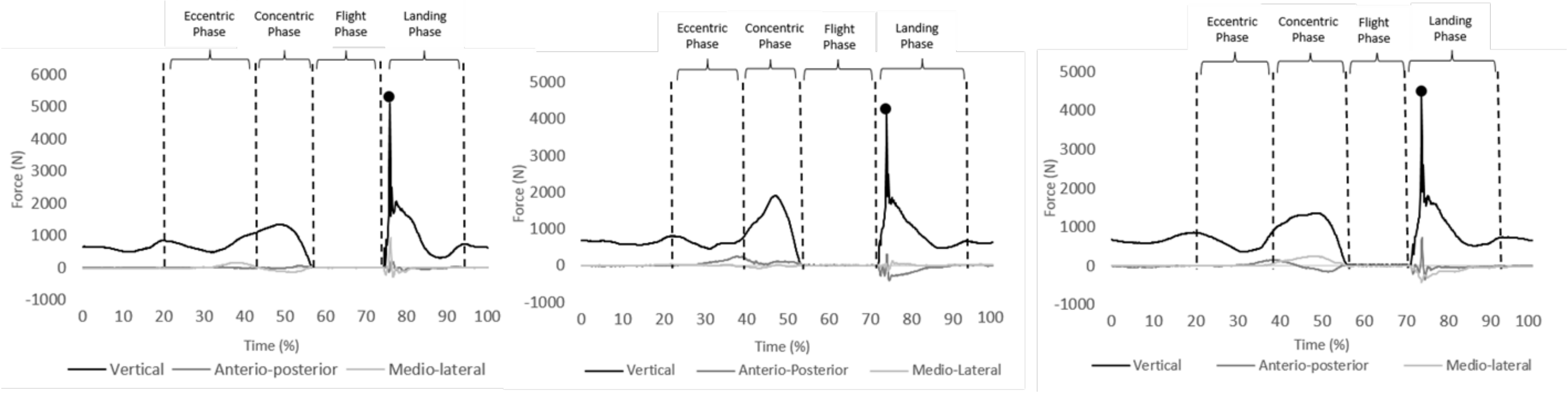


Figure 5.3 A typical vertical force profile of the vertical hop (left), forward hop (middle) and lateral hop (right). Dashed lines represent the various phases of the hops. The circles indicate peak landing forces.

5.3.4 Statistical Analyses

Stem and leaf plots were used to ascertain whether there were any outliers in the data for each variable. All values three or more box lengths from upper or lower edges of box were considered extreme outliers and were investigated carefully before being considered extreme outliers and were removed (Kwak & Kim, 2017). After extreme outliers were removed descriptive statistics were calculated and reported as mean and standard deviations. A 2-way (jump type x instruction type) ANOVA with Bonferroni's post hoc tests was used to determine if significant differences existed between the jump type and whether instruction was provided. A Shapiro-Wilk's test was used to show all data was normally distributed and met the assumptions associated with the 2-way ANOVA. Significance was accepted at the $p \leq .01$ level. All statistical analyses were carried out using Data Desk 6.01 for Windows (Data Description Inc., Ithaca, NY, USA). Effect sizes (ES = mean change/standard deviation of the sample scores) were calculated to quantify the magnitude of the effects associated with landings 'with instruction withdrawn'. Cohen (1998) applied qualitative descriptors were used for the effect sizes with ratios of 0.2, 0.5 and 0.8 indicating small, moderate and large changes, respectively (Cohen, 1988).

5.4 Results

The range of peak magnitudes (4.17 to 5.12 BW's) and peak rates of strain (239 to 334 BW/s) for vertical and resultant forces for the unilateral jump-landings in this study exceed previously defined osteogenic thresholds (>3 BW's and 43 BW/s) (Bassey et al., 1998) (Table 5.2).

No significant interactions were observed between jump type and instruction type (Table 5.3). Jump type was found to have a significant main effect ($p \leq .01$), with the vertical hop producing consistently higher GRF than the forward and lateral hop at all axes (except posterior) (↑10% to ↑92%; N and BW, respectively). Significantly higher ($p \leq .001$) posterior forces were observed for the forward hop and lateral hop when compared to the vertical hop (↑71% and ↑69%, respectively). In addition, lateral GRF's were significantly larger ($p \leq .0001$) for the lateral hop and vertical hop, when compared to the forward hop (↑35% and ↑42%, respectively). Peak rate of force development (↑2% to ↑20%; $p \leq .0001$) also showed a significant effect ($p \leq .01$) for jump type with the vertical hop producing higher rates of strain than the lateral hop and forward hop (↑2% to ↑20%; N and BW, respectively).

No significant main effects for ‘Instruction’ were observed. Decreases in force for all axes (except medial) were observed for the vertical hop (ES = -0.04 to -0.79), and the forward hop (ES = -0.06 to 0.59), with instruction withdrawn. Although trivial and small decreases in GRF’s were found for the lateral hop in the vertical, posterior and medial direction (ES = 0.02 to -0.42), small to large increases were observed in the anterior (ES = -0.79 and -0.78) and lateral (ES = 0.32 and 0.37) directions (N and BW, respectively).

Table 5.2 Ground reaction forces associated with the unilateral vertical forward and lateral jump landings with and without instruction

	Vertical Hop			Forward Hop			Lateral Hop		
Peak Force Parameters	WI	WO	ES	WI	WO	ES	WI	WO	ES
Vertical									
PVF (N)	3386 ± 947	3183 ± 762	0.24	3085 ± 775	2705 ± 755	0.50	2809 ± 680	2794 ± 919	0.02
PVF (BW)	5.07 ± 1.55	4.76 ± 1.19	0.23	4.62 ± 1.30	3.83 ± 1.40	0.59	4.19 ± 1.09	4.17 ± 1.46	0.02
Anterior									
PAF (N)	176 ± 91	170 ± 97	0.07	209 ± 150	156 ± 90	0.44	7 ± 4	12 ± 9	-0.79
PAF (BW)	0.26 ± 0.14	0.26 ± 0.15	0.05	0.32 ± 0.24	0.24 ± 0.15	0.44	0.01 ± 0.01	0.02 ± 0.01	-0.78
Posterior									
PPF (N)	-84 ± 31	-76 ± 26	-0.28	-301 ± 59	-275 ± 79	-0.38	-274 ± 76	-249 ± 71	-0.33
PPF (BW)	-0.12 ± 0.04	-0.11 ± 0.04	-0.23	-0.44 ± 0.07	-0.41 ± 0.12	-0.28	-0.40 ± 0.10	-0.36 ± 0.10	-0.42
Medial									
PMF (N)	485 ± 220	497 ± 203	-0.06	86 ± 34	91 ± 41	-0.15	396 ± 177	391 ± 234	0.02
PMF (BW)	0.73 ± 0.34	0.74 ± 0.30	-0.04	0.12 ± 0.06	0.12 ± 0.09	-0.06	0.60 ± 0.29	0.60 ± 0.40	0.02
Lateral									
PLF (N)	-239 ± 68	-195 ± 43	-0.79	-139 ± 66	-114 ± 61	-0.39	-186 ± 25	-202 ± 82	0.32
PLF (BW)	-0.36 ± 0.11	-0.30 ± 0.08	-0.63	-0.21 ± 0.12	-0.17 ± 0.10	-0.39	-0.27 ± 0.04	-0.30 ± 0.13	0.37
Resultant									
PRF (N)	3417 ± 959	3213 ± 774	0.23	3091 ± 779	2711 ± 757	0.49	2839 ± 690	2822 ± 938	0.02
PRF (BW)	5.12 ± 1.57	4.80 ± 1.21	0.23	4.63 ± 1.30	3.84 ± 1.41	0.58	4.24 ± 1.11	4.22 ± 1.49	0.02
RFD									
RFD (kN.s^{-1})	2152 ± 869	1940 ± 830	0.25	2211 ± 1075	1861 ± 1054	0.33	1572 ± 732	1641 ± 958	-0.08
RFD (BW.s^{-1})	319 ± 131	287 ± 122	0.25	333 ± 169	277 ± 160	0.34	238 ± 122	245 ± 149	-0.05

Key: Data expressed as mean ± SD
WI With Instruction; WO Without instruction; ES Effect size; N Newtons, BW Body weight; kN.s^{-1} kilo Newtons per second; BW.s^{-1} Body weight per second. RFD Rate of Force Development.

Table 5.3 Results of analysis of variance main effects of jump type on force variables

Peak Force Variables	Mean values VH	Mean values FH	Mean values LH	df	F-ratio	*p*-value
Vertical force (N)	3285	$2950^{\dagger}$	$2832^{\dagger}$	(2,99)	9.69	≤.001
Vertical force (BW)	4.82	4.35	4.17	(2,93)	10.3	≤.001
Anterior force (N)	175	$183^{\ddagger}$	$13.9^{\dagger}$	(2,97)	56.5	≤.001
Anterior force (BW)	0.26	$0.27^{\ddagger}$	$0.02^{\dagger}$	(2,96)	51.7	≤.001
Posterior force (N)	-80.9	$-288^{\dagger}$	$-266^{\dagger}$	(2,93)	217	≤.001
Posterior force (BW)	-0.12	$-0.42^{\dagger}$	$-0.39^{\dagger}$	(2,93)	191	≤.001
Medial force (N)	$491^{\ddagger}$	$110^{\dagger}$	$400^{\S}$	(2,95)	77.6	≤.001
Medial force (BW)	$0.75^{\S}$	$0.17^{\ddagger}$	$0.58^{\dagger}$	(2,94)	89.0	≤.001
Lateral force (N)	$-217^{\S}$	-127	$-199^{\S}$	(2,97)	31.4	≤.001
Lateral force (BW)	$-0.33^{\S}$	$-0.19^{\ddagger}$	-0.29	(2,98)	30.3	≤.001
Resultant force (N)	3315	$2956^{\dagger}$	$2862^{\dagger}$	(2,99)	9.87	≤.001
Resultant force (BW)	4.86	$4.36^{\dagger}$	$4.21^{\dagger}$	(2,93)	10.5	≤.001
RFD (kN.s^{-1})	2094	$2036^{\ddagger}$	$1692^{\dagger}$	(2,97)	6.07	.003
RFD (BW.s^{-1})	311	295	$249^{\dagger}$	(2,95)	6.63	.002

Key † significantly different to VH; ‡ significantly different to LH; § significantly different to FH
RFD Rate of Force Development. VH Vertical hop; FH Forward hop; LH Lateral hop;

5.5 Discussion

This is the first study to quantify the GRF's across all planes of motion associated with multidirectional hop-landings in premenopausal women 'with instruction' and 'instruction withdrawn'. The main findings of the current study with respect to the proposed hypotheses were: i) Vertical osteogenic thresholds for GRF magnitude and rate previously shown to improve bone mass at clinically relevant sites for premenopausal women were achieved and exceeded for vertical and multidirectional hop landings; ii) The hypothesis that vertical landing forces would be greater ($p \leq .01$) for the vertical hop was supported, with significantly ($p \leq .01$) different medio-lateral and anterio-posterior GRF's observed for the multidirectional hops; and, iii) In contrast to the original hypothesis, smaller ($p = .015$) magnitudes and rates of GRF occurred for hops performed with 'instruction withdrawn'.

The current study presents a range of GRF magnitudes (4.02 to 4.93 BW's) and rates of strain (237 to 319 BW/s) for vertical and resultant hop-landing forces, which easily exceeds previously defined vertical osteogenic thresholds (>3 BW's and 43 BW/s) (Bassey et al., 1998) developed using bilateral jump-landings with premenopausal women. Interestingly, although Bailey and Brooke-Wavell (2010) reported GRF's for vertical hops performed maximally which do not achieve the stated osteogenic thresholds (2.5 and 2.8 BW) they reported femoral BMD gains of nearly 2% for the female participants [34.6 (7.9) yr]. They speculated however that the single-leg landing forces may be equivalent to a total landing force of 5 - 6 BW's due to forces being transmitted through one leg only, and therefore easily exceeding the bone stimulation threshold.

The variability that exists when quantifying peak vertical landing forces (2 to 6 times body weights) for vertical jumps (bilateral and unilateral) in different studies (Bassey et al., 1998; Clissold et al., 2018; McKay et al., 2005; Tucker et al., 2014; Weeks & Beck, 2008), highlights the need to explore different aspects of jump technique and the way instruction can influence jump-landing GRFs. The Bailey and Brooke-Wavell study reported utilising a 'countermovement' style of jumping, however they were referring to knee flexion prior to jumping and provided no instructions for arm swing or landing mechanics. We believe cueing our participants to use a vigorous arm swing in a ‘countermovement’ style enhanced jump height and may have contributed to the substantially greater impact forces we observed for our participants (Lees et al., 2004). In addition, we cued our participants to ‘land stiffly’, with minimal knee flexion, which potentially enhanced the osteogenic potential of the hops (Clissold et al., 2018; Lees, 1981).

Interestingly, although no significant main effects were observed for instruction, we demonstrated that in contrast to the original hypothesis, smaller (*p* = .015; ES = 0.02 to -0.79) magnitudes and rates of GRF occurred in jump-landings performed one week later, with ‘instruction withdrawn’. Instruction was of interest to this study to determine whether similar or greater GRF’s could be achieved when instruction was withdrawn, as this could influence programming considerations. Although the current study reported reduced GRF’s at most axes for the non-instructed session, the landing forces for the hops (with instruction and with instruction ‘withdrawn’), exceeded magnitudes and rates of strain previously shown to improve femoral BMD in premenopausal women.

In spite of the small decreases in peak force production observed across all axes (except medial) for the forward hop (↑6% and no change) and the vertical hop (↑3% and ↑1%) with instruction withdrawn, small to large increases were observed for the lateral hop in the anterior (↑71% and ↑100%; ES = -0.79 and -0.78) and lateral (↑9% and ↑11%; ES = 0.32 and 0.37) direction (N and BW, respectively). These results may indicate that participants are more likely to improve their jump-landing ability hops in more unusual or unaccustomed directions (medial and lateral) when practiced over time due to initial unfamiliarity. This proposition was evident in the recent ‘Hip-Hop’ study which reported baseline GRF’s of 2.7 BW for hops performed by older men (70 (4) yr), which increased to 3 BW after 6 months of performing the hop programme (Allison et al., 2015). In addition to participants developing adaptations to both generate and tolerate increased landing forces over time, multidirectional hopping interventions have reported improvements in factors relevant to falls prevention, such as muscle strength and balance, in addition to enhanced BMD for premenopausal women at clinically relevant sites for osteoporosis prevention (Bailey & Brooke-Wavell, 2010a, 2010b).

Our study demonstrated that jump type had a significant effect, with greater forces observed in the vertical hop for all force variables measured (except posterior). Jump type was found to have a significant main effect ($p \leq .01$), with the vertical hop producing consistently higher GRF than the forward and lateral hop at all axes (except posterior) (↑10% to ↑92%; N and BW, respectively). Significantly higher ($p \leq .001$) posterior forces were observed for the forward hop and lateral hop when compared to the vertical hop (↑71% and ↑69%, respectively). In addition, lateral GRF's were significantly larger ($p \leq .0001$) for the lateral hop and vertical hop, when compared to the forward hop (↑35% and ↑42%, respectively). Peak rate of force development (↑2% to ↑20%; $p \leq .0001$) also showed a significant effect ($p \leq .01$) for jump type with the vertical hop producing higher rates of strain than the lateral hop and forward hop (↑2% to ↑20%; N and BW, respectively). A paucity of research exists in the area of quantifying landing forces associated with hop exercises, with an exclusive presentation of the vertical hop and vertical GRF's only (Allison, Folland, Rennie, Summers, & Brooke-Wavell, 2013; Bailey & Brooke-Wavell, 2009; McKay et al., 2005; Weeks & Beck, 2008). Therefore, a limitation exists for the interpretation of the force data across all planes of motion and the contribution of each vector to the overall osteogenic stimulus for bone. However, it is well accepted that unusual or unfamiliar directions of force application, as provided by multidirectional hops, may further enhance the overall osteogenic potential of mechanical loading and warrant further investigation.

Wolff's Law, is well described in terms of bones ability to adapt to mechanical loads, leading to bone formation, and Frost (1987) explored the forces to achieve skeletal adaptation in the development of his 'minimum effective strain', or 'mechanostat' theory, hypothesising that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation and increase bone mass and bone strength (Frost, 1987, 1992, 2003). Furthermore the 'error strain distribution hypothesis' suggests that unusual or novel directions of force application may have a greater osteogenic effect than magnitude and therefore vital to osteogenesis (Lanyon, 1987, 1996). Thus, the intention of quantifying multidirectional single leg landings in the current study was to provide unique and variably distributed forces to the skeleton, and specifically the femoral neck, and to provide opportunity for exercise progressions (i.e. variation and progressive overload) with respect to osteogenic programme design.

5.6 Conclusion

In conclusion, our results show that the multidirectional hop-landings, once cued to land ‘stiffly’, and to utilise a flat-footed ground contact, easily exceeded osteogenic thresholds previously shown to increase bone mass in premenopausal women. This has implications for multidirectional hops, as part of a wider osteogenic programme, to be performed effectively in the home-setting, after only one instructed session. As research has predominantly focussed on minimising postmenopausal BMD losses and risk factors associated with falling, exercise regimes for improving bone mass in adults are generic and lack specific recommendations for the premenopausal age group. Thus jump-landing exercises, including hopping and jumping, which have been quantified using premenopausal women could be utilised to develop a periodised jump-landing programme specifically relevant to this population. However, multidirectional hops, such as those described in the current study, may require pre-conditioning exercise, and the performance of bilateral jump-landings first, as part of a programme designed to safely optimise the impact stimulus required to promote bone formation in premenopausal women.

CHAPTER 6. THE DEVELOPMENT OF A LONGITUDINAL PERIODISED JUMP-LANDING PROGRAMME FOR PREMENOPAUSAL WOMEN

6.1 Prelude

The previous biomechanical studies (presented in Chapters 3 to 5) are the first to present force kinetics at all planes of motion for a series of bilateral and unilateral multidirectional jump-landings performed by premenopausal women. We were able to demonstrate that by utilising a reactive jump (defined as jumping immediately after the first jump landing) with a selection of bilateral jumps, and by cueing to land "stiffly" (for all jumps and hops), we were able to easily and consistently achieve the osteogenic thresholds for GFR magnitude and rate which have stimulated gains in bone at clinically relevant sites with premenopausal women. In addition, we considered the influence of loading direction variation which may be a particularly important consideration for osteogenic jump-landing programmes and for special populations such as older adults unable to tolerate high magnitude and rate of GRF. Thus, future research is required to develop a longitudinal periodised osteogenic jump-landing programme specifically for pre-menopausal women using a resource of quantified jump-landing exercises (bilateral and unilateral), with consideration for different loading activity variables (including; strain magnitude, strain rate and strain direction). Therefore, the purpose of this study was to develop a bone health exercise programme specifically for pre-menopausal women, utilising previously quantified jump-landing force data obtained from premenopausal women, whilst integrating current bone health guidelines, research and concepts of best practice strength and conditioning.

Clissold, T. L., Cronin, J. B., De Souza, M. J. & Winwood, P. W. (2019). The development of a jump-landing programme for premenopausal women based on quantified jump landings. Formatted for *Strength and Conditioning Journal*.

6.2 Introduction

Jumping and hopping exercises have been researched for their role in the achievement of peak bone mass in young people and for minimising age-related bone loss in females (Bailey & Brooke-Wavell, 2009, 2010b; Bassey et al., 1997; Bassey & Ramsdale, 1994; Bassey et al., 1998; Stiles et al., 2013; Weeks & Beck, 2008). Meta-analyses support exercise modalities which involve impact forces as having the greatest 'osteogenic potential', suggesting hypothetical gains in bone mineral density (BMD) of 3 - 5% for premenopausal women (30 - 50 years), during a time when normal bone loss is 0.5 - 1% per year (Babatunde et al., 2012; Martyn-St James & Carroll, 2010). However research has predominantly focused on minimising bone losses in "high risk" postmenopausal women and as a consequence exercise recommendations to improve bone health in adults are generic and lack specific recommendations for women before they experience the accelerated bone losses at menopause (Gómez-Cabello et al., 2012; Guadalupe-Grau et al., 2009). Thus, a quantified periodised osteogenic jump-landing programme which targets premenopausal women represent a "window of opportunity" to gain bone, and prevent or delay the time before the fracture threshold is surpassed in the postmenopausal years.

Based on human and animal studies, the measurement of ground reaction forces (GRF's), represented as body weight's (BW's) have been validated to estimate the influence of loading on bone (Bassey et al., 1997; Hsieh et al., 1999; C. H. Turner, 1999; C. H. Turner & Robling, 2003). Bassey and colleagues (1998), developed 'osteogenic thresholds' to represent cut-points specific to mechanical loading which correspond to 3 BW's and mean peak loading rates of 43 bodyweights per second ($BW \cdot s^{-1}$) for premenopausal women, after achieving significant increases in femoral BMD of 2.8% using countermovement jumps (50 jumps, 6 days/week). Osteoporosis Australia, and more recently Exercise and Sports Science Australia (ESSA), have published recommendations for moderate to high impact activities, such as jumping, skipping and hopping, be performed 3 - 5 times per week to promote bone health in adults (B. R. Beck et al., 2017; Ebeling et al., 2013). However, although the ESSA position statement identifies the types of exercises to be utilised, it lacks detail about jump-landing technique, overall programme design and the monitoring of daily and weekly loading.

Researchers recommend that an exercise regime should fulfil the following criteria to achieve an adaptive bone response: a) provide sufficient magnitude and rate of strain; b) deliver a range of diverse and unusual distribution patterns of strain; c) provide a limited number of loading cycles at each distribution; d) be of short duration; and e) provide adequate recovery periods (Bassey et al., 1997; Hsieh et al., 1999; C. H. Turner, 1999; C. H. Turner & Robling, 2003). Other programme variables to be considered include; jump-landing technique, instructions/cues provided, progression and mesocycle design (including loading and de-loading cycles), clinical bone site specificity, age-dependent response to loading and individualisation, (Fleck & Kraemer, 2014; Kraemer & Ratamess, 2004; C. H. Turner & Robling, 2005). Thus, a programme designed to safely optimise the impact stimulus required to promote bone formation must provide specific cues for jump-landings mechanics whilst adhering to best practice musculoskeletal programme design (Fleck & Kraemer, 2014; Kraemer & Ratamess, 2004; Mansfield, 2006; Mothersole et al., 2014). Therefore, the purpose of this review was to consider these factors whilst utilising previously quantified kinetic data for a selection of bilateral and unilateral jump-landings to develop a periodised jump-landing programme that can be used to safely organise and optimise the impact stimulus required to promote bone formation in healthy premenopausal women.

6.3 Osteogenic Programme Design

6.3.1 Bone Adaptation in Response to Mechanical Load

A review of the literature strongly supports that bone responds optimally to the net effect of different loading activity variables (including; strain magnitude, strain rate and strain direction). It is now well accepted that all of these loading variables collectively contribute to the overall osteogenic effect of mechanical loading and are as such interlinked and interdependent (Hart et al., 2017). In addition, the following factors need to be considered to optimise bone mechanosensitivity; frequency and number of loading cycles and rest and recovery between jump-landings and jump-landing sessions. Thus, an understanding about the effect of mechanical loading on bone strength is of critical importance to clinicians, physical therapists and researchers, given the incidence and severity of fractures related to osteopenia and osteoporosis. This review provides a summary of the factors to be considered when designing exercise programmes that will optimally stimulate an adaptive bone response based on the bone adaptation in response to mechanical load:

1. Strain magnitude

Wolff's Law states that bone has the ability to adapt to mechanical loads, suggesting that mechanically-induced strain is a key factor which affects bone formation. Frost (1987) explored the threshold of strain necessary to achieve skeletal adaptation in the development of his 'minimum effective strain' (MES) or 'mechanostat' theory, hypothesising that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation and increase bone mass and bone strength. The mechanical force required to stimulate bone uncoupling of bone remodelling to achieve bone formation has been identified as about 6% of the normal fracture strain threshold (1500-2000µ€) (Frost, 1992). Studies using rat tibia and ulnar determined a linear relationship between the magnitude of an externally applied load and bone strain magnitude (Hsieh et al., 1999) which supports the measurement of GRF, represented as BW, to be used to estimate the influence of this loading on bone. Ground reaction forces 2 to 6 times BW's have been previously shown to stimulate bone and result in bone formation according to more recent meta-analyses (Babatunde et al., 2012; Zhao et al., 2014).

2. Strain rate (Rate of force development)

Although magnitude of strain is considered an important factor to influence the adaptation of bone, the strain rate is considered equally important (Lanyon, 1987; Robling et al., 2006; C. H. Turner & Robling, 2003). Lanyon (1996), modified the original MES theory to include other osteogenic factors such as the rate of strain (MES-stimulus theory), proposing that the rate a bone is exposed to strain was more important than the magnitude of the strain on influencing the adaptive response (Robling et al., 2001; C. H. Turner & Robling, 2003). This suggests that the mechanisms identified for providing the greatest influence for stimulating bone formation are a function of both peak vertical force magnitude and peak rate of force production (O'Connor et al., 1982), with the suggestion that if peak rate of force production is sufficiently high then bone adaptation can be stimulated without using such high forces (Lanyon, 1987; O'Connor et al., 1982; C. H. Turner & Robling, 2003). Thus, both peak loading magnitude and peak loading rate are considered an appropriate way to represent osteogenic thresholds.

3. Strain direction

As researchers state that bone adaptation is blunted by habitual patterns of loading (e.g. walking and running), novel or diverse loading patterns are required and to stimulate an adaptive bone response (Lanyon, 1996; C. H. Turner & Robling, 2003). Therefore, exercises such as jumping and hopping, which are considered to provide ‘unusual’ or ‘unfamiliar’ patterns of strain in women who are habitually inactive and not involved in high-impact sports, have been shown to have a greater osteogenic effect than magnitude alone, with bone adaptation being observed at much lower GRF’s when these non-habitual strains are applied (Lanyon, 1987; C. H. Turner & Robling, 2003). Wolff’s Law, is well accepted in terms of bones ability to adapt to mechanical loads, and subsequent bone formation. Furthermore the ‘Error Strain Distribution’ hypothesis suggests that unusual or novel directions of force application may have a greater osteogenic effect than magnitude and therefore vital to osteogenesis (Lanyon, 1987, 1996). Hence, the influence of loading variation is a particularly important consideration for osteogenic jump-landing programmes and for special populations such as older adults unable to tolerate high magnitude and rate of GRF.

4. Frequency and number of loading cycles

The number of impacts is also been shown to affect the rate of bone formation, with animal studies showing a range of 5 - 100 loading cycles can stimulate bone formation and maintain the mechanosensitivity of bone (Lanyon, 1987; Robling et al., 2001; Umemura et al., 2002). Increases in BMD have previously been reported in premenopausal women using jumping interventions of between 10 - 100 jumps performed 3 - 7 times per week (Bassey & Ramsdale, 1994; Kato et al., 2006; Vainionpää et al., 2006; Winters-Stone & Snow, 2006). Although the optimal frequency of loading bouts has not been established, a study using a multidirectional hopping intervention concluded that hopping exercises need to be performed daily, when compared to other weekly frequencies, to increase femoral neck BMD (Bailey & Brooke-Wavell, 2010b).

5. Rest-recovery periods

Rodent studies have shown that bone quickly becomes desensitised to impact exercise as the loading bout continues without interruption (Robling et al., 2001; Umemura et al., 2002). These researchers also report that the maximal osteogenic effect occurs in the first few minutes of exercise, and that shorter exercise sessions are potentially more beneficial to bone than exercise of extended duration. Providing adequate recovery between loading cycles, and jumping sessions, has been shown to maintain the mechanosensitivity of bone and optimise the osteogenic response, by enhancing the surface area of bone actively forming new bone (Srinivasan et al., 2002). Studies using animal models showed that skeletal tissue becomes desensitised after 40 - 50 repetitive loading cycles, and a rest period of 24 hours is sufficient to restore bone mechanosensitivity (Robling et al., 2001). Furthermore, rest periods between loading bouts of around 15 seconds and up to 8 hours, have been shown to increase bone formation outcomes by 65% to 100% (Burr, 2003; Hart et al., 2017; Robling et al., 2001; Robling et al., 2006; Srinivasan et al., 2002; Tucker et al., 2014). Interpretation of this research suggests that the anabolic effect on bone could be enhanced with less than 50 repetitions of loading, 15 - 30 second rest intervals inserted between jumps and 24 hours between each jumping session. In addition, the design of the jump-landing programme must not only consider the optimisation of bone growth, as inserting appropriate rest periods is required to reduce the risk of bone micro damage, fatigue and to prevent injury (Burr, 2011, 2015).

6.3.2 Musculoskeletal Training Programme Considerations

Other training variables reviewed for programme design include; neural adaptation and progressive overload, specificity (bone site and life stage), individualisation, mesocycle design (including loading and de-loading cycles) and periodisation. Additional factors, such as jump-landing technique, the role of instructions and type of footwear must also be considered. It is important that best practice musculoskeletal programme design is adhered to at all times (Fleck & Kraemer, 2014; Kraemer &

Ratamess, 2004). This review provides a summary of the factors to be considered when designing exercise programmes that will optimally stimulate an adaptive bone response:

1. Neural Adaptation and Preparation for Jump-landings

A 4-week phase of strength and conditioning (4-week neural adaptation programme) would be necessary to implement prior to the introduction of a jump-landing programme to adequately prepare the participants for the impact intensities prescribed (Bompa & Haff, 2009; Haff & Triplett, 2015; Mansfield, 2006; Mothersole et al., 2014). In accordance with 'best practice' strength and conditioning programming, the first stage of a jumping or plyometric training programme should focus on developing competent movement patterns, general strength and balance (Kritz et al., 2009; Mothersole et al., 2014; Stone et al., 2006). It is recommended that the successful completion of a progressive weight-bearing programme, including strength and balance, will adequately prepare untrained individuals to tolerate the stresses involved with jump-landings to maximise benefits to bone health and reduce risk of injury (Clissold et al., 2018; Davies et al., 2015; Mansfield, 2006; Mothersole et al., 2014). This phase should be performed in a supervised capacity, as the ability to provide instruction and demonstrate proper technique is an important process for guiding exercise prescription and progression in a safe manner (Ashley & Weiss, 1994; Wang et al., 2016; Young et al., 1995). Taking into consideration the aforementioned factors the specific 4-week neural adaptation programme developed for the bone training study is presented in Table 6.1.

Table 6.1 Four-week neural adaptation programme‡

Movement Type	**Exercise**	**Sets**	**Reps**	**Rest**
1.Squat patterns *(Body weight)*	Squat	2	10	30 sec
	Lunge	2	10 (each leg)	30 sec
	Squat jump*	2	10	30 sec
2. Balance	Stork eyes open (20 sec)	2	1	30 sec
	Stork eyes closed (20 sec)	2	1	30 sec
	Left to right leg stork Right to left leg stork	2	2-3 (each leg)	30 sec
3.Gluteal work *(Body weight/bands)*	Hip Thrusts	2	15	30 sec
	Abduction	2	15	30 sec
	Clams	2	15	30 sec
4. Core work	Sit ups	2	10-15	30 sec
	Plank	2	30 sec	30 sec
	Ankle touches	3	10 (each side)	30 sec
	Back Extension “Superman’s”	3	20 sec	30 sec
*5. Jump familiarisation**¥	Countermovement jump	2	5	30 sec
	Star jump	2	5	30 sec
	Stride jump	2	5	30 sec
	Drop jump (Low)	2	5	30 sec

6. Stretches	Hip flexor/Quads Hamstrings Adductors/Abductors Calves	2 (of each)	30 – 60 sec holds	Nil

Key: * Exercises performed sub-maximally in a controlled manner; ¥ Jumps performed with single jump-landings, ‡ Training variables (sets, reps, time), associated with the programme may be progressed over the 4 weeks.

2. Progressive Overload and Periodisation

A jump-landing programme needs to progress in volume and technical difficulty over a 12-month period, and its development should consider findings from previous studies which have achieved BMD gains in premenopausal women over similar time periods. The general training principle of progressive overload states that we must overload the body beyond what it is normally required to stimulate the body to adapt to the new demands (Haff & Triplett, 2015). This can be achieved by progressively increasing the volume, intensity, frequency and variety of exercise (Haff & Triplett, 2015), however this has not been well defined in the area of bone health exercise. Thus, bone health programmes should be designed to increase in magnitude and rate of strain, number of ground contacts and technical difficulty (i.e. bilateral to unilateral) in a progressive manner. Therefore, it is necessary to utilise data obtained from studies which have previously quantified the GRF's for a variety of jump-landings specifically using premenopausal women (Bailey & Brooke-Wavell, 2010b; Bassey & Ramsdale, 1994; Bassey et al., 1998; Clissold et al., 2019; Clissold et al., 2018). A comparative analysis of existing data was undertaken and the stress stimulus of each exercise was calculated (see Table 6.2). Such data could determine the order these exercises may be introduced into the osteogenic jump-landing programme (Clissold et al., 2019; Clissold et al., 2018). In order for progression to be accomplished, it is well accepted that the loading should be carefully planned so that all sets and repetitions can be completed and the risk of overtraining or injury is minimised (Stone et al., 2006). Therefore, it is essential that participants are loaded and progressed within a 'Jump-landing Programme' according to several factors including; strength, balance, movement and technical proficiency, fitness level, injury status and comfort, to maximise potential for adaptation and minimise risk of injury (Davies et al., 2015; Mansfield, 2006; Mothersole et al., 2014).

Table 6.2 Ground reaction forces for jump-landings for previously quantified jumping exercises

Jump Type	Peak GRF Magnitude¥ (BW)	Peak RFDβ ($BW \cdot s^{-1}$)	Stress Stimulus
Bilateral jump-landings			
DJ+RJ	5.04	308	1
CMJ+RJ	4.97	299	2
SDJ+RJ	4.43	245	3
SJ+RJ	4.29	226	4
Unilateral jump-landings			
VH	4.80	303	5
FH	4.25	284	6
LH	4.15	241	7

Key: GRF Ground reaction force; RFD Rate of force development; BW Body weight; $BW \cdot s^{-1}$ Body weight per second; ¥ mean values presented as a total stimulus (both jump-landings combined); β resultant forces; CMJ+RJ Countermovement jump with a reactive jump-landing; DJ+RJ Drop jump with a reactive jump-landing; SJ+RJ Star jump with a reactive jump-landing; SDJ+RJ Stride jump with a reactive jump-landing; VH Vertical hop; FH Forward hop; LH Lateral hop.

3a. Specificity (Bone-site)

Evidence from cross-sectional studies describe athletes in weight-bearing sports (i.e. gymnastics, tennis, and volleyball) which involve high magnitude and rates of loading and novel or diverse loading patterns, as having greater bone mass at loaded skeletal sites compared to non-athletes or athletes in non-weight-bearing or lower-impact sports (Alfredson et al., 1997; Kontulainen et al., 2003; Snow et al., 2001). Researchers (Drake et al., 2015). Studies have demonstrated that the hip and lumbar spine are fracture sites most frequently associated with postmenopausal osteoporosis, which are primarily a consequence of trabecular bone losses due to oestrogen deficiency, however the hip is considered the most severe osteoporosis complication (Kanis, 2002). Therefore jump-landing programmes should be developed to be specific to the lower extremities, with a primary target on the femoral neck and lumbar spine regions. However, some researchers have suggested that jump-landings will not provide an effective stimulus for individuals aiming to improve bone strength at the spine, and recommend upper body resistance exercises as a better option (Winters-Stone & Snow, 2006). These researchers have suggested that jumping exercises fail to generate sufficient osteogenic stimulus for bone formation at the spine, as the mechanical load is attenuated before being translated to the lumbar area (Vainionpää et al., 2005; Winters-Stone & Snow, 2006). However, jump-landings performed whilst utilising a reactive jump-landing, and 'stiff' landing mechanics (Clissold et al., 2019; Clissold et al., 2018), have the potential to stimulate the lumbar spine, in addition to the femoral region. As musculoskeletal adaptations are specific to the areas where the stimulus is applied, future research is warranted to quantify a series of exercises (e.g. upper body) which can be utilised in a total body osteogenic programme.

3b. Specificity (Life-stage)

The response to osteogenic stimulus observed in several animal and human exercise intervention studies is age-dependent, with support for the hypothesis that the strongest response to mechanical loading occurs in young bone. Babatunde (2013) proposed a paradigm shift which identifies the need to consider life stage specificity for promoting preventative measures to reduce risk factors for osteoporosis. If we consider the concept that post-menopausal BMD is a consequence of peak BMD (achieved at skeletal maturity), menopause and the rate of bone loss as the women ages, then the period of bone growth during the pre-pubertal, pubertal and premenopausal years is the optimal time to focus on positive interventions for maximising bone health. Interestingly, a vertical jumping intervention in premenopausal women which increased femoral neck BMD by 2.8%, failed to achieve a significant change for the postmenopausal group when compared with the control group after 12 months (Bassey et al., 1998). This finding indicates that the loading forces required to achieve an osteogenic response in older (> 50 years) women may be higher than for younger women (< 50 years) (Gomez-Cabello et al., 2012; Guadalupe-Grau et al., 2009; Lanyon, 1996). However, other studies have shown that mechanical loading (i.e. resistance training) after the menopause can play a role in preventing or slowing bone loss which would normally occur during this time (Kemmler, Engelke, & von Stengel, 2015; Kemmler et al., 2007). Thus, the key message is to optimise bone health throughout all stages of life, however high-impact loading (i.e. jumping and hopping) appears to be a beneficial approach in healthy premenopausal women.

4. Individualisation

A limitation of current exercise recommendations for osteoporosis management and prevention, is the lack of consideration for individual difference, existing bone health, movement competency and functional capacity. Therefore, a safe and effective osteogenic jump-landing programme must consider risk factors which may compromise the safety for performing such a programme such as; age, frailty, pre-existing osteoporosis, musculoskeletal pain or injury, osteoarthritis and history of fractures or falls (Gallagher & Tella, 2013). It is therefore recommended that before individuals seek to undertake jump-landing exercises, pre-conditioning exercise may be needed to tolerate the stresses involved with jump-landing exercises to maximise benefits to bone health and reduce risk of injury. A position statement recently published recommendations for exercise prescription for the prevention and management of osteoporosis, in which they classify individuals into three levels of risk for fragility fracture (low, moderate and high), using the World Health Organisation (WHO) defined T-scores (B. R. Beck et al., 2017). According to this classification, low risk individuals are defined as having normal BMD (T-score above -1.0 SD), and no clinical risk factors for falls or fracture, and deemed safe to participate in a jump-landing programme (as described in this article). Individuals classed as moderate and high risk (T-score -1.0 to -2.5 SD and less than -2.5 SD, respectively), are recommended to also perform jump-landings (2 - 3 BW), with an emphasis on conditioning the musculoskeletal system, gradual loading increments, pain-free competency and safety in terms of falls prevention (B. R. Beck et al., 2017). In addition, the frequency of performing the jump-landings should be determined by the recovery requirements of individual participants, with no more than two consecutive jump training days permitted before a rest day must be taken.

5. Mesocycle design

A jump-landing programme must utilise a model of periodisation to ensure that training principles are manipulated safely and effectively to achieve long-term benefit to bone health. Hence the concept of clustering the jumps can be utilised to optimise the osteogenic effect over time, whilst adhering to safe programming guidelines. The loading of the first mesocycle (4-week block of training) in a jump-landing programme provided, could utilise a 3:1 structure involving a progressive increase in jumping volume (loading) over the first 3 weeks, followed by a de-loading week characterised by low volume to enhance musculoskeletal adaptations and provides opportunity for bone to re-sensitise before introducing a new jumping stimulus (Bompa & Haff, 2009; Fleck & Kraemer, 2014; Haff & Triplett, 2015).

6. Jump-landing technique

Researchers have suggested that jumping and hopping exercises may only be useful in terms of osteogenic benefit, if aspects of jumping and jump-landing technique are clarified for this purpose (Clissold et al., 2019; Clissold et al., 2018). It would seem that cueing participants to jump maximally, minimise ground contact time and employ vigorous arm-swing, can significantly influence this aspect of force production (Bobbert et al., 1987; Bobbert et al., 1986; Clissold et al., 2019; Clissold et al., 2018; Lees, 1981; Lees et al., 2004). Clissold and colleagues (2018, 2019), who recently published a series of studies focussed on premenopausal women, suggested that jump-landing technique is a major factor that can influence the osteogenic effectiveness of jumps, and explored the effectiveness of repeated jump-landings to heighten bone stimulation. They stated that providing specific cues for the jump-landings (i.e. think of the ground as a hot plate) and therefore to 'jump immediately after the initial jump-landing' (a "reactive jump"), will cause the participant to flex minimally upon landing and push off quickly thereafter, thus preventing a "soft" landing and reducing the absorption of impact energy by the leg musculature. By utilising this technique, Clissold et al. (2018) reported easily achieving previously established osteogenic thresholds for GRF magnitude and rates for all jump-landings, and significantly larger landing forces (↑10 - 20%; $p < 0.05$) for the second jump-landing (post-reactive jump). These findings support the importance of jump-landing technique on the osteogenic effectiveness of jump-landings, and the value of cueing for a more ballistic jump-landing to enhance bone stimulation.

7. Instructions provided

Researchers have shown that we can successfully employ a specific jumping style after being instructed only once (Bobbert et al., 1986; Richter et al., 2011; Young et al., 1995), which implies that being that once proficient, jumps do not need further coaching and can be performed in the home setting with the knowledge that the appropriate GRF's and subsequent osteogenic thresholds will be met. Although existing literature documenting jump-landing impact forces utilises a variety of different instructions for arm position and effort during jumping, Clissold and colleagues (2018, 2019), believe that cueing participants to use a vigorous arm swing in a "countermovement" maximises jump height and hence impact forces, and consequently the osteogenic potential of the exercise. They also demonstrated the importance of cueing participants to land quickly and stiffly, to enhance the osteogenic effectiveness of the jump-landings. Their research showed that participants can achieve similar or greater jump-landing forces after only one instructed session, due to learning or practice effects, which has clinical implications for an osteogenic jump-landing programme being delivered in an unsupervised setting (Clissold et al., 2019; Clissold et al., 2018).

8. Type of Footwear

Early research by Bassey and Ramsdale (1994), compared jumping activities with subjects 'wearing' and 'not wearing shoes' to assess the factors which could influence the forces generated in bone and inform future studies in this area. They observed nearly 20% increase in jump height when participants wore trainers, which significantly increased both GRFs and rate of force development, but potentially compromised safety (Bassey & Ramsdale, 1994). Further research involved a case study where an instrumented titanium strain-gauge was implanted into the femur of a hip replacement patient confirmed an increased magnitude and rate of compressive loading of the femur whilst jumping wearing trainers (Bassey et al., 1997). They concluded that the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise and recommend jump-landings to be performed on a firm surface in a barefooted condition.

6.4 A Periodised Osteogenic Jump-Landing Programme

The previously quantified jumping exercises to be included in the 12-month periodised osteogenic jump-landing programme include a combination of vertical and multidirectional bilateral and unilateral jumps; 1) Countermovement jump with reactive jump-landing (CMJ+RJ), 2) Drop jump with reactive jump-landing (DJ+RJ), 3) Star jump with reactive jump-landing (SJ+RJ), 4) Stride jump with reactive jump-landing (SDJ+RJ), 5) Vertical hop (VH), 6) Forward hop (FH), and 7) Lateral hop (LH). The 12-month jump landing programme (presented in Table 6.3) encapsulates current bone health research guidelines, previously determined jump-landing stress stimulus data and incorporates the principles of best strength and conditioning practice.

Table 6.3 Jump-landing programme created for the 12-month training study.

Week	**Jump Type**	**Frequency**[ʊ] **(per week)**	**Sets x Reps**	**Volume (landings per day)**	**Volume (landings per week)**	**Rest (between jumps)**	**Rest (between sets)**
Phase 1. *B1.* *(1-4)*	CMJ+RJ	2x	4 x 4	32	64	5 sec	30 sec
		3x	4 x 4	32	96		
		4x	4 x 4	32	128		
		3x	4 x 4	32	96		
B2. *(5-8)*	CMJ+RJ SJ+RJ	4x	2 x 4 2 x 4	32	128	5 sec	30 sec
B3. *(9-12)*	CMJ+RJ SDJ+RJ	4x	2 x 4 2 x 4	32	128	5 sec	30 sec
Phase 2. *B4.* *(13-16)*	DJ+RJ SJ+RJ	4-5x	2 x 4 2 x 4	32	128-160	5 sec	30 sec
B5. *(17-20)*	DJ+RJ SDJ+RJ	4-5x	2 x 4 2 x 4	32	128-160	5 sec	30 sec
B6. *(21-23)*	CMJ+RJ SJ+RJ SDJ+RJ	4-5x	2 x 3 2 x 3 2 x 3	36	144-180	5 sec	30 sec
B7. *(24-26)*	DJ+RJ SJ+RJ SDJ+RJ	4-5x	2 x 3 2 x 3 2 x 3	36	144-180	5 sec	30 sec

Phase 3. *BU1.* *(27-30)*	CMJ+RJ	4-5x	2 x 4	32	128-160	5 sec	30 sec
	LH$^{\infty}$		2 x 4				
BU2. *(31-34)*	DJ+RJ	4-5x	2 x 4	32	128-160	5 sec	30 sec
	FH$^{\infty}$		2 x 4				
BU3. *(35-38*	CMJ+RJ	4-5x	2 x 4	32	128-160	5 sec	30 sec
	VH$^{\infty}$		2 x 4				
Phase 4. *BU4.* *(39-42)*	SJ+RJ	4-5x	2 x 3	36	144-180	5 sec	30 sec
	VH$^{\infty}$		2 x 3				
	FH$^{\infty}$		2 x 3				
BU5. *(43-46)*	SDJ+RJ	4-5x	2 x 3	36	144-180	5 sec	30 sec
	VH$^{\infty}$		2 x 3				
	LH$^{\infty}$		2 x 3				
BU6. *(47-52)*	CMJ+RJ	4-5x	1 x 2	40	160-200	5 sec	30 sec
	DJ+RJ		1 x 2				
	SJ+RJ		1 x 2				
	SDJ+RJ		1 x 2				
	VH$^{\infty}$		2 x 2				
	FH$^{\infty}$		2 x 2				
	LH$^{\infty}$		2 x 2				

Key: CMJ+RJ Countermovement jump with a reactive jump-landing; DJ+RJ Drop jump with a reactive jump-landing; SJ+RJ Star jump with a reactive jump-landing; SDJ+RJ Stride jump with a reactive jump-landing; VH Vertical hop; FH Forward hop; LH Lateral hop. B Bilateral jump-landings only; BU Bilateral and Unilateral jump-landings; ∞ All unilateral jump-landings to be performed on both legs; $^{\upsilon}$The frequency of performing the jumps will be determined by the recovery requirements of individual participants, with no more than two consecutive jump training days permitted before a rest day must be taken. The shaded area depicts the initial 4-week mesocycle including examples of progressive overload and a de-loading week before a new jump-landing stimulus is introduced

The following section gives detailed instructions on how to perform the jump-landing exercises for participants in an unsupervised setting.

6.4.1 Bilateral Jumps (Vertical and Multidirectional)

For the CMJ+RJ, stand with feet shoulder-width apart with arms raised above the head. Then flex the knees and hips with arms "swinging" downwards (during the eccentric phase) and then jump upwards with arms "swinging" in the intended direction of travel (in the concentric phase) to perform a maximal jump for height, then immediately jump again after the initial jump-landing. For the DJ+RJ, step up and off a 20 cm box and only allow a small downward knee movement after landing, followed quickly by a second maximal jump. It is important to land as if the ground is a "hot plate" (first jump-landing; reactive jump), and to immediately jump again for maximal height before landing again (second jump-landing; post-reactive jump). A pictorial representation of the phases of the bilateral vertical jumps utilised in this programme can be observed in Figure 6.1.

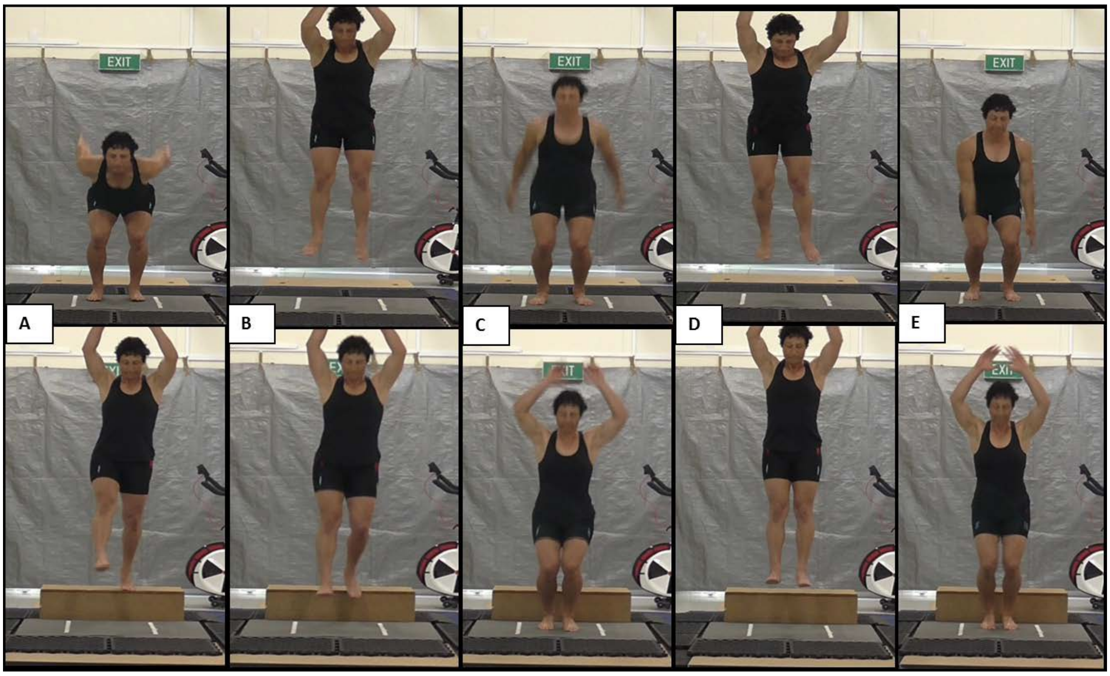


Figure 6.1 Pictorial representation of the phases of the countermovement jump and reactive jump (top row) and drop jump and reactive jump (bottom row), as described in this programme: A) Start of the jump; B) First flight phase 1; C) First impact for jump-landing 1; D) Second flight phase 2; E) Second impact for jump-landing 2.

For the SJ combined with a reactive jump, stand with feet together and arms by your side. First flex the knees and hips slightly (during the eccentric phase) then quickly jump upwards (during the concentric phase) with arms ‘swinging’ upwards and legs ‘swinging’ outwards to land in a shortened ‘star’ position with feet flat on the ground. Then immediately jump again after the initial jump-landing (i.e. think of the ground as a hot plate), ‘pulling’ the arms and legs back to a stiff starting position. For the SDJ combined with a reactive jump, started in a stride position with one leg forward and one leg back with heels flat on the ground. Then bend the knees and hips slightly (during the eccentric phase) to perform a maximal jump for height (during the concentric phase) with legs ‘swinging’ to land with the opposite foot forward in a shortened position, with feet flat on the ground (first jump-landing; reactive jump). Then immediately jump again after the initial jump-landing (i.e. think of the ground as a hot plate), and back to a stiff starting position (second jump-landing; post-reactive jump). To combat the rotary actions of the hips, vigorously move the arms in opposite directions to the legs. A pictorial representation of the phases of the bilateral multidirectional jumps utilised in this study can be observed in Figure 6.2.

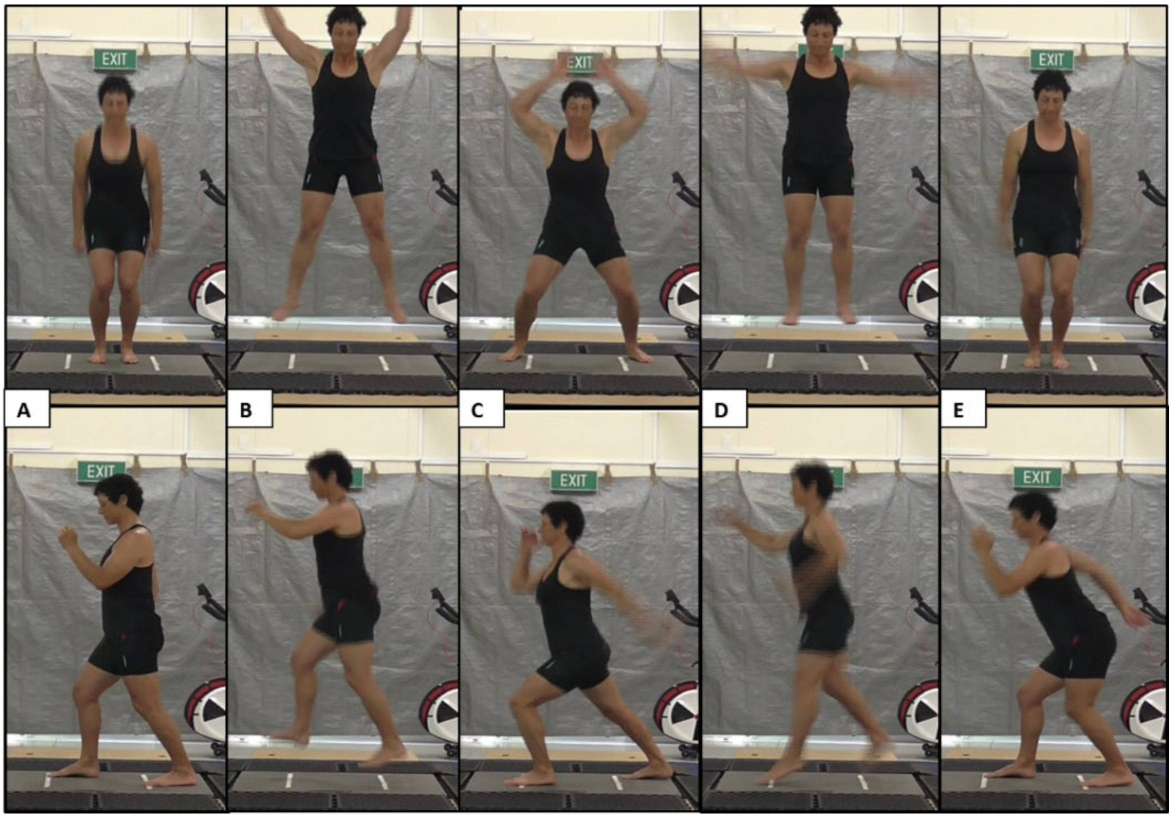


Figure 6.2 Pictorial representation of the phases of the stride jump and reactive jump (top row) and stride jump and reactive jump (bottom row), as described in this programme: A) Start of the jump; B) Flight phase 1; C) First impact for jump-landing 1; D) Flight phase 2; E) Second impact for jump-landing 2.

6.4.2 Unilateral Jumps (Vertical and Multidirectional)

For the VH, stand with feet shoulder-width apart with arms above the head, then flex the knees and hips (during the eccentric phase) and quickly jump upwards (during the concentric phase) with arms ‘swinging’ in a countermovement style, to land stiffly on one leg. For the FH and LH, stand with feet shoulder-width apart before leaping forward or sideways, and landing stiffly on one foot. Try to land with minimal flexion of the hip and knee, and to utilise a flat-footed ground contact. A pictorial representation of the phases of the hops included in this study are depicted in Figure 6.3.

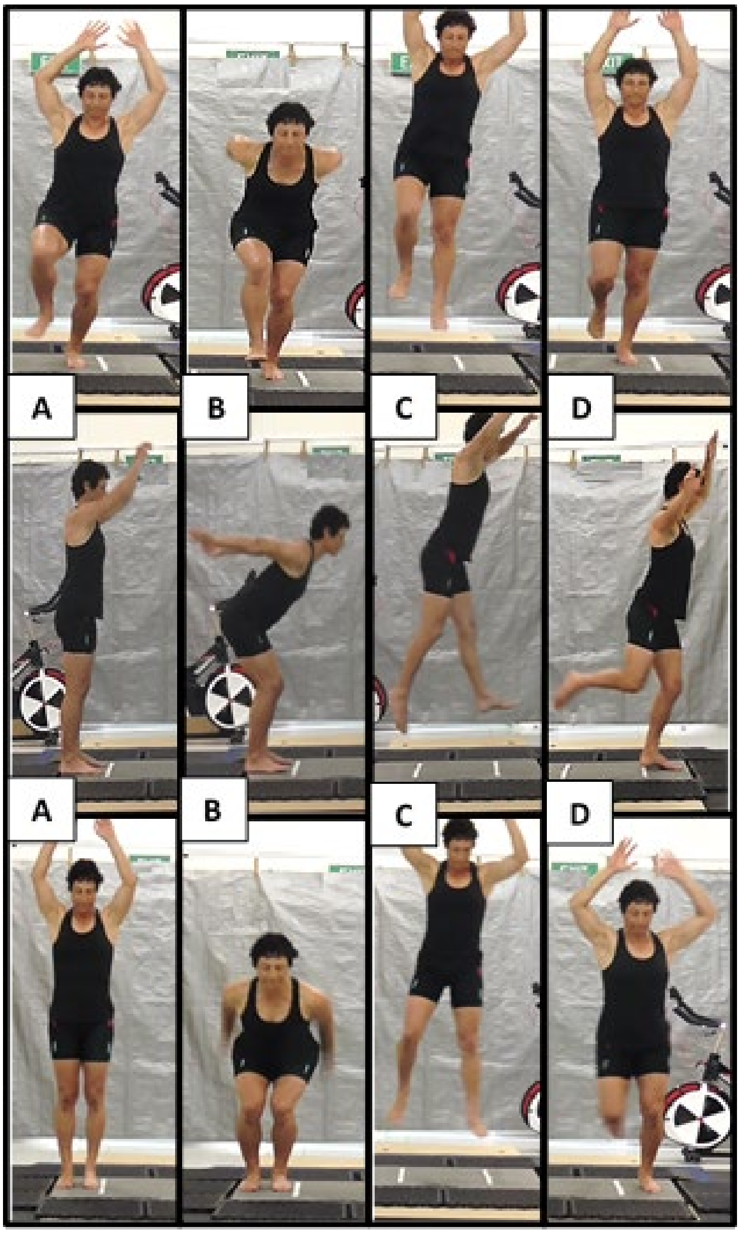


Figure 6.3 Pictorial representation of the phases of the vertical hop (top), forward hop (middle) and lateral hop (below), as described in this programme: A) Start of eccentric phase; B) Start of concentric phase; C) Flight phase; D) Jump-landing phase

6.5 Conclusion

Whilst osteogenic programmes are currently lacking and many diverse protocols have been used in exercise and BMD research (Babatunde et al., 2012; B. R. Beck et al., 2017; Ebeling et al., 2013; Weaver et al., 2016; Zhao et al., 2014), this 12-month periodised osteogenic jump-landing programme consisting of quantified jump-landing exercises provides a strong foundation for bone specific programming with consideration to specific training principles i.e. progressive overload, novel stress and technical progression. This periodised osteogenic jump-landing programme has been designed to optimise and create a novel impact stimulus required to promote bone formation in healthy premenopausal women. However, before individuals seek to undertake the jump-landing programme, pre-exercise screening, and/or undertaking a pre-conditioning exercise programme (i.e. 4-week neural adaptation programme) may be needed to tolerate the stresses involved with jump-landing exercises to maximise benefits to bone health and reduce risk of injury in premenopausal women. As musculoskeletal adaptations are specific to the areas where the stimulus is applied, a limitation of this osteogenic jump-landing programme is the focus on the lower body and associated clinically relevant sites (hip and lumbar spine). Therefore, identifying a need to investigate ways to apply and quantify reactive forces associated with upper body focussed exercises, which can be utilised in a total body osteogenic exercise programme.

CHAPTER 7. RELIABILITY OF BONE MINERAL DENSITY AND BODY COMPOSITION USING DEXA (DUAL ENERGY X-RAY ABSORPTIOMETRY) IN PREMENOPAUSAL WOMEN (TECHNICAL REPORT)

7.1 Prelude

It is well accepted that the measurement of bone mineral density (BMD), using bone densitometry, is a valid and reliable method when defining the risk of osteoporotic fracture. However, the ability to be able to determine whether a change in BMD over time is statistically significant, is important when considering the statistical concept of precision. The precision of dual x-ray absorptiometry (DEXA) is excellent, but not perfect, and therefore as precision represents variability in the results, the smaller the variability the better. It is therefore important to determine the change in BMD required, relative to the precision error of the test, to conclude that a real biological change has occurred in response to an intervention.

Although researchers have previously examined the reliability of DEXA technology, most have only reported coefficients of variation (CV’s). In addition, these values of absolute consistency (CV’s) have only been presented for BMD at the femoral neck and lumbar spine, with most studies failing to report any consistency values for bone mineral content (BMC), hip structural analysis or body composition. The International Society for Clinical Densitometry recommends that a reliability/precision study be performed by every densitometry facility to establish a specific precision value for each skeletal site that is measured (Lenchik, Kiebzak, & Blunt, 2002), however this may represent the in-house precision error of the laboratory rather than technician precision using a specific population.

Therefore, the purpose of this study was to quantify the variability associated with DEXA measurements of interest for premenopausal women, by providing measures of absolute (CV) and relative consistency (ICC). Given the importance of the DEXA derived variables to assess the effectiveness of the jump-landing intervention to be implemented for 12-months (Chapter 8), this study sought to determine the intra-rater test-retest reliability of a DEXA machine for assessing clinically relevant bone and body composition variables in premenopausal women.

Clissold, T. L., Winwood, P. W., Cronin, J. B. & De Souza, M. J. (2020). Reliability of bone mineral density and body composition measures using DEXA (Dual energy x-ray absorptiometry) in premenopausal women. Formatted for *Journal of Applied Biomechanics*. 2020

7.2 Introduction

Currently, Dual Energy X-Ray Absorptiometry (DEXA) is considered the ‘gold standard’ tool in the diagnosis and management of osteoporosis, and is used to define fracture risk using WHO T-score criteria (Kanis & Kanis, 1994). DEXA can provide measures of bone mineral density (BMD), bone mineral content (BMC), hip structural analysis (HSA) and body composition. With regards to understanding the utility of these measurements, it is important to quantify the variability associated with these assessments. Previous researchers reporting BMD in premenopausal women have reported coefficients of variation (CV’s) ranging from 0.5% to 2.0% for femoral neck and lumbar spine (Bailey & Brooke-Wavell, 2010b; Bassey et al., 1998; Heinonen et al., 1996; Kato et al., 2006; Winters-Stone & Snow, 2006), however these were not always reported (Niu et al., 2010; Tucker et al., 2014; Vainionpää et al., 2005). A further limitation is that only one study has reported CV’s for BMC, and this value was only presented for the femoral neck (Bailey & Brooke-Wavell, 2010b).

In addition, some of these studies (Heinonen et al., 1996; Kato et al., 2006), provided CV’s which represented in-house precision error values, rather than establishing test-retest reliability of a particular technician quantifying the variability associated with a particular sample. Furthermore, only one study has reported test-retest reliability associated with hip structural analysis in premenopausal women, CV’s for hip structural analysis variables (section modulus, Z, and minimal femoral neck width) were 4.1% and 1.4%, respectively (Bailey & Brooke-Wavell, 2010b). However, no CVs were reported for cortical thickness or cross-sectional area. For a full understanding of the variability associated with measurements it is recommended that the measures of absolute (CV) and relative consistency (intra-class correlation coefficients - ICC) should be presented (Hopkins, 2000). Given these limitations, the purpose of this study was to quantify both absolute and relative consistency for the variability associated with: a) BMD and BMC at the femoral neck and lumbar spine (L1 - L4); b) hip geometry variables (cortical thickness, cross-sectional area and section modulus) at the femoral neck using hip structural analysis software (HSA); and c) body composition variables (total mass, lean mass, fat mass and body fat percentage).

7.3 Methods

7.3.1 Experimental Approach to the Problem

A test-retest design was utilised to quantify the reliability of the DEXA variables of interest (BMD, BMC, bone geometry variables and body composition). Data was collected using specialised hip structural analysis (HSA) software (Hologic Discovery QDR Series Bone Densitometer, Bedford, Massachusetts). Data was collected for each participant over two testing sessions separated by no more than seven days as recommended by the International Society for Clinical Densitometry.

7.3.2 Participants

Seventeen healthy premenopausal women (20 – 50 yr), volunteered to participate in this study (see Table 7.1). All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) and inclusion criteria required participants to be younger than 51 years of age, in conjunction with the participants reporting a regular menstrual cycle, which was used to determine premenopausal status. All participants provided written informed consent after having being briefed on the potential risks associated with this research. The methods and procedures used in this study were approved by the New Zealand Health and Disability Ethics Committees (17/NTB/155).

Table 7.1 Baseline characteristics of the participants (mean ± SD)

Demographics	All Participants (n = 17)
Age (yr)	32.3 ± 7.70
Height (cm)	166.5 ± 5.90
Body mass (kg)	69.1 ± 23.2
BMI ($kg \cdot m^{-2}$)	24.6 ± 7.70
Body fat (%)	27.5 ± 6.70

7.3.3 Testing Protocol

During the first session participants filled in a pre-screening questionnaire prior to having their height (wall-mounted stadiometer to the nearest 0.1cm) and weight measured using Tanita electronic floor scales (Cloverdale, Western Australia). Prior to scanning, calibration was performed using a criterion phantom device in accordance with the manufacturer guidelines. Procedures were standardised according to the recommendations of the Australian and New Zealand Bone and Mineral Density Society, to minimise any scanning errors. The participants were all positioned within the scan range, with the leg position standardised, and secured with straps (hip scan only) to reduce positioning error. The participants removed metal objects or jewellery from their body prior to scanning and wore similar clothing for each scan. A fan beam DEXA (Hologic Discovery QDR Series Bone Densitometer, Bedford, Massachusetts) device was used, for both testing sessions, to perform the following scans; BMD and BMC at the proximal femur (neck and trochanter), and lumbar spine (L1 - L4); hip geometry (cortical thickness, cross-sectional area and section modulus) utilising specialised HSA software; and body composition (total mass, lean muscle mass, fat mass). Both DEXA testing sessions were performed using the same machine (see Figure 7.1) by the same technician, at a similar time of day and testing order was standardised for all participants.

Figure 7.1 Pictorial representation of the DEXA equipment utilised in this study

7.3.4 Statistical Analyses

Descriptive statistics were used to describe the cohort characteristics. Reliability of DEXA bone mineral density and body composition measures was evaluated by intraclass correlation coefficients (ICC) using a two-way random effects model, absolute agreement and average measures ICC (Shrout & Fleiss, 1979). ICCs were classified as follows: 'poor' (≤ 0.40), 'moderate' (0.41 - 0.60), 'good' (0.61 - 0.80), or 'excellent' (≥ 0.81) (Enderlein, 1988; Shrout & Fleiss, 1979). 95% confidence intervals (95% CI) were calculated to assess relative consistency for all reliability measures. Coefficients of variation (CV) were also calculated (CV = SD/mean * 100) for each dependant variable to assess absolute consistency. Although a CV < 10% is considered acceptable in clinical trials, the International Society for Clinical Densitometry guidelines indicate acceptable precision to be 1.9% at the lumbar spine and 2.5% at the femoral neck. Data analyses were conducted using SPSS 22.0 for Windows (SPSS Inc., Chicago, IL, USA). Significance was set at $p < 0.05$.

7.4 Results

Cohort Characteristics

There were 17 participants that completed the DEXA scanning twice over the seven-day period, with an average of 1.4 ± 2.0 days between testing sessions. Participants were between 20 and 50 years of age, with 59% also recruited for the 12-month jump-landing study (Table 7.1).

Bone Mineral Density and Bone Mineral Content

The test-retest reliability data for DEXA left hip and lumbar measures are reported in Table 7.2. Relative consistency (ICC) for all measures ranged between 0.98 to 1.00, the lowest ICC was associated with femoral neck BMC. Absolute consistency ranged between 0.70 to 2.01%, the greatest CV was also associated with femoral neck BMC.

Hip Structural Analysis

The test-retest reliability data for DEXA left hip structural analysis measures can be observed in Table 7.2. Relative consistency was excellent for all left hip structural analysis measures (ICC's = 0.91 to 0.99), the lowest ICC associated with narrow neck cross-sectional area. Absolute consistency ranged from 1.45 to 1.88%, the highest CV was associated with the narrow neck section modulus.

Body Composition

The test-retest reliability data for DEXA body composition measures are detailed in Table 7.2. Relative consistency for all measures was 1.00, and the absolute consistency ranged between 0.32 to 1.23%. The greatest CV was also associated with total body mass and total body fat percentage (1.23%).

Please note that the variables reported in this results section are the principle variables of interest to this thesis and those reported the most in the literature. A full analysis of all variables can be observed in the supplementary material in the appendices.

Table 7.2 Test-retest reliability of DEXA for left hip and lumbar spine (L1 - L4) BMD, BMC, hip structural analysis (left hip only) and total body composition measures

Test – retest reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Test 1	Test 2				
Femoral Neck						
Neck BMC (g)	4.74 ±0.63	4.70 ±0.76	0.98^{s}	0.94 to 0.99	2.01	Excellent
Neck BMD (g/cm^2)	0.95 ±0.11	0.96 ±0.11	0.99^{s}	0.97 to 1.00	1.12	Excellent
Total BMC (g)	37.2 ±6.25	37.2 ±6.27	1.00^{s}	0.99 to 1.00	1.12	Excellent
Total BMD (g/cm^2)	1.07 ±0.12	1.07 ±0.12	1.00^{s}	0.99 to 1.00	0.64	Excellent
Lumbar Spine (L1 - L4)						
Total BMC (g)	72.2 ±8.91	73.5 ±9.02	1.00^{s}	0.99 to 1.00	0.70	Excellent
Total BMD (g/cm^2)	1.16 ±0.15	1.15 ±0.15	0.99^{s}	0.98 to 1.00	1.08	Excellent
Hip Structural Analysis						
Narrow Neck CSA (cm^2)	3.50 ±0.51	3.52 ±0.58	0.91^{s}	0.98 to 1.00	1.56	Excellent
Narrow Neck Z (cm^3)	1.64 ±0.32	1.64 ±0.31	0.99^{s}	0.97 to 1.00	1.88	Excellent
Narrow Neck Cort. Thick. (cm)	0.23 ±0.03	0.23 ±0.03	0.99^{s}	0.95 to 1.00	1.45	Excellent
Body Composition						
Total Body Fat Mass (g)	20630 ±9019	20409 ±9107	1.00^{s}	0.99 to 1.00	1.23	Excellent
Total Body Lean + BMC (g)	52021 ±7793	52179 ±7837	1.00^{s}	0.99 to 1.00	0.69	Excellent
Total Body Mass (g)	72586 ±15343	72588 ±15441	1.00^{s}	1.00 to 1.00	0.32	Excellent
Total Body Fat (%)	27.5 ±6.70	27.2 ±6.77	1.00^{s}	0.99 to 1.00	1.23	Excellent

Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.001$; CV Coefficient of Variation; BMC Bone mineral content; BMD Bone mineral density; CSA Cross sectional area; Z Section modulus; Cort Cortical; Thick Thickness

7.5 Discussion

The purpose of this study was to present a full understanding of the variability associated with DEXA measurements of interest for premenopausal women, by providing measures of absolute (CV) and relative consistency (ICC). Previously these values have not been reported for femoral neck and lumbar spine BMC, bone geometry variables and body composition in this population. In addition, test-retest reliability has not previously achieved the rigour associated with presenting absolute and relative consistency values for these measures, and these values can represent generic in-house values rather than that of a specific technician using a study-specific population. The main findings of this study were that reliability was excellent for all DEXA measures (ICC’s = 0.91 to 1.00; CV’s = 0.32 to 2.01%).

The test-retest reliability data for DEXA left hip and lumbar BMD and BMC measures were excellent, and relative consistency ranged between 0.98 to 1.00. Absolute consistency for BMD ranged between 0.64 to 1.12%, which is comparable to values (1.0 to 1.4%) reported by researchers who utilised a sub-sample of the premenopausal participants in their intervention (Bailey & Brooke-Wavell, 2010b; Bassey et al., 1998; Winters-Stone & Snow, 2006). Absolute consistency ranged between 0.70 to 2.01% for BMC with the greatest CV associated with femoral neck. As only one study has presented test-retest reliability for BMC in premenopausal women (Bailey & Brooke-Wavell, 2010b), and only at the femoral neck (CV = 1.7%), future studies need to report on this variable.

The DEXA left hip structural analysis reliability data was excellent for all measures (ICC’s = 0.91 to 0.99; CV’s = 1.45 to 1.88%). Any variability may have arisen from technical error generated by the failure to standardise the positioning of the participant in exactly the same position to replicate the rotation at the hip joint, however our results are favourable in comparison to values previously presented (1.4 and 4.1%; for femoral neck width and section modulus respectively) (Bailey & Brooke-Wavell, 2010b). Further research is required to gain a better understanding about the variability associated with HSA, as currently only one study to our knowledge has presented such data in premenopausal women (Bailey & Brooke-Wavell, 2010b).

Participant positioning has also been suggested to influence DEXA estimates for body composition in addition to biological variation, including hydration status and the effects of diet, exercise, food and fluid in the hours prior to the scan (Nana, Slater, Hopkins, & Burke, 2012). However, the test-retest procedures used for determining DEXA body composition measures of premenopausal women produced stable data over two testing occasions. Relative consistency for all measures was 1.00, and the absolute consistency ranged between 0.32 to 1.23%. Although CV values for body composition were either not assessed or not presented for most DEXA studies involving premenopausal women, Winters and colleagues (2006) reported absolute consistency values of <1.5% which are similar to our results, all CVs < 1.25%.

As previously only measures of absolute consistency have been presented for the variability associated with DEXA measurements, the purpose of this study was to improve the rigour of test-retest reliability by presenting both absolute and relative consistency values for these measures in premenopausal women. It is therefore recommended that both CV and ICC values should be presented to describe a full understanding of the variability associated with DEXA measurements in this specific population. In addition, it is recommended that test-retest reliability values presented must represent the error associated with a specific technician using a study-specific population, rather than generic in-house values.

7.6 Conclusion

We have provided a comprehensive description of the reliability (relative and absolute consistency) associated with DEXA measurements not previously presented for premenopausal women. In addition, we have reported excellent reliability results for BMC, HSA and body composition, which are values not reported in previous studies. It is therefore recommended that future research using DEXA should provide precision error values for these variables to enable acceptable precision ranges to be established for this population. Furthermore, it is advised that test-retest reliability should represent the variability associated with a specific technician utilising a specific population rather than in-house precision error values.

CHAPTER 8. THE CHRONIC EFFECTS OF A QUANTIFIED JUMP-LANDING PROGRAMME ON BONE HEALTH, BODY COMPOSITION AND PERFORMANCE PARAMETERS IN PREMENOPAUSAL WOMEN

8.1 Prelude

While the first five studies (Chapters 3 - 7) in this thesis gave insight into the development of a periodised osteogenic jump-landing programme specifically designed for premenopausal women, currently no evidence exists about the chronic effects of utilising such a programme. Authors of meta-analyses proposed that jump-landing programmes that; utilised brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), are 4 - 18 months duration, and present loading magnitudes of between 2 - 6 BW, can result in significant gains in femoral neck BMD of 0.5 - 3% in premenopausal women during a time when normal bone loss is 0.5% - 1% per year. However, limitations exist for these jumping protocols, in terms of jump-landing technique, monitoring of the daily and weekly loading and adherence to best practice musculoskeletal programme design. In addition, the focus on jump-landing technique and utilising a reactive jump component within a 12-month periodised osteogenic training programme has not been previously presented. Furthermore, future research is required to describe the geometry of bone, as limitations exist for using a two-dimensional imaging technique (DEXA) to assess a three-dimensional structure. Thus, this study will utilise additional software (hip structural analysis) to provide an opportunity to assess variables used to describe the overall strength and fracture resistance of bone in response to the jump-landing intervention. Therefore, the purpose of this final study was to determine the effects of a periodised osteogenic jump-landing programme on functional performance parameters, body composition and bone remodelling at clinically relevant sites in premenopausal women. Such information will provide clinicians, primary carers, strength and conditioning coaches and the general population with a greater understanding of the benefits and limitations of utilising a brief (2 - 3 min), jump-landing programme to improve bone health in this population.

Clissold, T. L., Winwood, P. W., Cronin, J. B. & De Souza, M. J. (2021). The chronic effects of a quantified jump-landing programme on bone health, body composition and performance parameters in premenopausal women. *Journal of Bone Mineral Research Plus* (under second review).

8.2 Introduction

Osteoporosis has been described as a silent epidemic responsible for fractures in 50% of women and 20% of men worldwide (Lippuner et al., 2009). In the United States approximately 52 million women and men have osteoporosis or osteopenia (low bone mass) and it is predicted to increase to more than 61 million by 2020 if additional efforts are not made to address this disease (Weaver et al., 2016). It is well accepted that women have less total bone mass than men and experience rapid bone loss during menopause. Generally women experience bone losses of approximately 1% per year after the fourth decade of life, however annual losses of 3 - 5% bone mineral density (BMD) can be experienced during early post-menopause ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993). The National Osteoporosis Foundation of America estimate up to 20% of BMD can be lost in the 5 - 7 years after menopause, with lifetime bone losses estimated to be 30 - 40% of peak bone mass ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993; Sipila & Poutamo, 2003).

Wolff's Law states that bone has the ability to adapt to mechanical loads, suggesting that mechanically-induced strain is a key factor which affects bone formation. Frost (1987) explored the threshold of strain necessary to achieve skeletal adaptation in the development of his 'minimum effective strain' or 'mechanostat' theory, hypothesising that mechanical forces exceeding this remodelling threshold would therefore stimulate bone formation and increase bone mass and bone strength. Although the magnitude of strain is an important factor to influence the adaptation of bone, strain rate, frequency and distribution are also recognised as integral determinants to be considered (Lanyon, 1987; Robling et al., 2006; C. H. Turner & Robling, 2003). The measurement of ground reaction forces (GRF's), represented as body weight's (BW's) have been used to estimate the influence of loading on bone (Bassey et al., 1997; Hsieh et al., 1999; C. H. Turner, 1999; C. H. Turner & Robling, 2003), and researchers have suggested that to achieve an adaptive bone response an exercise regime should satisfy the following criteria: a) be of sufficient magnitude and rate of strain; b) present its strain in a range of diverse and unusual distribution patterns; c) provide a limited number of loading cycles at each distribution; d) be of short duration; and e) provide adequate recovery periods. However, research has predominantly focused on “high risk” postmenopausal women and as a consequence, exercise regimes for minimising bone loss in adults are generic and lack specific recommendations for women before they experience accelerated bone losses during and post menopause (Gómez-Cabello et al., 2012; Guadalupe-Grau et al., 2009).

Jumping and hopping exercises have been researched for their role in enhancing bone mass in young people and for minimising age-related bone loss in females (Bailey & Brooke-Wavell, 2009, 2010b; Bassey et al., 1997; Bassey & Ramsdale, 1994; Bassey et al., 1998; Stiles et al., 2013; Weeks & Beck, 2008). Exercises, with emphasis on the jump-landing, may be of special interest given their role in increasing peak bone mass in premenopausal women and minimising age-related bone loss (Babatunde et al., 2012; Bassey et al., 1998; Kato et al., 2006; Zhao et al., 2014). A study involving untrained premenopausal women (Bassey et al., 1998) reported peak landing vertical forces which corresponded to 3 BW’s and mean peak loading rates of 43 bodyweights per second ($BW \cdot s^{-1}$), using countermovement jumps (50 jumps at 8 cm, 6 days/week), and resulted in significant increases in femoral BMD of 2.8%. Furthermore, authors of meta-analyses concluded (Babatunde et al., 2012; Zhao et al., 2014) that jump-landing programmes that; utilised brief jumping protocols (10 - 100 jumps/day, 3 - 7 days/week), are 4 - 18 months duration, and present loading magnitudes of between 2 - 6 BW, can result in significant gains in femoral neck BMD of 0.5 - 3% in premenopausal women during a time when normal bone loss is 0.5% - 1% per year (Babatunde et al., 2012; Martyn-St James & Carroll, 2010).

Recently researchers investigated the vertical and resultant GRF’s associated with bilateral vertical jumps, countermovement and drop jumps combined with a reactive jump (defined as ‘jumping immediately after an initial jump-landing’) as a potential osteogenic-stimuli for premenopausal women (Clissold et al., 2019; Clissold et al., 2018). The authors reported peak vertical landing forces (4.6 - 5.5 BW) which were substantially higher (1.2 to 1.8 times greater) than the values previously reported for the same jump-landings performed by a similar population (Bassey et al., 1998; Kato et al., 2006; Tucker et al., 2014). The use of repeated jumps requires the participant to flex minimally upon landing and push off quickly thereafter, thus preventing a 'soft' landing and the absorption of impact energy by the leg musculature (Bobbert et al., 1986; Lees, 1981; McNitt-Gray, 1993). Clissold and colleagues suggested that the jump-landing technique employed is a major factor that can influence the osteogenic effectiveness of jumps, and that repeated jump-landings may provide enhanced bone stimulation. Clissold et al. (2018), also reported that significantly larger landing forces, (↑10 - 20%; $p < 0.05$) were observed for the second jump-landing (post-reactive jump), and GRF's increased (ES = 0.22 to 0.42; $p = 0.06$) after only one instructed session indicating a learning and practice effect occurred.

Recent exercise prescription guidelines for the prevention and management of osteoporosis have been published by Exercise and Sports Science Australia (ESSA), according to level of risk of fragility fracture (B. R. Beck et al., 2017). Individuals classified as 'low risk' (T score < -1.0), are recommended to perform moderate to high-impact weight-bearing activities (50 jumps per session), defined as greater than two body weights (BW) (moderate impact), to greater than four body weights (high impact) of ground reaction forces, four to seven times each week. Although the position statement identifies the types of jumps to be performed, it lacks specific detail in terms of jump-landing technique, programme design, and monitoring of the daily and weekly loading. Therefore, a programme to safely optimise the impact stimulus required to promote bone formation needs to provide specific cues for jump-landings and adhere to best practice musculoskeletal programme design (Fleck & Kraemer, 2014; Kraemer & Ratamess, 2004; Mansfield, 2006; Mothersole et al., 2014). Programme variables to be considered include; force magnitude, rate of force production, direction of force application (medio-lateral, anterio-posterior, vertical and resultant), progressive overload, specificity, variation, individualisation, and mesocycle design (including loading and de-loading cycles) (Fleck & Kraemer, 2014; Kraemer & Ratamess, 2004; C. H. Turner & Robling, 2005).

Although the effects of jumping exercises on bone health in premenopausal women have been documented by several research groups, many diverse protocols are used in exercise and BMD research, making it challenging to compare outcomes. In addition, the focus on jump-landing technique and utilising a reactive jump component within a 12-month periodised osteogenic training programme has not been previously presented. Given the limitation identified, the primary outcome this study sought to determine was whether the jump group (JL) would achieve and exceed gains in bone mass, and improved aspects of bone geometry at the femoral narrow neck (cortical thickness, cross-sectional area, section modulus). We were also interested in secondary measures associated with the reduction of falls risk, including; lower body explosive power, muscle reactivity, balance performance parameters and body composition. Due to the scope of the study, several hypotheses were generated; i) Bone mineral density and bone mineral content will increase at the femoral neck, total hip and lumbar spine in the JL and age-predicted BMD losses (≤ 1%) will occur in the control group (CON); ii) Bone geometry variables will increase at the femoral neck in the JL and decrease in the CON; iii) Improvements in functional performance parameters (i.e. lower body explosive power, muscle reactivity and balance), will be observed in the JL only; and, iv) The JL will achieve improvements in body composition (i.e. increased fat free mass and decreased fat mass and body fat percentage), with no improvements in the CON.

8.3 Methods

8.3.1 Experimental Approach to the Problem

A longitudinal controlled trial was implemented for a period of 12-months to determine the effects of a quantified jump-landing programme on measurements of bone health in premenopausal women. Eighty premenopausal women (30 - 51 years) were assigned to either the JL or CON. Participants utilised an online registration form in which they could indicate a preference for treatment, control or either. Fifty percent (n = 40) chose either and were randomised (Excel) into the control or treatment groups. The remaining participants were allocated based on their choice and willingness to participate in the daily jump-landing program (in their own homes), and attend jump-landing group classes regularly. Such methodology was deemed necessary as previously published longitudinal exercise studies involving premenopausal women have reported high drop rates 38% to 50% (Tucker et al., 2014; Vainionpää et al., 2006; Winters-Stone & Snow, 2006). Our study design sought to improve the adherence to the jump-landing training program (Winters-Stone & Snow, 2006) and to determine the true effect of the mechanical stimulus. Although it was not possible to blind the intervention providers due to their specific expertise in the field of this research, blinding was applied for the process of data entry and analysis. Participants in the CON were asked to maintain their normal activity level and to attend 3-monthly testing sessions. No significant differences for any physiological measures were observed between the CON and JL group at baseline.

Dual energy x-ray absorptiometry (DXA) was used to measure body composition, bone mineral density and bone mineral content at the proximal femur (femoral neck and total hip), and lumbar spine (L1 - L4). Additional analysis included cross sectional area, cortical thickness and section modulus of the femoral narrow neck. Functional performance parameters (vertical jump, reactive jump, and single leg balance) were measured in conjunction with DXA variables to help give insight into other factors (i.e. strength, balance, reactivity) that may contribute to reducing the risk of falls and fracture incidence (Lusardi et al., 2017; Vellas et al., 1997). All testing was performed at baseline, 3, 6, 9 and 12-month intervals in a Sports Science laboratory at a local Institute of Technology. All participants provided written informed consent after being briefed on the potential risks associated with this research. The methods and procedures used in this study were approved by the New Zealand Health and Disability Ethics Committees (17/NTB/155), and registered with the Australian New Zealand Clinical Trials Registry (ACTRN12617001145392p) (Appendix 2).

8.3.2 Participants

Eighty healthy premenopausal women (30 - 51 years), from the Bay of Plenty community, New Zealand (including; Toi Ohomai Institute of Technology and Sport Bay of Plenty), New Zealand volunteered to participate in this study in response to intra and inter-institution advertisement. This sample size is comparable to other studies which have used a similar design and length of study (Babatunde & Forsyth, 2013; Bassey et al., 1998; Niu et al., 2010). A flow diagram depicting the recruitment and retention of participants during the study is presented (Appendix 22). Of the eighty participants, eight did not meet the inclusion criteria due to regular participation in sport or exercise involving high impact activities (n = 8). A further fifteen women were removed from the study due to either; becoming pregnant (n = 4), sustaining an unrelated injury (n = 6), leaving the region (n = 3), or withdrawing for personal reasons (n = 2). The results from this study are based on the data obtained by the remaining 57 participants. A summary of the participants baseline characteristics are presented in Table 8.1.

All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) (Appendix 4b and 4d) and inclusion criteria required participants to be between 30 and 51 years of age, which was used in conjunction with a regular menstrual cycle (9 - 12 menstrual cycles in the previous 12 months) to determine premenopausal status. Although menstrual cycle was not formally monitored, no participants reported any change in menstrual status throughout the study. According to statistics the average woman reaches menopause at 51 years of age (Lawton et al., 2008). Participants were excluded if any medical problems were reported, using a comprehensive online medical and pre-exercise questionnaire, that compromised their participation or performance in this study: including having a recent or current musculoskeletal injury; osteoporosis, osteoarthritis; and, any condition of impaired balance or coordination. Participants were also excluded if currently (or in the past 12 months), engaged in regular physical activity involving impact exercise (i.e. playing sports such as tennis, squash and netball), and if taking corticosteroids. In addition, pregnant women were excluded from the study due to contraindications related to DEXA testing.

Table 8.1 Baseline characteristics of the participants (mean ± SD)

	Jump (n = 32)	Control (n = 25)
Demographics		
Age (yr)	43.0 ± 5.30	41.5 ± 5.8
Height (cm)	165 ± 0.10	165 ± 0.10
Body mass (kg)	70.8 ± 11.0	68.9 ± 12.6
BMI ($kg\cdot m^{-2}$)	25.9 ± 3.70	25.4 ± 4.20
Nutritional Status		
Calcium intake (mg)€	867 ± 368	838 ± 260
Protein (g) €	97.4 ± 33.3	95.2 ± 27.4
Bone Mineral Density ($g\cdot cm^2$)		
Femoral neck*	0.877 ± 0.15	0.839 ± 0.10
Total hip*	1.008 ± 0.14	0.979 ± 0.09
Lumbar spine (L1 - L4) *	1.104 ± 0.14	1.059 ± 0.09
Body Composition		
Fat free mass (kg)*	48.0 ± 5.90	47.0 ± 6.85
Fat mass (kg)*	23.1 ± 7.32	22.0 ± 7.20
Body fat (%) *	31.9 ± 6.50	31.3 ± 5.80
Performance Tests		
Jump height (Vertec, cm)	35.2 ± 7.70	35.4 ± 5.40
Ground contact time (ms)	0.309 ± 0.10	0.261 ± 0.11
Balance Measures		
Path length (cm)	111 ± 37.5	128 ± 35.2
Mean sway velocity (m/s)	3.78 ± 1.22	4.28 ± 1.17

Key: Data expressed as mean ± SD. * DEXA; € Determined using 3-day food diary and Foodworks software analysis. No significant differences were observed between the JL and CON at baseline.

8.3.3 Testing Procedures

During the first session, less than one month after recruitment, participants filled in pre-screening questionnaires (Appendix 4b and 4d). Both JL and CON groups were subjected to the same testing protocol (DEXA, balance, muscle reactivity and maximal vertical jump) at the same time of day. A 3-day food diary (including 2-week days and 1 weekend day), was used to assess dietary status at baseline. Dietary assessment software Foodworks Professional 8 (Xyris Software, Australia), was used to determine average estimated energy intake (KJ/day), protein and calcium intake (mg/day), from food, fluids and supplements (Appendix 8). An information sheet was provided to all study participants describing the role of calcium for bone health and to promote the recommended dietary intake (RDI) of 1000mg

("Calcium," 2014). In addition, participants in both groups completed a 7-day activity diary (Appendix 7) to determine participation in regular high-impact physical activity and eligibility to participate in this study.

8.3.3.1 Anthropometry and Bone Mineral Density

Participants had their height measured (wall-mounted stadiometer to the nearest 0.1cm) (Appendix 17a) prior to having BMD assessed ($g{\cdot}cm^2$) at the proximal femur (femoral neck and total hip) and lumbar spine (L1 - L4) using dual energy x-ray absorptiometry (DEXA) utilising specialised hip structural analysis (HSA) software (Hologic Discovery QDR Series Bone Densitometer, Bedford, Massachusetts) (Figure 8.1) (Appendix 5 and 14). The measurement of BMD, using bone densitometry, is well accepted as a major determinant when defining the risk of osteoporotic fracture and currently the tool considered the 'gold standard' in the diagnosis and management of osteoporosis due to the strong correlation with fracture risk using WHO T-score criteria (Kanis & Kanis, 1994). However, BMD represents an important but not exclusive dimension of bone strength (describes 50 - 70% of the strength of bone) (Ammann & Rizzoli, 2003; Cheng et al., 1997; Kanis, 2002), with geometric properties relating to the complex three-dimensional nature of bone also playing an important role in determining the strength of bone and predicting fracture risk (Kaptoge et al., 2008). Due to limitations resulting from the two-dimensional analysis provided by DEXA to determine BMD, a complex biomechanical index was derived based on hip structural analysis (HSA) (T. J. Beck et al., 1990). This programme not only measures BMD of the hip area, but also estimates the geometrical and mechanical properties using cross-sections traversing the proximal femur at sites of clinical significance. Geometric properties relating to the complex three-dimensional nature of bone include; bone girth (cross-sectional area), cortical bone thickness and sectional modulus (a geometric index of bone bending strength. Researchers comparing HSA, computed tomography (CT) and quantified computed tomography (QCT), suggested that the geometry of the proximal femur is well described by DEXA (Ohnaru et al., 2013; Prevrhal et al., 2008). For example, data from these studies using postmenopausal women used both CT and DEXA (using HSA), to scan the proximal hip, and reported a favourable comparison for these scanning techniques ($r^2 = 0.67$ and $r^2 = 0.60 - 0.90$, $p \leq 0.001$ for femoral neck BMD), supporting the validity of using

DXA for assessing the key structural parameters (Ohnaru et al., 2013; Prevrhal et al., 2008).

Body mass and composition (total tissue mass, lean muscle mass, fat mass) was also measured using DXA, as this technology is one of the methods considered as "Gold Standard" for this measurement (Borga et al., 2018; Branski et al., 2010). Precision and calibration were carried out in accordance with manufacturer instructions. Participants were instructed to standardise clothing (workout clothing without metal), and nutrition (maintain hydration and not be fasted), for each scanning session. Prior to the start of the study 17-participants performed two DEXA tests within 7-days (Chapter 7). Test-retest reliability was evaluated by intra-class correlation coefficients (ICC) using a two-way random effects model, absolute agreement and average measures. Coefficients of variation (CV) were also calculated (CV = SD/mean * 100) for each dependant variable. Significant correlations ($p < 0.001$) were observed for all measures and reliability was excellent for all bone mineral density (ICC's = 0.99 - 1.0; CV's = 0.31 – 2.13%), bone mineral content (ICC's = 0.98 - 1.00; CV's = 0.43 - 1.53%), hip structural analysis of the narrow neck (cortical thickness, cross-sectional area and section modulus) (ICC's = 0.99 - 1.00; CV's = 0.76 - 1.47%) and body composition measures (ICC's = 1.00; CV = 0.32 - 1.23%). All statistical analyses were carried out using SPSS 25.0 for Windows (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 9.0; Microsoft, Seattle, WA).

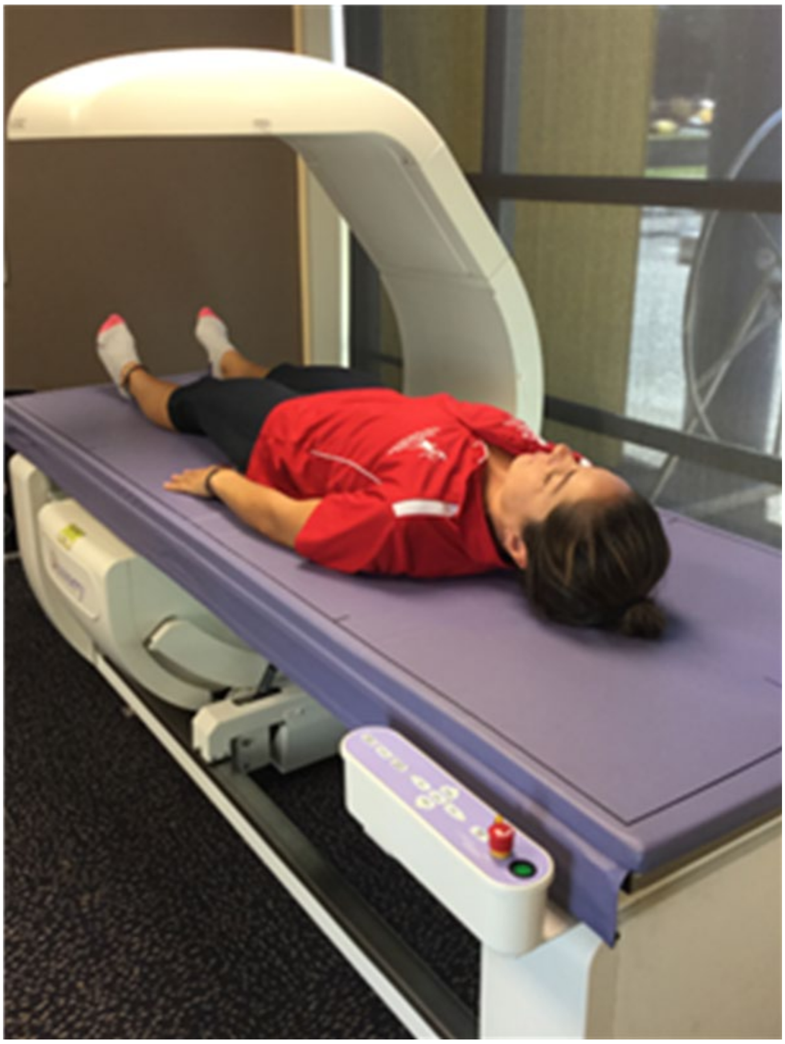


Figure 8.1 Pictorial representation of the DEXA testing equipment

8.3.3.2 Performance Testing

For each testing session, participants performed a ten-minute standardised warm up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilisation exercises. Testing commenced five minutes after the warm up. All instructions, and order of performing tests was standardised for every participant. All testing for this study was undertaken at a similar time of day with participants instructed to maintain their normal dietary intake before and after each testing session. Participants completed an activity questionnaire between testing sessions to monitor physical activity and ensure that inter-session physiological status was similar (Appendix 7). We did not control for nutrition, or hydration levels but participants were told not to make any changes in the above during the testing period.

All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

8.3.3.2.1 Static Balance

A 30 second one-leg static balance test was used to measure postural sway using an Accusway force plate (AccuSway, AMTI, Watertown, MA, USA) (Figure 8.2) (Appendix 15). This test has been shown to be a significant and easy-to-administer predictor of injurious falls (Vellas et al., 1997). Each participant completed two trials on each leg (alternating legs), with 1-minute rest between each trial, and force plate output variables were represented as an average of the two trials. Within session reliability of balance measures was evaluated by ICC using a two-way random effects model, absolute agreement and average measures ICC. Coefficients of variation (CV) were also calculated (CV = SD/mean * 100) for each dependant variable. Of the balance data collected, path length, and average sway velocity were the only balance measures to have acceptable reliability (ICC’s = 0.72 to 0.82; CV’s = 8.4 to 10.1%) for analysing performance changes over time in both legs, with significant correlations (magnitude; $p < 0.001$) observed for these measures. See Appendix 20 for the technical report detailing the within-trial reliability of the AMTI Accusway force plate.

Figure 8.2 Pictorial representation of the balance test utilised in this study

8.3.3.2.2 Muscle Reactivity

Participants were instructed to step off a 20 cm step and land with both feet together on a contact mat (Swift Performance Equipment, Queensland, Australia), and jump again as quickly as possible (i.e. to think of the mat as a ‘hot plate’) (Figure 8.3). Each participant performed two practice jumps, followed by two jumps, where ground contact time (ms) was collected. Each jump was separated by a 30-second rest interval. The best ground contact time of the two jumps was used for analysis.

Figure 8.3 Pictorial representation of the muscle reactivity test utilised in this study

8.3.3.2.3 Leg Extensor Power

The Vertec Yardstick (Swift Performance Equipment, Queensland, Australia), a portable device used to measure vertical jump height, was used to determine jumping ability and as a surrogate measure for tracking change in lower body explosive power (Leard et al., 2007; Wulf & Dufek, 2009) (Figure 8.4) (Appendix 16). Before jump commencement the participants reach height was determined, then they were encouraged to use a countermovement arm swing to jump and touch the highest vane of the Vertec device. Each participant performed three maximal vertical jumps, with each jump separated by a 30-second rest interval. The maximum jump height was used for analysis.

Figure 8.4 Pictorial representation of the leg extensor power test utilised in this study

8.3.4 Introduction to the ‘Jump-landing Programme’

A 4-week phase of strength and conditioning (neural adaptation programme) was implemented prior to the introduction of the jump-landing program to adequately prepare JL participants for the impact intensities prescribed (Mansfield, 2006) (Appendix 11). Participants were required to attend weekly group exercise sessions (jump-landing classes) and perform the jump-landing programme in a group environment. These were instructional sessions for participants to demonstrate proper technique for each of the jumps in the jump-landing programme. This requirement was expected to positively affect compliance to the programme by creating a ‘club like environment as well as providing regular opportunities to monitor participants jumping proficiency (Wang et al., 2016). Please refer to Chapter 6. for details.

8.3.5 ‘Jump-landing Programme’

Participants were introduced to the bilateral vertical and multidirectional jumps combined with a reactive jump which had previously been quantified and shown to easily exceed osteogenic thresholds which achieved BMD gains premenopausal women (Clissold et al., 2019; Clissold et al., 2018). The unilateral jumps were implemented six months into the jump-landing programme, and were demonstrated and practiced before they were introduced. For bilateral jumps, participants were instructed to land as if the ground was a “hot plate” (first jump-landing; reactive jump), and to immediately jump again for maximal height before landing again (second jump-landing; post-reactive jump). For unilateral jumps, participants were asked to land stiffly and to minimise knee flexion. Participants in the CON were asked to maintain their normal activity level.

The jump-landing programme was designed to progressively increase in magnitude and rate of strain, number of ground contacts (32 - 42 per day), frequency (2 - 5 sessions per week), and technical difficulty (i.e. bilateral to unilateral) over the 12-month period (see supplementary content; Appendix 23). Therefore, it was necessary to utilise data obtained from previously quantified jump-landings to determine the order these exercises should be introduced into the osteogenic jump-landing programme (Clissold et al., 2019; Clissold et al., 2018). A stress stimulus rating was developed based on previously determined jump-landing force variables for each of the jumps utilised in the 12-month periodised programme. The minimum adherence threshold determined for performing the jump-landing programme was set at an average of 3-times each week over the 12-month study period.

Each jump was separated by a 5-second interval, with 30-seconds rest inserted between each set (4 - 5) of jumps, as adequate recovery between loading cycles has been shown to maintain the mechano-sensitivity of bone and optimise the osteogenic response (Robling et al., 2001; Umemura et al., 2002). All jumps in this study were performed barefooted as researchers have suggested the natural elastic components of the body provide a greater protective effect than artificial footwear against excessive load during voluntary exercise (Bassey et al., 1997; Bassey & Ramsdale, 1994).

Website and social media

The JL were emailed their exercise programmes (Appendix 6a and 6b), and were provided additional resources via a 'Bone health study' website (Appendix 9 and 12). Compliance to the exercise regime during the intervention period was monitored via a 'Jump-tracker' feature on the website (Appendix 4e), which was filled in weekly and uploaded to a group spreadsheet that was accessed online. Regular feedback was provided using weekly infographics (Appendix 10), emails, phone calls and text messages (eTXT), with participants encouraged to contact the researcher any time about any concerns or issues they might have. The use of social media platform 'Facebook' was also utilised to allow social interaction among participants to promote greater 'buy in' and thus adherence to the training study over the 12-month period (Appendix 13).

8.3.6 Statistical Analyses

A restricted maximum likelihood linear mixed model (LMM) with fixed effects was performed to investigate the effect of the variables 'group' (JL and CON) and 'time' (baseline, 3-months, 6-months, 9-months and 12-months) for all clinically relevant dependant variables. The linear mixed model with fixed effects could accommodate for correlated data, unequal variances and missing data points encountered in the longitudinal dataset. Basic analytic assumptions were met: data were of normal and equal variance. The Sidak confidence interval adjustment was used to compare all main effects. Significance was accepted at the $p \leq 0.05$ level. Percentage changes and modified effect sizes (ES = mean change/standard deviation of the sample scores) using ratios of 0.10 - 0.19, 0.20 - 0.29, ≥ 0.30 indicating small, moderate and large changes, respectively, were calculated to determine the magnitude of change of bone from baseline to 12-months. The modified effect size classification was calculated based on significant improvements (ES = 0.15 to 0.26) on BMD previously reported in this population (Bassey et al., 1998; Vainionpää et al., 2005; Winters-Stone & Snow, 2006) (Appendix 18). Cohen's classifications of effect size (0.2 to 0.5, 0.51 to 0.8 and >0.8) (Cohen, 1988) were calculated to determine the magnitude of the change differences for all other variables (body composition and performance parameters) between the two groups. The smallest worthwhile change (%) for each dependant variable was calculated (SWC = ES * Standard Deviation) (Appendix 19). Coefficients of variation (CV) were also calculated (CV = SD/mean * 100) for each dependant variable. Significant correlations ($p < 0.001$) were observed for all measures and reliability was excellent for all bone mineral density (ICC's = 0.99 - 1.0; CV's = 0.31 – 2.13%), bone mineral content (ICC's = 0.98 - 1.00; CV's = 0.43 - 1.53%), hip structural analysis of the narrow neck (ICC's = 0.99 - 1.00; CV's = 0.76 - 1.47%) and body composition measures (ICC's = 1.00; CV = 0.32 - 1.23%). All statistical analyses were carried out using SPSS 25.0 for Windows (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 9.0; Microsoft, Seattle, WA).

8.4 Results

All JL participants performed the jump-landing program an average of 3-times each week over 12-months, as determined using a self-reported online jump tracker. The required minimum adherence for participating in the JL program was 3-times each week, which equated to 80% adherence to the JL program. Although all JL participants met this inclusion criteria for analysis in this study, eight participants were removed due to participation in additional high impact physical activity, as determined by 3-monthly activity questionnaires (Appendix 22). Data obtained from these questionnaires reported no injury or adverse effects relating to performance of the jump-landing program. Changes in habitual physical activity were evident for study participants (JL and CON), during the course of the 12 months, with trends observed for increased participation in low impact activities (i.e. walking and resistance training) as determined using activity questionnaires completed 3-monthly.

Total Body BMD and BMC

No significant main effects were observed for total body BMD, however a small increase occurred in the JL (↑2.34%; E = 0.17) compared to a trivial loss in the CON (↓0.12%; ES = -0.01). Both groups reported a loss in total body BMC, with a moderate bone loss occurring in the CON (↓2.49%; ES = -0.26) compared to a trivial loss in the JL (↓0.82%; ES = -0.05).

Femoral Neck

Significant group effects ($p < 0.01$) in favour of the JL for femoral neck BMD (↑3.44% versus ↓0.19; df = 263, F = 11.1, $p = 0.001$), BMC (↑2.61% versus ↓0.11; df = 252, F = 6.65, $p = 0.011$), femoral narrow neck cross-sectional area (CSA) (↑2.78% versus

↓0.64; df = 247, F = 6.65, *p* = 0.004) and cortical thickness (↑3.84% versus ↑0.84; df =261, F = 9.77, *p* = 0.002) were observed. Small to moderate positive changes (based on modified ES classifications) were observed for all femoral neck variables between baseline and 12-months (ES = 0.13 to 0.20) for the JL. A graphical representation of the changes in bone at the femoral neck and femoral narrow neck, is presented in Figure 8.5. The expected age-related losses (based on initial baseline data) were calculated and presented for BMD and BMC.

A significant group effect in favour of the JL for section modulus (a geometric index of bone bending strength at the femoral narrow neck) (↑3.22% vs ↓0.43, df =265, F = 7.15, *p* = 0.008) was observed. The effect size between baseline and 12-months demonstrated a small worthwhile change (ES = 0.15) in section modulus. A graphical representation of the changes in section modulus is presented in Figure 8.6.

Total Hip BMD and BMC

A significant group effect in favour of the JL for total hip BMD (↑2.34% vs ↓0.12%; df =257, F = 7.20, *p* = 0.008) and total BMC (↑3.72% vs ↑1.26; df =257, F = 4.96, *p* = 0.027) was observed. Small to moderate increases were observed for the JL for total hip BMD and BMC baseline and 12-months (ES = 0.17 to 0.19). A graphical representation of the changes in bone at the hip (with age-expected losses) is presented in Figure 8.7.

Total Lumbar Spine BMD and BMC (L1 - L4)

A significant group effect in favour of the JL for total lumbar BMD (↑0.41% vs ↓0.15%; df = 253, F = 13.21, p < 0.001) and total lumbar BMC (↑3.13% vs ↑0.45%; df =236, F = 7.57, *p* = 0.006) were observed. Small worthwhile increases (ES = 0.15) in total lumbar BMC were observed for the JL between baseline and 12-months. A graphical representation of the changes in the bone at the total lumbar spine (L1 - L4) (with age-expected losses) is presented in Figure 8.8.

Body Composition

A significant time effect (df = 263, F = 3.08, *p* = 0.017) was observed for fat percentage with moderate losses being observed in both the JL (↓13.8%; ES = -0.68) and CON (↓9.56%; ES = -0.52) over the study duration. While small increases in fat free mass

(↑5.44% and ↑4.63%, ES = 0.43 and 0.32) and small to moderate reductions in fat mass (↓15.0% and ↓8.86%; ES = -0.50 and -0.40) were identified between baseline and 12-months for both the JL and CON (respectively), no significant main effects were observed over the 12 months.

Performance Parameters

A significant group X time interaction (df =244, F = 3.27, *p* = 0.012) and a significant effect for time (df =244, F = 2.92, *p* = 0.022) was observed for ground contact time. Significant group effects in favour of the JL were observed for ground contact time (↓21.9% vs ↑8.86%; df = 244, F = 6.10, *p* = 0.014), representing large reductions (ES = -0.91) in ground contact time achieved over the 12-month study. A significant effect for time (df =244, F = 2.92, *p* = 0.022) and a significant group X time interaction (df = 244, F = 3.27, *p* = 0.012) was also observed. No significant effects were observed in the vertical jump, however group effects that approached significance were in favour of the JL (↑7.54% vs ↓0.24%, df = 244, F = 3.22, *p* = 0.074). No significant main effects were observed for any balance measures (path length and average sway velocity) over the 12-month study duration. A graphical representation of the performance changes in ground contact time and vertical jump performance is presented in Figure 8.9.

Table 8.2 Within group changes and effect sizes in bone from baseline to 12 months

	Jump (n = 32)					Control (n =25)				
	Baseline	12-months	Percentage Change (%)	SWC (%)	ES	Baseline	12-months	Percentage Change (%)	SWC (%)	ES
Total body										
Bone mineral density (g·cm^2)	1.01 ± 0.14 *(0.96 – 1.06)*	1.03 ± 0.14 *(0.98 – 1.08)*	2.34	0.19	0.17^t	0.98 ± 0.09 *(0.94 – 1.02)*	0.98 ± 0.09 *(0.94 – 1.02)*	-0.12	0.19	-0.01
Bone mineral content (g)	2344 ± 369 *(2216 – 2472)*	2324 ± 348 *(2203 – 2445)*	-0.82	0.14	-0.05	2323 ± 225 *(2235 – 2411)*	2265 ± 227 *(2176 – 2354)*	-2.49	0.16	-0.26*
Femoral neck										
Bone mineral density (g·cm^2)	0.88 ± 0.15 *(0.83 – 0.93)*	0.91 ± 0.15 *(0.86 – 0.96)*	3.44	0.19	0.20*	0.84 ± 0.15 *(0.78 -0.90)*	0.84 ± 0.10 *(0.80 -0.88)*	-0.15	0.34	-0.01
Bone mineral content (g)	4.31 ± 0.84 *(4.02 – 4.60)*	4.42 ± 0.83 *(4.13 – 4.71)*	2.61	0.36	0.13^t	4.14 ± 0.59 *(3.91 -4.37)*	4.13 ± 0.55 *(3.91 4.35)*	-0.11	0.40	-0.01
Cross-sectional area (cm^2)	3.26 ± 0.60 *(3.05 – 3.47)*	3.35 ± 0.60 *(3.14 -3.56)*	2.78	0.19	0.15^t	3.11 ± 0.44 *(2.94 – 3.28)*	3.09 ± 0.42 *(2.93 3.25)*	-0.64	0.33	-0.05
Cortical thickness (cm)	0.21 ± 0.04 *(0.20 – 0.22)*	0.22 ± 0.04 *(0.21 – 0.23)*	3.84	0.45	0.20*	0.20 ± 0.03 *0.19 -0.21)*	0.20 ± 0.03 *(0.19 -0.21)*	0.84	0.55	0.06
Section modulus, Z (cm^3)	1.54 ± 0.32 *(1.43 – 1.65)*	1.59 ± 0.33 *(1.48 – 1.70)*	3.20	0.51	0.15^t	1.47 ± 0.26 *(1.37 – 1.57)*	1.46 ± 0.26 *(1.36 -1.56)*	-0.40	0.49	-0.07
Total hip										
Bone mineral density (g·cm^2)	1.01 ± 0.14 *(0.96 – 1.06)*	1.03 ± 0.14 *(0.98 -1.08)*	2.30	0.19	0.17^t	0.98 ± 0.09 *(0.94 -1.02)*	0.98 ± 0.09 *(0.94 – 1.02)*	-0.12	0.19	-0.01
Bone mineral content (g)	34.2 ± 6.23 *(32.0 -36.4)*	35.5 ± 7.01 *(33.1 -37.9)*	3.72	0.45	0.19^t	33.0 ± 4.77 *(31.1 – 34.9)*	33.4 ± 4.73 *(31.6 -35.3)*	1.26	0.36	0.09
Lumbar spine (L1-L4)										
Bone mineral density (g·cm^2)	1.11 ± 0.12 *(1.07 – 1.15)*	1.11 ± 0.13 *(0.98 -1.24)*	0.41	0.26	0.04	1.05 ± 0.09 *(1.01 – 1.09)*	1.05 ± 0.09 *(1.01 – 1.09)*	-0.15	0.33	-0.02
Bone mineral content (g)	67.2 ± 14.2 *(62.3 – 72.1)*	69.3 ± 13.5 *(53.7 -80.7)*	3.13	0.37	0.15^t	63.8 ± 8.34 *(60.5 -67.1)*	64.1 ± 8.31 *(60.8 -67.4)*	0.45	0.41	0.03

Key: Within group baseline and 12-month data expressed and mean ± SD with percentage changes and effect sizes for each variable. ES = Effect size, ^{t} small ES; * moderate ES, SWC = Smallest worthwhile change (SWC = ES 0.1 * Standard Deviation). Values in brackets denote 95% Confidence Intervals.

Table 8.3 Within group changes and effects in body composition and performance parameters from baseline to 12 months

	Jump (n = 32)					Control (n = 25)				
	Baseline	12-months	Percentage Change (%)	SWC (%)	ES	Baseline	12-months	Percentage Change (%)	SWC (%)	ES
Body Composition										
Fat free mass (kg)#	48.1 ± 5.9	50.7 ± 6.2	5.44	0.72	0.43^{t}	47.0 ± 6.9	49.2 ± 7.0	4.63	0.72	0.32^{t}
	(46.1 -50.1)	*(48.6 – 52.9)*				*(44.3 – 49.7)*	*(46.5 – 51.9)*			
Fat mass (kg)#	22.9 ± 7.3	19.5 ± 6.4	-15.0	-2.20	0.50*	22.9 ± 7.3	20.1 ± 6.8	-8.86	-2.18	-0.40^{t}
	(20.4 -25.4)	*(17.3 – 21.7)*				*(20.0 – 25.8)*	*(17.4 – 22.8)*			
Body fat (%)#	31.7 ± 6.6	27.4 ± 6.1	-13.8	-1.79	0.68*	31.3 ± 5.8	28.3 ± 5.8	-9.56	-1.82	-0.52*
	(29.4 -34.0)	*(25.3 – 29.5)*				*(29.0 -33.6)*	*(26.0 -30.6)*			
Vertec										
Vertical Jump (cm)	34.9 ± 7.4	37.5 ± 6.4	7.54	3.35	0.38^{t}	35.4 ± 5.4	35.3 ± 7.1	-0.24	3.11	-0.01
	(32.3 -37.5)	*(35.3 – 39.7)*				*(33.3 – 37.5)*	*(32.5 – 38.1)*			
Contact Mat										
Ground contact time (ms)	0.31 ± 0.10	0.24 ± 0.05	-21.9	-5.62	0.91^	0.27 ± 0.10	0.30 ± 0.09	8.86	-5.41	0.26^{t}
	(0.28 -0.34)	*(0.22 -0.26)*				*(0.23 – 0.31)*	*(0.26 -0.34)*			
Balance Force plate										
Path length (cm)	111.0 ± 37.5	109.7 ± 34.1	-1.20	-2.82	0.04	128.4 ± 35.1	123.9 ± 49.4	-4.22	-3.19	0.13
	(98.0 – 124.0)	*(97.9 – 121.5)*				*(114.6 – 124.2)*	*(104.5 – 143.3)*			
Average velocity (m/s)	3.78 ± 1.22	3.98 ± 1.30	5.29	-2.81	0.16	4.28 ± 1.17	4.58 ± 3.47	7.01	-3.12	0.13
	(3.36 -4.40)	*(3.53 – 4.43)*				*(3.82 – 4.74)*	*(3.22 – 5.94)*			

Key: Within group baseline and 12-month data expressed as mean ± SD with percentage changes and effect sizes over the 12 months presented for each variable. # DEXA, ES = Effect size, ^{t} small ES; * moderate ES, ^ large ES, SWC = Smallest worthwhile change (SWC = ES 0.2 * Standard Deviation). Values in brackets denote 95% Confidence Intervals.

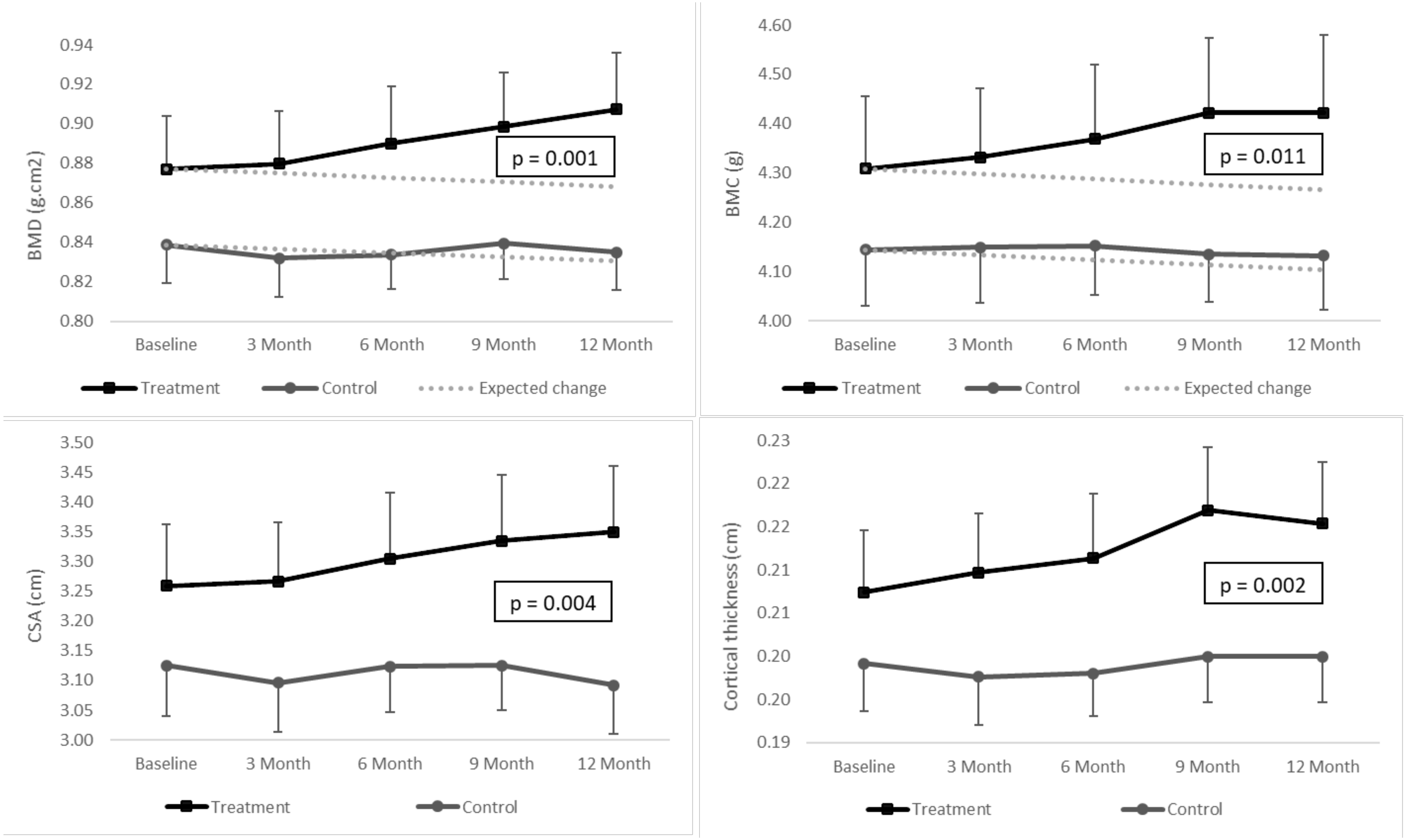


Figure 8.5 The jump and control group average time course of change for femoral neck bone mineral density (top left), bone mineral content (top right), and femoral narrow neck cross sectional area (bottom left) and cortical thickness (bottom right) across the 12-month study duration. P values depict significant group main effects. Error bars represent standard error.

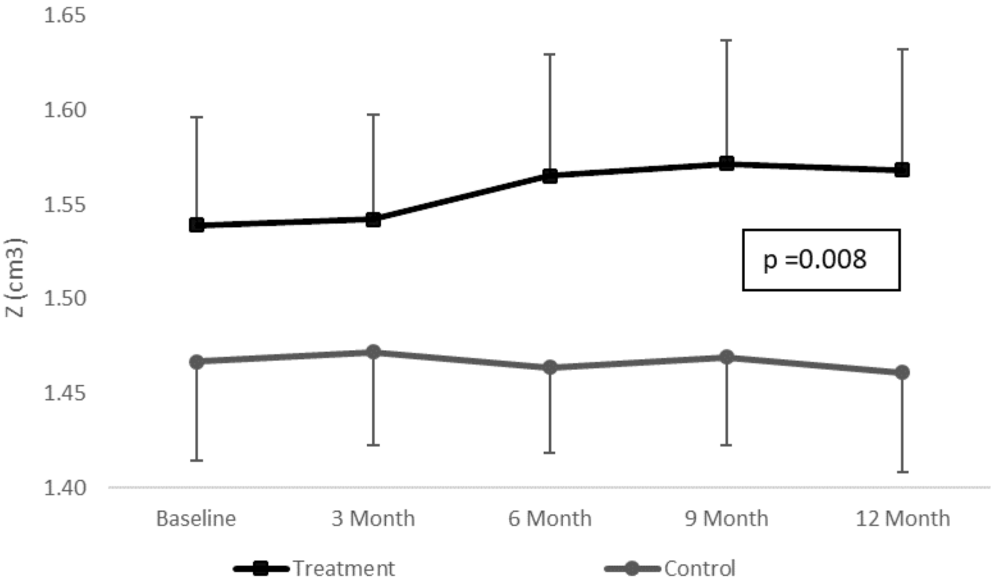


Figure 8.6 The jump and control group average time course of change for section modulus at the femoral narrow neck (Z cm3) across the 12-month study duration. P values depict significant group main effects. Error bars represent standard error.

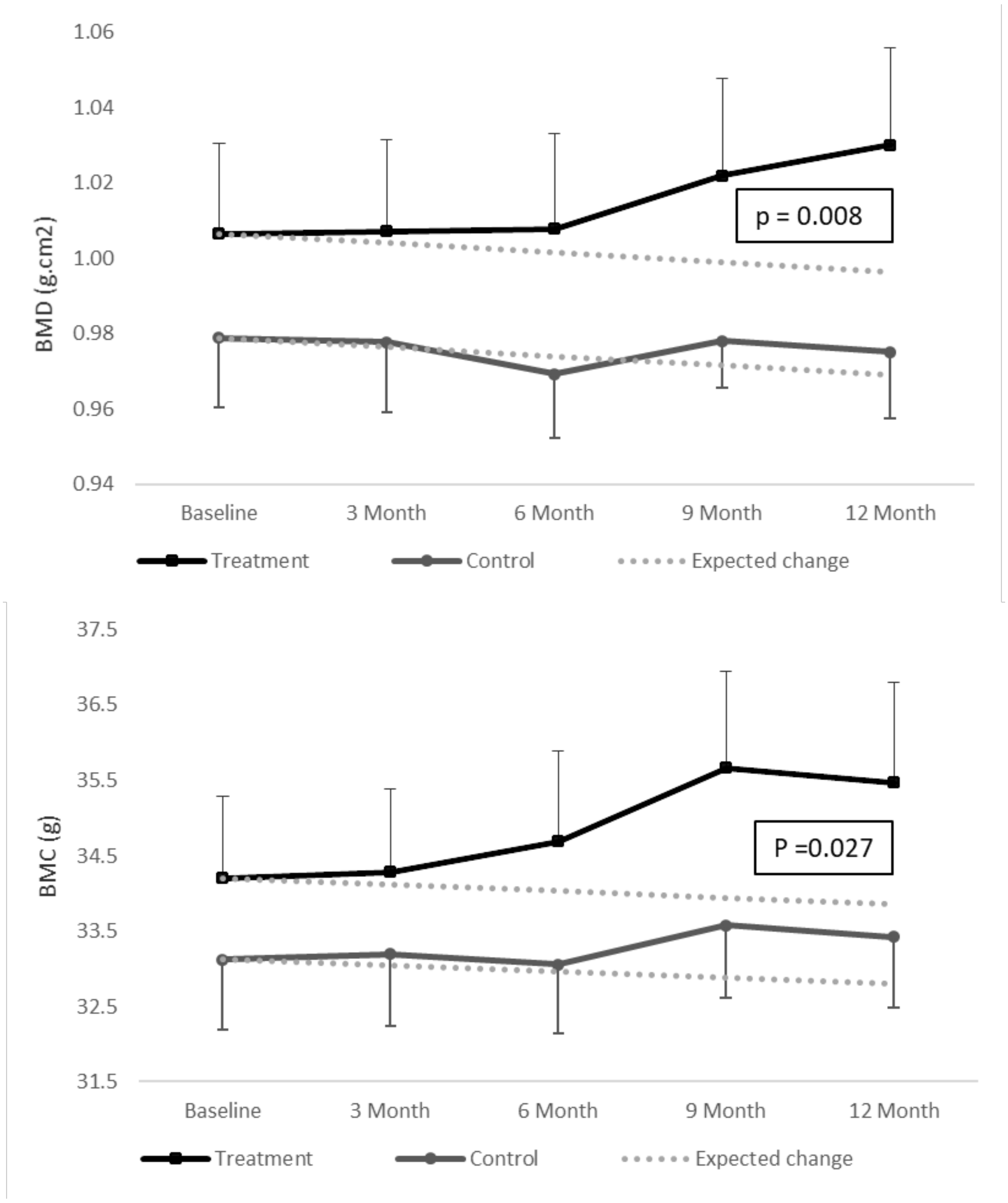


Figure 8.7 The jump and control group average time course of change for total hip bone mineral density (top) and bone mineral content (bottom), across the 12-month study duration. P values depict significant group main effects. Error bars represent standard error.

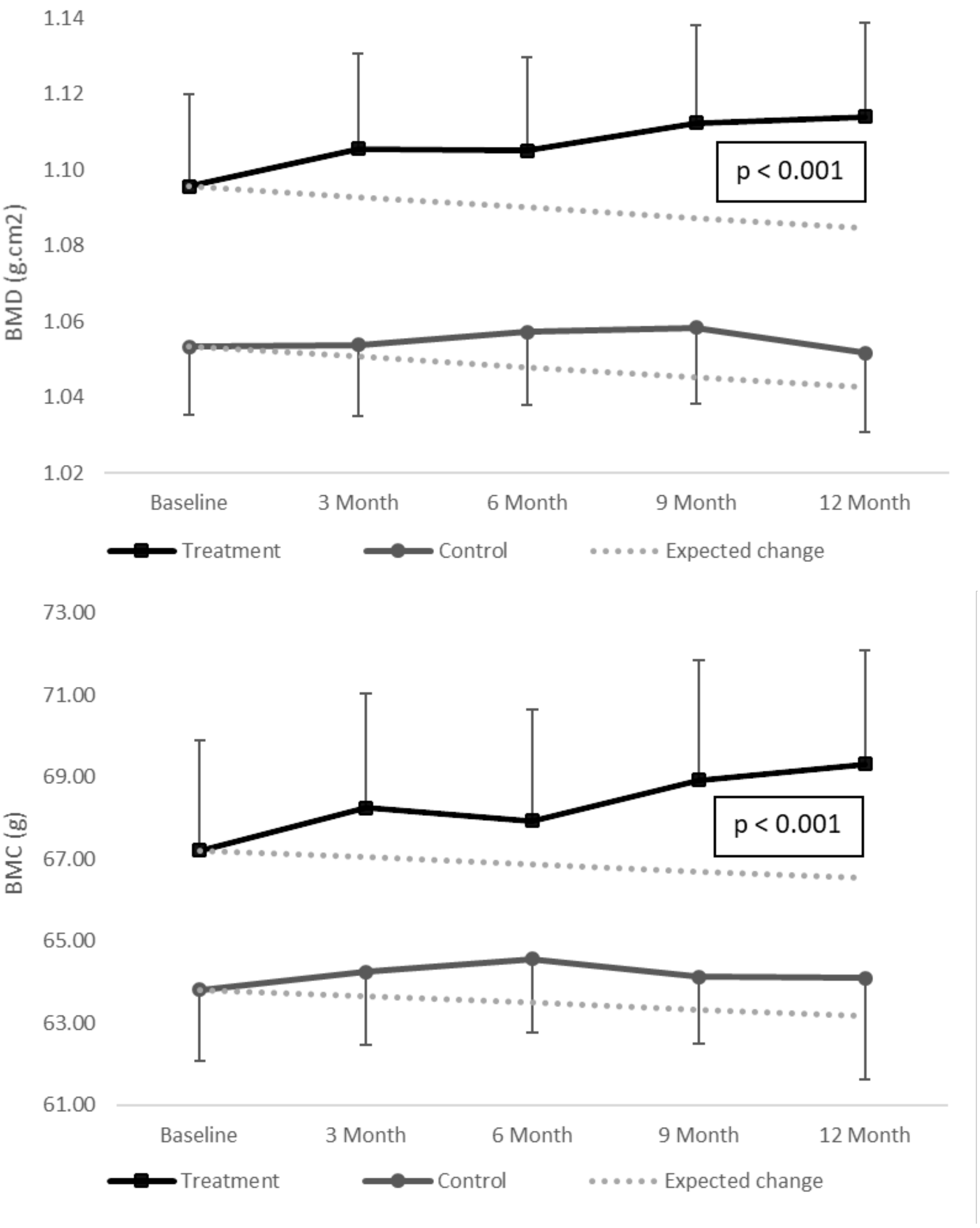


Figure 8.8 The jump and control group average time course of change for total lumbar spine (L1 - L4) bone mineral density (top) and bone mineral content (bottom), across the 12-month study duration. P values depict significant group main effects. Error bars represent standard error.

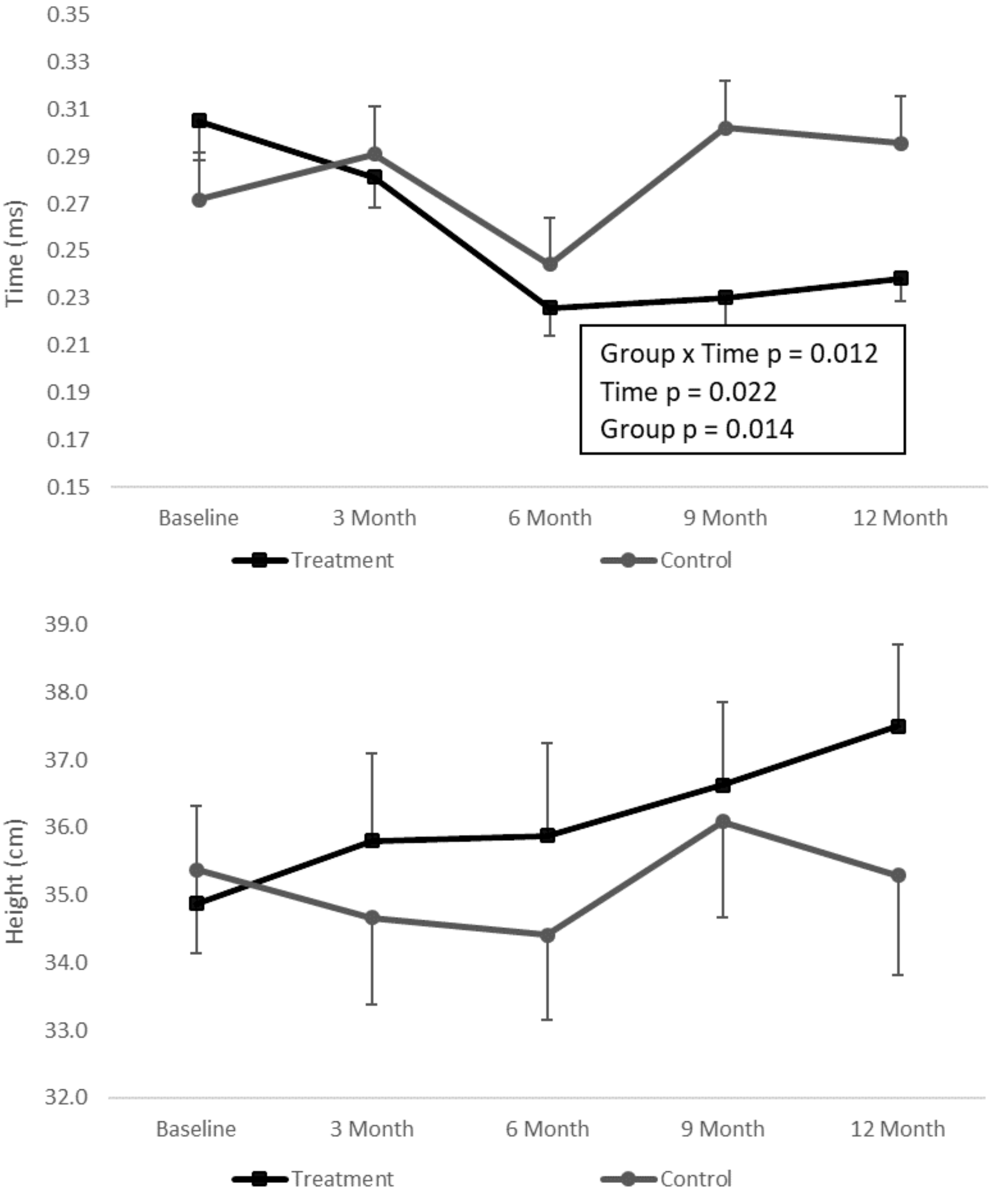


Figure 8.9 The jump and control group average time course of change for ground contact time (top) and vertical jump height (bottom), across the 12-month study duration. P values depict significant group main effects. Error bars represent standard error.

8.5 Discussion

This study is unique in its presentation of a quantified periodized, jump-landing program on parameters of bone strength and overall fracture resistance for premenopausal women over a 12-month period. The main findings of the current study support the initial hypotheses and demonstrate that a quantified jump landing programme performed over 12-months can; (i) Improve bone health (compared to the CON) with significant (*p* < 0.05) worthwhile improvements being observed in lumbar spine BMD and BMC (↑O.41 to ↑3.13%; ES = 0.04 and 0.15, respectively), and femoral neck BMD and BMC (↑3.44% and ↑2.61%; ES = 0.20 and 0.13, respectively) measures; (ii) Significant (*p* < 0.01) improvements in bone geometry variables at the femoral neck (↑2.78 - ↑3.84%; ES = 0.15 - 0.20) in the JL with losses (↓0.64 - ↓0.84%; ES = -0.05 to -0.07) being observed in the CON, except a trivial increase for cortical thickness (↑0.84; ES = 0.06); (iii) Improve jump performance parameters with significant increases (*p* < 0.05) in muscle reactivity (↓21.9%; ES = -0.91) and non-significant increases in vertical jump performance (↑7.54%; ES = 0.38), for the JL, in contrast to the performance decrements observed in the CON (↑8.86% and ↓0.24%; respectively); (iv) Improve body composition changes, however contrary to the initial hypothesis a significant time effect (*p* = 0.017) was observed for body fat percentage with moderate fat losses observed in both the JL (↓13.8%; ES = -0.68) and CON (↓9.56%; ES = -0.52).

The current study primarily focused on measuring changes in bone at the hip and lumbar spine over 12-months. Researchers (Drake et al., 2015), have demonstrated that the hip and lumbar spine are fracture sites most frequently associated with post-menopausal osteoporosis, which are primarily a consequence of trabecular bone losses due to oestrogen deficiency, however the hip is considered the most severe osteoporosis complication (Kanis, 2002). In the current study, we observed significant (*p* < 0.01) BMD gains at the femoral neck (↑3.44%) and the total hip (↑2.34%) for the JL, compared to the CON, where a reduction in BMD was observed (↓0.11 to ↓0.15 %). Our findings have important clinical implications with reference to the 1% per year expected bone loss at this site for women between 40 and 50 years old ("Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis," 1993). The significant (*p* < 0.05) gains also observed for BMC for femoral neck and total hip (↑2.61% and ↑3.72%, respectively) in our JL suggest that the increase of bone mass at the femoral neck site are an ‘actual’ gain and not just a reallocation of existing hip bone mineral. In comparison, the CON experienced small losses in BMC at the femoral neck (↓0.11%), suggestive that the stimulus provided by the jump-landings was effective in targeting the hip region, and specifically the femoral neck. Our study demonstrated that a brief (2 - 3 min) quantified osteogenic jump-landing programme performed at least 3-times a week can not only maintain bone health but can reverse the trend of expected age-related bone loss at these clinically relevant sites.

As the jump-landing exercises in our periodised programme primarily involved the lower body, it was unclear as to whether gains in BMD and BMC would be observed in the lumbar spine region. Researchers have suggested that jump-landings would not provide an effective stimulus for individuals aiming to improve bone strength at the spine, and recommend upper body resistance exercises as a better option (Winters-Stone & Snow, 2006). We however observed significant ($p < 0.001$) gains in BMD (↑0.41%) at the lumbar spine (L1 - L4) for our JL, with BMD losses occurring in the CON (↓0.15%). Our JL also amassed significantly ($p < 0.01$) greater BMC than the CON at the lumbar spine (L1 - L4) (↑3.13% vs ↑0.45%, respectively). Such results demonstrate that the lower body focussed jump-landings utilised in this study were able to provide the required stimulus for positive bone adaptation at this additional clinically relevant site. The authors propose that the utility of a reactive jump (to jump again immediately after the first jump-landing), and instruction provided to use a vigorous arm swing and land stiffly, was effective in transmitting greater landing forces to the hip and lumbar spine (Clissold et al., 2018).

Osteoporosis is characterised by decreasing bone strength leading to an increased risk of fracture, however bone density is only one of the contributors to bone strength (Kanis, 2002). Several factors have been identified to describe bone quality including; bone micro and macro architecture, bone material properties and bone remodelling levels (Asikainen et al., 2004; Chopin et al., 2012). In this study, the JL achieved significant ($p < 0.01$) increases in bone geometry variables at the narrow neck (narrowest section of the femoral neck) including; cross-sectional area (CSA) (↑2.78% vs ↓0.64), cortical thickness (↑3.84% vs ↑0.84) and section modulus (a measure of bone stiffness closely related to the bending and torsional strength of bone) (↑3.22% vs ↓0.43), when compared with the CON.

A paediatric study reported gains in femoral neck BMD (↑2.6%), CSA and section modulus (↑4.0%) in prepubertal girls (10.0 ± 0.6 yr), in response to a 7-month jumping program (50 - 100 jumps, 3 times/week) (McKay et al., 2005). These increases in aspects of bone strength observed for the JL participants relating to bone girth and quality are proposed to translate directly to overall bone strength and increased fracture resistance (Petit et al., 2002; C. H. Turner & Robling, 2003). Interestingly, studies showing large increases in BMD and BMC resulting from pharmacologic therapy result in very small increases in fracture resistance (Kohrt et al., 2009). In comparison, mechanical loading as determined using animal studies achieved smaller gains in BMD and BMC, which translated to very large increases in bone strength and resistance to fracture (64 - 94%) (C. H. Turner & Robling, 2003). Although limitations exist for using a two-dimensional imaging technique to assess a three-dimensional structure, the hip structural analysis utilised in this study provided an opportunity to assess variables used to describe the overall strength and fracture resistance of bone in response to our jump-landing intervention.

Loss of musculoskeletal mass and function has been described as “a natural ageing trait, reinforced by an unhealthy lifestyle” (Nedergaard et al., 2013). Researchers have suggested that targeting exercises that reduce the likelihood of falling by improving muscle strength, balance, mobility & posture should also be included in an osteoporosis prevention programme (de Vreede, Samson, van Meeteren, Duursma, & Verhaar, 2005; Guadalupe-Grau et al., 2009). Our JL improved their maximal jumping ability (↑7.54%), in contrast to the CON who experienced a reduction in lower body explosive power (↓0.24%). Similarly, improvements ($p < 0.05$) were observed in the JL for lower body muscle reactivity (determined by reduced ground contact time when performing a drop jump) when compared with the CON (↑21.9% vs ↓8.86%, respectively). The reduction in ground contact time observed in the JL participants may be attributed to adaptations induced from performing the reactive jump and thereby the stretch shortening cycle (Lees, 1981; van Ingen Schenau et al., 1997). Interestingly, no significant main effects were found for balance measures (i.e. path length, and average sway velocity) between the groups. It may be that the use of a static single-legged balance test, as utilised in this study, may not have captured the potential coordinative adaptations resulting from the dynamically applied jump-landing programme.

All participants in the current study experienced favourable body composition changes, with moderate body fat percentage losses observed in both the JL (↓13.8%; ES = -0.68) and CON (↓9.56%; ES = -0.52). In addition, JL and CON participants experienced small increases in fat free mass (↑5.44% and ↑4.63%, respectively), over the 12-month study period. Previous research has associated lean mass with linear increases in hip bone strength (BMD and CSA) in postmenopausal women (Leslie et al., 2014; Shi et al., 2019), and in premenopausal women (BMD and section modulus) (Bailey & Brooke-Wavell, 2010a), suggesting that gravitational loading, muscle-contractions and associated hormonal factors may be responsible for the positive relationship between skeletal muscle and bone. In addition, a recent study investigating the relationship between body composition and osteoporosis including premenopausal women (n = 10, 884) concluded that individuals with low strength and low muscle mass were two times more likely to have osteopenia or osteoporosis (He et al., 2016).

Our original hypothesis posed that gains in muscle and losses in body fat would only be observed in the JL, and therefore our results possibly obscure the training effect we expected from the jump-landing programme. However, activity questionnaires completed at each testing session (3-monthly intervals), showed that physical activity levels (walking, cycling and resistance training) had increased substantially from baseline for the CON and may explain the changes observed. We concluded that sharing DEXA body composition results with the participants (both JL and CON) during the study period, whilst potentially helpful in improving study adherence, was a limitation to the study design with participants stating this increased their motivation to make positive lifestyle changes. Interestingly, although improvements in body composition were observed for the CON, their increased participation in non-weight bearing exercise did not translate into gains in BMD. In addition, the initial assignment of some participants to either group (JL or CON) based on their choice, may be need to be considered when interpreting the findings from this study. This limitation is acknowledged by using a controlled trial experimental design, as the primary focus was to determine the “true effect” of the mechanical stimulus provided by the jump-landing programme, which required long-term adherence.

The jump-landing programme utilised in the current study was specific to the lower extremities, with a primary target on the femoral neck and lumbar spine regions. As musculoskeletal adaptations are specific to the areas where the stimulus is applied, future research is required to quantify a series of exercises (e.g. upper body) which can be utilised in a total body osteogenic programme. This will require further investigation into ways to incorporate the use of reactive forces, utilised in the current study, to be applied to the upper body. In addition, researchers have suggested that once participants stop performing the jumps regularly and the osteogenic thresholds are no longer achieved, bone gains will regress back to baseline (Winters & Snow, 2000). Thus, future studies are required to gain a better understanding about how to achieve long-term bone adaptations, maintenance of bone gains and the time-course of reversibility.

8.6 Conclusion

To the authors knowledge, this is the first study to assess the effect of a 12-month periodised and quantified osteogenic exercise programme using low repetition, rapid-onset, high-intensity jumps offering unusually distributed strains, and utilising a repeated jump-landing technique. This study has shown that a brief (2 - 3 minute) jump programme, with a specific focus on the jump-landing technique has been shown to easily achieve the osteogenic thresholds for magnitude and rate (>3 BW and >43BW·s) required to stimulate bone at clinically relevant sites (Clissold et al., 2018). Thus, it can be concluded that such preventative interventions which are cost-effective and easily implemented in the home setting represent a “window of opportunity” for premenopausal women to prevent or delay the time before the fracture threshold is surpassed in the postmenopausal years. In addition to improving overall bone health during a life-stage normally associated with progressive bone losses, the regular performance of jump-landings with a reactive component may also contribute to a reduced falls risk by improving muscle strength and reactive muscle qualities.

CHAPTER 9. SUMMARY, PRACTICAL APPLICATIONS, LIMITATIONS, FUTURE RESEARCH DIRECTIONS AND CONCLUSIONS

9.1 Summary

The overarching question of this thesis was "Can a periodised osteogenic jump-landing programme improve bone health, body composition and performance parameters in premenopausal women"? To answer this question, three main areas were investigated: 1) What are the effects of instruction, jump type and jump-landing techniques on ground reaction forces for a selection of bilateral and unilateral jumps, whilst utilising a reactive jump, across all planes of motion? 2) Can a periodised osteogenic jump-landing programme be developed specifically for premenopausal women based on quantified jump-landings? And, 3) What are the chronic effects of a periodised osteogenic jump-landing programme on bone health, body composition and performance parameters in premenopausal women.

The basis for the overarching question was formulated and guided by gaps identified in the literature. Specifically: 1) no study had quantified the full spectrum of ground reaction forces associated with jump-landings for a selection of bilateral and unilateral vertical and multidirectional jumps in premenopausal women; 2) no study had investigated the use of reactive jump-landings to optimise the osteogenic stimulus for jump-landings when performed by premenopausal women.; 3) no study had attempted to develop a quantified 12-month periodised osteogenic jump-landing programme to be specifically utilised by premenopausal women to improve bone health; and, 4) no study had investigated the chronic effects of a 12-month periodised osteogenic jump-landing programme on functional performance parameters, body composition and bone remodelling at clinically relevant sites in premenopausal women. Therefore, addressing these gaps in the literature has provided the foundation for this thesis.

From Chapter 2 it was apparent that very little research had investigated the factors that influence jump-landing ground reaction forces in premenopausal women. The main jumping and jump-landing factors deemed important in achieving greater GRFs included the cueing of participants to; (i) use a vigorous arm swing in a "countermovement" style; and, (ii) 'land stiffly' and 'immediately jump again for maximal height' (reactive jump). However, a clear understanding about these variables had yet to be established. With these instructions provided, GRF's for all CMJ and DJ jump-landings for magnitude (4.6 to 5.5 BW's) and rate of strain (264 to 359 BW·s^{-1}), easily exceeded the previously defined vertical osteogenic thresholds (>3 BW's and 43 BW·s^{-1}), shown to improve bone mass at clinically relevant sites for premenopausal women (Chapter 3). In addition, we observed greater magnitudes and rates of GRF's (ES = 0.22 to 0.42), for jump-landings performed with 'instruction withdrawn', one week later after only one instructed jump-landing session. As mean values for peak landing forces of both jump-landings in this study were substantially higher than the values previously reported for this type of jump in the same population, it would seem that the jumping and jump-landing techniques utilised in our study significantly influenced this aspect of force production. As the focus of jump-landing forces had been in the vertical direction only, the quantification of multiplanar jumps across all planes of motion required investigation.

From the findings in Chapter 4, GRF's for all jump-landings for the star jump and stride jump easily achieved the previously defined vertical osteogenic thresholds, for magnitude (3.87 to 5.33 BW's) and rate of strain (192 to 329 BW·s^{-1}), respectively. Significantly greater forces were observed in the second jump-landing (post-reactive jump), for the majority of the force variables measured in all force axes (↑11% to ↑49%), for both the star and stride jump. Although vertical landing forces were similar for both jumps, substantially different medio-lateral (↑85% to ↑466%, for star jump) and anterio-posterior (↑103% to ↑316%, for stride jump), GRF's were observed between the jumps. The multidirectional nature of these jumps presented an opportunity to maintain and enhance mechanical bone stimulation after the bone becomes saturated to vertical loading cycles, however this is poorly understood for unilateral jump-landings.

Chapter 5 was the first study to report GRF's across all planes of motion associated with multiplanar hop-landings in premenopausal women. Our results showed that when instructed to land 'stiffly', and to utilise a flat-footed ground contact, the multiplanar hop-landings (4.17 to 5.12 BW's, and 239 to 334 BW·s^{-1}), easily exceeded osteogenic thresholds for GRF magnitude and rate, previously established using bilateral jump-landings. As we expected, significant differences in jump-landing forces were observed for the hops based on directional focus including; highest vertical GRF's for the vertical hop (↑10% to ↑92%, compared to lateral and forward), highest posterior GRF's for the lateral and forward hop (↑71% and ↑69%, compared to the vertical hop), and higher lateral GRF's were observed for the lateral hop and vertical hop (↑35% and ↑42%, compared to the forward hop).

Chapter 6 was the first study to utilise kinetic data, previously quantified for a selection of bilateral and unilateral jumps (Chapters 3 - 5), to develop a 12-month periodised osteogenic jump-landing programme for premenopausal women. The data was organised into a bone-specific 'stress stimulus rating' based on GRF magnitude (>3BW), GRF rate (>43 BW·s^{-1}), and technical difficulty (i.e. vertical bilateral to multiplanar unilateral) in a progressive manner over a 12-month period. We demonstrated the effectiveness of repeated or reactive jump-landings to increase GRF's (magnitude and rate), thus provided instruction for "stiff" and "flat-footed" jump-landings and cued participants to 'jump immediately after the initial jump-landing', for bilateral jumps. The 12-month periodised osteogenic jump-landing programme was defined by; a limited number of ground contacts per session (< 50 per session), rest intervals inserted between each jump (15 seconds), and adequate recovery between daily (3 - 5 times per week) sessions (at least 24 hours).

While the first four studies (Chapters 3 - 6) in this thesis provided insight into the development of a periodised osteogenic jump-landing programme specifically designed for premenopausal women, no evidence currently existed as to the effectiveness of such a programme. The chronic findings for Chapter 8 have clearly shown that a brief (2 - 3 minute) jump programme, with a specific focus on the jump-landing technique has provided the required stimulus to improve bone at clinically relevant sites. Generally, women experience bone losses of approximately 1% per year after the fourth decade of life, however our jump participants (versus control group) increased BMD (↑0.41 to ↑3.44% versus ↓0.12 to ↓0.15%) and BMC (↑2.61 to ↑3.72% versus ↑1.26% to ↓0.11%) at the femoral neck, total hip and lumbar spine (L1 - L4). In addition, the jump group improved bone geometry variables, at the narrow neck (narrowest section of the femoral neck) in comparison with the control group (↑2.78 to ↑3.78% versus ↑0.84 to ↓0.64%). Furthermore, moderate body fat percentage losses were observed in both the jump and control group (↓13.8% versus ↓9.56%; ES = -0.68 and -0.52), with all participants experiencing small increases in fat free mass (↑5.44% and ↑4.63%, ES = 0.43 and 0.32). The excellent test-retest reliability demonstrated for BMD, BMC, bone geometry and body composition provided the ability to determine that the changes we detected over time were statistically and clinically significant (Chapter 7).

9.2 Practical Applications

The following practical applications have been developed from the research in this thesis:

1) Jumping and hopping are valuable exercises which can be used for improving bone health in premenopausal women.

2) Jumping and hopping, when performed regularly, can be considered as possible non-pharmacologic alternatives to help prevent and delay osteoporosis in premenopausal women.

3) Jump-landing technique is a major factor that can influence the osteogenic effectiveness of jump-landings. To maximise the osteogenic training stimulus clients should be instructed to land stiffly with minimal flexion at the hip, knees, ankle and foot (i.e. flat foot landing).

4) To further enhance landing forces for bilateral jumps (CMJ, DJ, SJ and SDJ) clients should be instructed to perform a repeated jump-landing (a reactive jump). Providing instruction for the first jump-landing (i.e. think of the ground as a hot plate) to ‘jump immediately after the initial jump-landing’ (a “reactive jump”), will cause the participant to flex minimally upon landing and push off quickly thereafter.

5) To maximise jump height, jump-landing impact forces, and consequently the osteogenic potential of the exercise, clients should be instructed to use a vigorous arm swing in a “countermovement” style.

6) To maintain and enhance mechanical bone stimulation after the bone becomes saturated to vertical loading cycles, we recommend that multiplanar jumps and hops (i.e. star jump, forward hop) should be utilised. This has implications for osteogenic programme design in terms of clustering of jumps to enhance mechanosensitivity and for long-term adaptation to the jump-landing stimulus.

7) We recommend that clients are provided initial instruction for how to perform the jump-landing technique we have utilised in our research. Instructions such as to "land stiffly", "flat-footed" and to "minimise ground contact" between jump-landings can help participants to optimise GRF's and achieve similar or greater jump-landing forces one week after only one instructed session. We proposed that this was due to learning or practice effects, which has clinical implications for an osteogenic jump-landing programme being delivered in an unsupervised setting.

8) Jumping and hopping exercises which achieve the osteogenic thresholds for landing forces (magnitude and rate) need to be organised and periodised when programming for chronic adaptation in premenopausal women. Factors to be considered to determine how the jumps would be introduced and clustered within a 12-month periodised osteogenic jump-landing programme include; GRF magnitude, GRF rate, GRF direction and technical difficulty (i.e. bilateral to unilateral).

9) Multidirectional hops, such as those utilised in our research, may require pre-conditioning exercises, and the performance of bilateral jump-landings first, as part of a periodised osteogenic programme designed to safely optimise the impact stimulus required to promote bone formation in premenopausal women.

10) We recommend the completion of an 'introductory' progressive weight-bearing programme (4-weeks), which includes strength and balance, for adequate preparation of untrained individuals to be able to tolerate the stresses involved with jump-landings, to maximise the benefits to bone health and reduce any risk of injury.

11) A jump-landing programme needs to be designed to load and progress participants within the jump-landing programme according to several factors including; strength,

balance, movement and technical proficiency, fitness level, injury status and comfort, to maximise potential for adaptation and minimise risk of injury.

12) To maximise the osteogenic potential of jump-landing exercises, we recommend less than 50 repetitions of loading in one session, with a 15 - 30 second rest interval inserted between short sets of jumps and 24 hours between jumping sessions. We also suggested participants should perform the 2 - 3minute jump-landing programme at least three times per week.

13) We recommended that all jumps should be performed in the barefooted condition on a firm surface such as a firm mat, carpeted floor or grass, however further research is required in this area.

9.3 Limitations and Delimitations

Some of the limitations and delimitations of the work in this thesis are acknowledged.

1) Osteogenic thresholds for jump-landing GRF's (>3BW's and >43BW·s^{-1}, magnitude and rate of strain, respectively), have been previously determined based on gains in bone mass observed in premenopausal women. Currently only a small number of studies have explored bone health in premenopausal women, therefore a limitation exists for the use of these thresholds.

2) Given that the existing literature documenting vertical jump-landing impact forces for premenopausal women provided a variety of different instructions for arm swing and effort during jumping, and little if any focus on jump-landing technique, it was difficult to make comparisons between the studies reviewed.

3) Many different methods have been developed to calculate rate of force production, and thus a factor which must be acknowledged in terms of the validity of comparison with osteogenic thresholds. We chose to use the calculation method described by Bassey et al. (1998), to enable comparisons to be made to the osteogenic thresholds defined by these researchers using premenopausal women.

4) We observed significantly greater landing forces for the second jump-landing (post-reactive jump), for most of the force variables measured using bilateral jumps (CMJ, DJ, SJ and SDJ). However, we acknowledge that by not collecting single jump-landing GRF data, provided a limitation to the interpretation of our findings.

5) Although we were unable to establish a significant effect for 'Instruction' on jump-landing forces after one week, there were indications that 'Instruction' and test-retest effects may have had some influence on vertical and resultant forces. Non-significant increases in these forces were measured with 'Instruction withdrawn'. In light of these observations, it may have been of value to have carried out additional retesting sessions to determine the effect of the 'instruction withdrawn' condition on jump-landing forces after longer periods of time (i.e. 1 month).

6) Although it was observed that greater forces were associated with the second jump-landing for all bilateral jumps, we were unable to clarify the mechanism responsible as this would have required videography, which was not utilised in this study.

7) This is the first research in this area to have presented jump-landing forces across all planes of motion, thus a limitation exists as to the interpretation of the multiplanar force data and the contribution of each vector to the overall osteogenic stimulus for bone. As clinical data reporting force thresholds required to increase BMD are typically in the vertical direction only, it is therefore unknown whether the same conclusion can be drawn from the resultant, medio-lateral and anterio-posterior forces without further research.

8) We utilised a longitudinal quasi-randomised controlled trial experimental design to determine the effects of our 12-month jump-landing programme on measurements of bone health in premenopausal women. This meant participants were assigned to either the jump or control group based on their choice and willingness to participate in the daily jump-landing programme (in their own homes), and to attend jump-landing group classes regularly. Although this experimental design may be considered a limitation, as participants were not randomised using a blinded or double-blinded method, such a design was deemed necessary to improve the adherence to the jump-landing training programme (Winters-Stone & Snow, 2006) and to determine if the jump-landing programme could be successful in an unsupervised context.

9) Limitations exist for using a two-dimensional imaging technique to assess a three-dimensional structure, however the hip structural analysis software (HSA) utilised in this study provided an opportunity to assess variables used to describe aspects of bone geometry, which translate to the overall strength and fracture resistance of bone.

10) Other technologies such as computerised tomography (CT) and quantitative computed tomography (QCT) are considered a more accurate method of representing the three-dimensional structure of bone, however these deliver the equivalent of two years of background radiation per scan, compared to only three hours for bone densitometry (DEXA) thus the reason for using DEXA in our design.

11) We observed increases in bone geometry variables at the narrow neck (narrowest section of the femoral neck), including; cross-sectional area, cortical thickness and section modulus (a measure of bone stiffness closely related to the bending and torsional strength of bone) using HSA technology. However, a limitation exists for the interpretation of this data, as to our knowledge, only one study has utilised HSA or 3-dimensional bone scans in their description of overall bone strength, for premenopausal women. In addition, there is currently an absence of normative data or value thresholds identified for bone geometry measurements for this specific population.

12) Although researchers have previously examined the reliability of DEXA technology, most have only reported coefficients of variation (CV's). In addition, these values of absolute consistency (CV's) have only been presented for BMD at the femoral neck and lumbar spine, with most studies failing to report any consistency values for bone mineral content (BMC), hip structural analysis or body composition. Although we presented a full understanding of the variability associated with DEXA measurements of interest for premenopausal women, we were limited in our interpretation of our precision error values for these variables in the absence of acceptable precision ranges for this population.

13) Although we conducted a reliability study for the AMTI Accusway balance force plate (Appendix 20), to provide focus on the variables we could use in our training intervention, we acknowledge there were limitations to the methodology we utilised for this purpose. Although our within-trial reliability study provided focus for the

measures that were reliable within-trial, we recognise that we did not conduct the testing methodology required to determine test-retest reliability for these balance variables.

14) Interestingly, no significant main effects were found for balance measures (i.e. path length, and average sway velocity) between the groups. It may be that the use of the static single-legged balance test we utilised in this study is a limitation, and may not have captured the potential coordinative adaptations resulting from the dynamically applied jump-landing programme.

15) To determine the clinical significance of small changes in BMD to overall bone strength, we developed modified effect sizes (ES = mean change/standard deviation of the sample scores). We used ratios of 0.10 - 0.19, 0.20 - 0.29, ≥ 0.30 which indicated small, moderate and large changes, respectively, to calculate and determine the magnitude of change of bone from baseline to 12-months. The modified effect size classification was calculated based on significant improvements (ES = 0.15 to 0.26) on BMD previously reported in this population (Bassey et al., 1998; Vainionpää et al., 2005; Winters-Stone & Snow, 2006). We acknowledge that this classification is new and further research is required to establish validity and utility in this population.

16) We concluded that sharing DEXA body composition results with the participants (both groups) during the 12-month study period, whilst potentially helpful in improving study adherence, was a limitation to the study design with participants stating this increased their motivation to make positive lifestyle changes.

9.4 Directions for Future Research

The findings from this research have highlighted several considerations for future research:

1) Although osteogenic thresholds (GRF magnitude and rate) are useful for describing effective jump-landing intensities, the variability that exists between individuals when determining a safe effective dose of impact exercise requires further investigation.

2) Researchers have predominantly focused on minimising bone losses in “high risk” postmenopausal women and as a consequence, exercise recommendations to improve bone health in adults are generic and lack specific recommendations for women before they experience the accelerated bone losses at menopause. Further research is required to determine optimal exercise recommendations to improve bone health across all life-stages, including specific guidelines for males.

3) To the authors knowledge, this is the first periodised osteogenic jump-landing programme designed specifically for premenopausal women. Although this research provides a strong foundation for bone specific programming with consideration to specific training principles i.e. progressive overload, novel stress and technical progression, continued research in this area is warranted to continue to optimise the programme design for this ‘at risk’ population.

4) As musculoskeletal adaptations are specific to the areas where the stimulus is applied, future research is required to quantify a series of exercises (e.g. upper body) which can be utilised in a total body osteogenic programme. This will require future biomechanical investigation into ways to incorporate the use of reactive forces, utilised in the current study, to be applied to the upper body.

5) We recommend that future research using DEXA technology should provide precision error values for BMC, HSA and body composition, to enable acceptable precision ranges to be established for this population.

6) We also recommend that future research using DEXA technology should provide test-retest reliability values for relative (ICC’s) and absolute (CV’s) consistency values for BMD, BMC, HSA and body composition, for studies using premenopausal women.

7) Researchers have suggested that once participants stop performing the jumps regularly and the osteogenic thresholds are no longer achieved, bone gains will regress back to baseline. Future studies are required to gain a better understanding about how to achieve long-term bone adaptations, maintenance of bone gains and the time-course of reversibility.

8) Researchers should investigate the long-term chronic adaptations associated with performing a periodised osteogenic jump-landing programme using larger cohorts of women of different ages and representing different ethnic groups. These studies need to be implemented for at least 12-months and should incorporate exercises targeting all clinically relevant bone sites (hip, lumbar spine and radius). Such studies would build on the findings of this research and provide health providers and practitioners with an evidence base on the long-term benefits of performing these jump-landings to enhance bone health for everybody at every stage of life.

9) We have already shown that our periodised osteogenic jump-landing programme positively influences markers of bone health, in pre-menopausal women in a clinical setting. Future research is required to determine efficacy and scalability of this programme across the age span in females in multiple community settings, by designing resources and systems to engage and improve adherence to a preventative health intervention. Therefore, the effects of specifically designed website and app resources for improving functional performance parameters, falls risk predictors, body composition and bone remodelling at clinically relevant sites among women during various life stages (i.e. adolescent, young adult, pre- and post-menopausal) is warranted.

9.5 Conclusions

This thesis provides original academic research into the use of specific jump-landings as an effective way to improve bone health and contribute to the field of preventative health care. It is important that clinicians, physical therapists, strength and conditioning practitioners and the general population are informed about scientific evidence describing the benefits and potential risks associated with performing jumping and hopping exercises to improve bone health in premenopausal women. Furthermore, we recommend that serious recommendation needs to be given for implementing such a programme as we have described for premenopausal women, across all life-stages, with consideration for the earlier the better.

REFERENCES

REFERENCES

Alfredson, H., Nordstrom, P., & Lorentzon, R. (1997). Bone mass in female volleyball players: a comparison of total and regional bone mass in female volleyball players and nonactive females. *Calcif Tissue Int, 60*(4), 338-342.

Allison, S. J., Folland, J. P., Rennie, W. J., Summers, G. D., & Brooke-Wavell, K. (2013). High impact exercise increased femoral neck bone mineral density in older men: a randomised unilateral intervention. *Bone, 53*(2), 321-328. doi: 10.1016/j.bone.2012.12.045

Allison, S. J., Poole, K. E., Treece, G. M., Gee, A. H., Tonkin, C., Rennie, W. J., . . . Brooke-Wavell, K. (2015). The Influence of High-Impact Exercise on Cortical and Trabecular Bone Mineral Content and 3D Distribution Across the Proximal Femur in Older Men: A Randomized Controlled Unilateral Intervention. *J Bone Miner Res, 30*(9), 1709-1716. doi: 10.1002/jbmr.2499

Ammann, P., & Rizzoli, R. (2003). Bone strength and its determinants. *Osteoporos Int, 14 Suppl 3*, S13-18. doi: 10.1007/s00198-002-1345-4

Ashley, C. D., & Weiss, L. W. (1994). Vertical jump performance and selected physiological characteristics of women. *Journal of Strength & Conditioning Research, 8*(1), 5-11.

Asikainen, T. M., Kukkonen-Harjula, K., & Miilunpalo, S. (2004). Exercise for health for early postmenopausal women: a systematic review of randomised controlled trials. *Sports Med, 34*(11), 753-778.

Babatunde, O. O. (2013). Primary Prevention of Osteoporosis: Time to Redefine the Wheel? *Journal of Osteoporosis & Physical Activity, 2*(1). doi: http://dx.doi.org/10.4172/2329-9509.1000e107

Babatunde, O. O., & Forsyth, J. J. (2013). Effects of lifestyle exercise on premenopausal bone health: a randomised controlled trial. *Journal of Bone and Mineral Metabolism*, 1-10. doi: 10.1007/s00774-013-0527-9

Babatunde, O. O., Forsyth, J. J., & Gidlow, C. J. (2012). A meta-analysis of brief high-impact exercises for enhancing bone health in premenopausal women. *Osteoporosis International, 23*(1), 109-119. doi: http://dx.doi.org/10.1249/01.MSS.0000355432.86381.ac
http://dx.doi.org/10.1007/s00198-011-1801-0

Bailey, C. A., & Brooke-Wavell, K. (2008). Exercise for optimising peak bone mass in women. *The Proceedings of the Nutrition Society, 67*(1), 9-18. doi: 10.1017/S0029665108005971

Bailey, C. A., & Brooke-Wavell, K. (2009). Daily exercise is most effective for increasing hip bone mineral density: A randomized high-impact, unilateral intervention. *Bone, 44, Supplement 1*(0), S100-S101. doi: http://dx.doi.org/10.1016/j.bone.2009.01.219

Bailey, C. A., & Brooke-Wavell, K. (2010a). Association of body composition and muscle function with hip geometry and BMD in premenopausal women. *Annals of Human Biology, 37*(4), 524-535.

Bailey, C. A., & Brooke-Wavell, K. (2010b). Optimum frequency of exercise for bone health: Randomised controlled trial of a high-impact unilateral intervention. *Bone, 46*(4), 1043-1049. doi: http://dx.doi.org/10.1016/j.bone.2009.12.001

Ban, K.-M. (2009). Concluding remarks at Forum on Global Health. United Nations News Centre.

Bassey, E. J., Littlewood, J. J., & Taylor, S. J. G. (1997). Relations between compressive axial forces in an instrumented massive femoral implant, ground reaction forces, and integrated electromyographs from vastus lateralis during various 'osteogenic' exercises. *Journal of Biomechanics, 30*(3), 213-223. doi: http://dx.doi.org/10.1016/S0021-9290(96)00043-7

Bassey, E. J., & Ramsdale, S. J. (1994). Increase in femoral bone density in young women following high-impact exercise. *Osteoporosis International, 4*(2), 72-75. doi: 10.1007/BF01623226

Bassey, E. J., & Ramsdale, S. J. (1995). Weight-bearing exercise and ground reaction forces: A 12-month randomized controlled trial of effects on bone mineral density in healthy postmenopausal women. *Bone, 16*(4), 469-476. doi: http://dx.doi.org/10.1016/8756-3282(95)90193-0

Bassey, E. J., Rothwell, M. C., Littlewood, J. J., & Pye, D. W. (1998). Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *Journal of Bone and Mineral Research, 13*(12), 1805-1813. doi: 10.1359/jbmr.1998.13.12.1805

Beck, B. R., Daly, R. M., Singh, M. A. F., & Taaffe, D. R. (2017). Exercise and Sports Science Australia (ESSA) position statement on exercise prescription for the prevention and management of osteoporosis. *Journal of Science and Medicine in Sport, 20*(5), 438-445. doi: http://dx.doi.org/10.1016/j.jsams.2016.10.001

Beck, T. J., Ruff, C. B., Warden, K. E., Scott, W. W. J., & Rao, G. U. (1990). Predicting femoral neck strength from bone mineral data: A structural approach. *Investigative Radiology, 25*(1), 6-18.

Black, D. M., Delmas, P. D., Eastell, R., Reid, I. R., Boonen, S., Cauley, J. A., . . . Cummings, S. R. (2007). Once-Yearly Zoledronic Acid for Treatment of Postmenopausal Osteoporosis. *The New England Journal of Medicine, 356*(18), 1809-1822.

Bobbert, M. F., Gerritsen, K. G. M., Litjens, M. C. A., & Van Soest, A. J. (1996). Why is countermovement jump height greater than squat jump height? . *Medicine & Science in Sports & Exercise, 28*(11), 1402-1412.

Bobbert, M. F., Huijing, P. A., & Van Ingen Schenau, G. J. (1987). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine & Science in Sports & Exercise, 19*(4), 332-338.

Bobbert, M. F., Mackay, M., Schinkelshoek, D., Huijing, P. A., & van Ingen Schenau, G. J. (1986). Biomechanical analysis of drop and countermovement jumps. *Eur J Appl Physiol Occup Physiol, 54*(6), 566-573.

Bompa, T. O., & Haff, G. G. (2009). *Periodization: Theory and methodology of training*: Human Kinetics Publishers.

Borga, M., West, J., Bell, J. D., Harvey, N. C., Romu, T., Heymsfield, S. B., & Dahlqvist Leinhard, O. (2018). Advanced body composition assessment: from body mass index to body composition profiling. *Journal of Investigative Medicine, 66*(5), 1. doi: 10.1136/jim-2018-000722

Branski, L. K., Norbury, W. B., Herndon, D. N., Chinkes, D. L., Cochran, A., Suman, O., . . . Jeschke, M. G. (2010). Measurement of body composition in burned children: is there a gold standard? *JPEN. Journal of parenteral and enteral nutrition, 34*(1), 55-63. doi: 10.1177/0148607109336601

Brown, P., McNeill, R., Leung, W., Radwan, E., & Willingale, J. (2011). Current and Future Economic Burden of Osteoporosis in New Zealand. *Applied Health Economics and Health Policy, 9*(2), 111-123.

Burr, D. B. (2003). Introduction - Bone turnover and fracture risk. *Journal of Musculoskeletal and Neuronal Interactions, 3*(4), 408-409.

Burr, D. B. (2011). Why bones bend but don't break. *J Musculoskelet Neuronal Interact, 11*(4), 270-285.

Burr, D. B. (2015). The complex relationship between bone remodeling and the physical and material properties of bone. *Osteoporosis International, 26*(3), 845-847. doi: 10.1007/s00198-014-2970-4

Calcium. (2014, 2014). *Nutrient Reference Values for Austrailia and New Zealand* 2019, from https://www.nrv.gov.au/nutrients/calcium

Cheng, X. G., Lowet, G., Boonen, S., Nicholson, P. H., Brys, P., Nijs, J., & Dequeker, J. (1997). Assessment of the strength of proximal femur in vitro: relationship to femoral bone mineral density and femoral geometry. *Bone, 20*(3), 213-218.

Chopin, F., Biver, E. A. B., Funck-Brentano, T., Bouvard, B., Coiffier, G., Garnero, P., & Thomas, T. (2012). Prognostic interest of bone turnover markers in the management of postmenopausal osteoporosis. *Joint Bone Spine, 79*(1), 26-31. doi: http://dx.doi.org/10.1016/j.jbspin.2011.05.004

Christgau, S., Bitsch-Jensen, O., Hanover Bjarnason, N., Gamwell Henriksen, E., Qvist, P., Alexandersen, P., & Bang Henriksen, D. (2000). Serum CrossLaps for monitoring the response in individuals undergoing antiresorptive therapy. *Bone, 26*(5), 505-511. doi: http://dx.doi.org/10.1016/S8756-3282(00)00248-9

Chubb, S. A. P. (2012). Measurement of C-terminal telopeptide of type I collagen (CTX) in serum. *Clinical Biochemistry, 45*(12), 928-935. doi: http://dx.doi.org/10.1016/j.clinbiochem.2012.03.035

Clarke, B. (2008). Normal Bone Anatomy and Physiology. *Clinical Journal of the American Society of Nephrology, 3*(Supplement 3), S131-S139. doi: 10.2215/cjn.04151206

Clissold, T. L., Cronin, J. B., De Souza, M. J., Wilson, D., & Winwood, P. W. (2019). Bilateral multidirectional jumps with reactive jump-landings achieve osteogenic thresholds with and without instruction in premenopausal women. *Clin Biomech (Bristol, Avon), 73*, 1-8. doi: 10.1016/j.clinbiomech.2019.12.025

Clissold, T. L., Winwood, P. W., Cronin, J. B., & De Souza, M. J. (2018). Do Bilateral Vertical Jumps With Reactive Jump Landings Achieve Osteogenic Thresholds With and Without Instruction in Premenopausal Women? *Journal of Applied Biomechanics, 34*(2), 118-126. doi: 10.1123/jab.2017-0114

Clowes, J. A., Hannon, R. A., Yap, T. S., Hoyle, N. R., Blumsohn, A., & Eastell, R. (2002). Effect of feeding on bone turnover markers and its impact on biological variability of measurements. *Bone, 30*(6), 886-890. doi: http://dx.doi.org/10.1016/S8756-3282(02)00728-7

Cohen, J. (1988). *Statistical power analysis for the behavioural science.* Hillside, New Jersey: Lawrence Erlbaum Associates.

Compston, J. E. (2001). Sex steroids and bone. *Physiological Reviews, 81*(1), 419-447.

. Consensus development conference: Diagnosis, prophylaxis, and treatment of osteoporosis. (1993) *Am J Med* (Vol. 94, pp. 646-650).

Copeland, J. L., Chu, S. Y., & Tremblay, M. S. (2004). Aging, physical activity, and hormones in women - a review. *Journal of Aging & Physical Activity, 12*(1), 101-116.

Dahlman-Wright, K., Cavailles, V., Fuqua, S. A., Jordan, V. C., Katzenellenbogen, J. A., Korach, K. S., . . . Gustafsson, J.-Å. (2006). International Union of Pharmacology. LXIV. Estrogen Receptors. *Pharmacological Reviews, 58*(4), 773-781. doi: 10.1124/pr.58.4.8

Davies, G., Riemann, B. L., & Manske, R. (2015). CURRENT CONCEPTS OF PLYOMETRIC EXERCISE. *International Journal of Sports Physical Therapy, 10*(6), 760-786.

de Papp, A. E., Bone, H. G., Caulfield, M. P., Kagan, R., Buinewicz, A., Chen, E., . . . Reitz, R. E. (2007). A cross-sectional study of bone turnover markers in healthy premenopausal women. *Bone, 40*(5), 1222-1230. doi: http://dx.doi.org/10.1016/j.bone.2007.01.008

De Souza, M. J., West, S. L., Jamal, S. A., Hawker, G. A., Gundberg, C. M., & Williams, N. I. (2008). The presence of both an energy deficiency and estrogen deficiency exacerbate alterations of bone metabolism in exercising women. *Bone, 43*(1), 140-148. doi: 10.1016/j.bone.2008.03.013

de Vreede, P. L., Samson, M. M., van Meeteren, N. L. U., Duursma, S. A., & Verhaar, H. J. J. (2005). Functional-task exercise versus resistance strength exercise to improve daily function in older women. *Journal of the American Geriatrics Society, 53*(1), 2-10. doi: 10.1111/j.1532-5415.2005.53003.x

Dempster, D. W., & Reeve, J. (2006). The development of parathyroid hormone as anabolic therapy for osteoporosis. *Clinical Reviews in Bone and Mineral Metabolism, 4*(4), 227-231. doi: 10.1385/BMM:4:4:227

Drake, M. T., Clarke, B. L., & Lewiecki, E. M. (2015). The Pathophysiology and Treatment of Osteoporosis. *Clin Ther, 37*(8), 1837-1850. doi: https://doi.org/10.1016/j.clinthera.2015.06.006

Dreyer, P., & Viera, J., G., H. (2010). Bone turnover assessment: a good surrogate marker? *Brazilian Archives of Endocrinology and Metabolism, 54*(2), 99-105.

Duque, G. (2013). Osteoporosis in older persons: current pharmacotherapy and future directions. *Expert Opinion on Pharmacotherapy, 14*(14), 1949-1958. doi: doi:10.1517/14656566.2013.822861

Eastell, R., Jacques, R., & Naylor, K. (2012). Monitoring anti-resorptive treatments for osteoporosis using bone turnover markers. *IBMS BoneKEy, 9*.

Ebben, W. P., Fauth, M. L., Kaufmann, C. E., & Petushek, E. J. (2010). Magnitude and Rate of Mechanical Loading of a Variety of Exercise Modes. *Journal of Strength and Conditioning Research, 24*(1), 213-217. doi: 10.1519/JSC.0b013e3181c27da3

Ebeling, P., Daly, R. M., Kerr, D. A., & Kimlim, M. G. (2013). Building healthy bones throughout life: An evidence-informed strategy to prevent osteoporosis in Australia. *Medical Journal of Australia, 2*(Supplement 1). doi: 10.5694/mjao12.11363

Ekdahl, C., Jarnlo, G. B., & Andersson, S. I. (1989). Standing balance in healthy subjects. Evaluation of a quantitative test battery on a force platform. *Scand J Rehabil Med, 21*(4), 187-195.

Emery, C. A. (2003). Is there a clinical standing balance measurement appropriate for use in sports medicine? A review of the literature. *Journal of Science and Medicine in Sport, 6*(4), 492-504. doi: https://doi.org/10.1016/S1440-2440(03)80274-8

Enderlein, G. (1988). Fleiss, J. L.: The Design and Analysis of Clinical Experiments. Wiley, New York – Chichester – Brislane – Toronto – Singapore 1986, 432 S., £38.35. *Biometrical Journal, 30*(3), 304-304. doi: 10.1002/bimj.4710300308

Erickson, C. R., & Vukovich, M. D. (2010). Osteogenic Index and changes in bone markers during a jump training program: A pilot study. *Medicine & Science in Sports & Exercise, 42*(8), 1485-1492.

Fleck, S. J., & Kraemer, W. (2014). *Designing Resistance Training Programs, 4E*: Human Kinetics.

Frost, H. M. (1987). Bone "mass" and the "mechanostat": A proposal. *The Anatomical Record, 219*(1), 1-9. doi: 10.1002/ar.1092190104

Frost, H. M. (1992). Perspectives: The role of changes in mechanical usage set points in the pathogenesis of osteoporosis. *Journal of Bone and Mineral Research, 7*(3), 253-261. doi: 10.1002/jbmr.5650070303

Frost, H. M. (2003). Bone's mechanostat: A 2003 update. *The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology, 275A*(2), 1081-1101. doi: 10.1002/ar.a.10119

Gallagher, J. C., & Tella, S. H. (2013). Prevention and treatment of postmenopausal osteoporosis. *The Journal of Steroid Biochemistry and Molecular Biology*(0). doi: http://dx.doi.org/10.1016/j.jsbmb.2013.09.008

Garnero, P., Sornay-Rendu, E., Claustrat, B., & Delmas, P. D. (2000). Biochemical Markers of Bone Turnover, Endogenous Hormones and the Risk of Fractures in Postmenopausal Women: The OFELY Study. *Journal of Bone and Mineral Research, 15*(8), 1526-1536. doi: 10.1359/jbmr.2000.15.8.1526

Gass, M. L. M. D. B. A. M. A., Kagan, R. M. D. F., Kohles, J. D. P., & Martens, M. G. M. D. (2008). Bone turnover marker profile in relation to the menstrual cycle of premenopausal healthy women. *Menopause July/August, 15*(4), 667-675.

Geusens, P., Dequeker, J., Verstraeten, A., & Nijs, J. (1986). Age-, Sex-, and Menopause-Related Changes of Vertebral and Peripheral Bone: Population Study Using Dual and Single Photon Absorptiometry and Radiogrammetry. *Journal of Nuclear Medicine, 27*(10), 1540-1549.

Glover, S. J., Garnero, P., Naylor, K., Rogers, A., & Eastell, R. (2008). Establishing a reference range for bone turnover markers in young, healthy women. *Bone, 42*(4), 623-630. doi: http://dx.doi.org/10.1016/j.bone.2007.12.218

Gomez-Cabello, A., Ara, I., Gonzalez-Aguero, A., Casajus, J. A., & Vicente-Rodriguez, G. (2012). Effects of training on bone mass in older adults: a systematic review. *Sports Med, 42*(4), 301-325. doi: 10.2165/11597670-000000000-00000

Gómez-Cabello, A., Ara, I., González-Agüero, A., Casajüs, J. A., & Vicente-Rodríguez, G. (2012). Effects of training on bone mass in older adults: A systematic review. *Sports Medicine, 42*(4), 301-325.

Greendale, G. A., Sowers, M., Han, W., Huang, M. H., Finkelstein, J. S., Crandall, C. J., . . . Karlamangla, A. S. (2012). Bone mineral density loss in relation to the final menstrual period in a multiethnic cohort: results from the Study of Women's Health Across the Nation (SWAN). *J Bone Miner Res, 27*(1), 111-118. doi: 10.1002/jbmr.534

Guadalupe-Grau, A., Fuentes, T., Guerra, B., & Calbet, J. A. L. (2009). Exercise and Bone Mass in Adults. *Sports Medicine, 39*(6), 439-468.

Haff, G. G., & Triplett, N. T. (2015). *Essentials of Strength Training and Conditioning 4th Edition*: Human kinetics.

Hahn, T., Foldspang, A., Vestergaard, E., & Ingemann-Hansen, T. (1999). One-leg standing balance and sports activity. *Scand J Med Sci Sports, 9*(1), 15-18.

Han, J., Anson, J., Waddington, G., Adams, R., & Liu, Y. (2015). The Role of Ankle Proprioception for Balance Control in relation to Sports Performance and Injury.

Hansen, K. T., Cronin, J. B., & Newton, M. J. (2011). Three methods of calculating force-time variables in the rebound jump squat. *Journal of Strength & Conditioning Research, 25*(3), 867-871.

Hart, N. H., Nimphius, S., Rantalainen, T., Ireland, A., Siafarikas, A., & Newton, R. U. (2017). Mechanical basis of bone strength: influence of bone material, bone structure and muscle action. *J Musculoskelet Neuronal Interact, 17*(3), 114-139.

He, H., Liu, Y., Tian, Q., Papasian, C. J., Hu, T., & Deng, H.-W. (2016). Relationship of sarcopenia and body composition with osteoporosis. *Osteoporosis International, 27*(2), 473-482. doi: 10.1007/s00198-015-3241-8

Heinonen, A., Kannus, P., Sievänen, H., Oja, P., Pasanen, M., Rinne, M., . . . Vuori, I. (1996). Randomised controlled trial of effect of high-impact exercise on selected risk factors for osteoporotic fractures. *The Lancet, 348*(9038), 1343-1347. doi: http://dx.doi.org/10.1016/S0140-6736(96)04214-6

Heldring, N., Pike, A., Andersson, S., Matthews, J., Cheng, G., Hartman, J. W., . . . Gustafsson, J.-A. (2007). Estrogen receptors: How do they signal and what are their targets. *Physiological Reviews, 87*(3), 905-931. doi: 10.1152/physrev.00026.2006

Hernandez, C. J., Beaupré, G. S., & Carter, D. R. (2003). A theoretical analysis of the relative influences of peak BMD, age-related bone loss and menopause on the development of osteoporosis. *Osteoporosis International, 14*(10), 843-847. doi: 10.1007/s00198-003-1454-8

Hlaing, T. T., & Compston, J. E. (2014). Biochemical markers of bone turnover – uses and limitations. *Annals of Clinical Biochemistry: An international journal of biochemistry and laboratory medicine, 51*(2), 189-202. doi: 10.1177/0004563213515190

Hoffman, M., Schrader, J., Applegate, T., & Koceja, D. (1998). Unilateral postural control of the functionally dominant and nondominant extremities of healthy subjects. *Journal of athletic training, 33*(4), 319-322.

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med, 30*(1), 1-15. doi: 10.2165/00007256-200030010-00001

Horak, F. B. (1987). Clinical measurement of postural control in adults. *Phys Ther, 67*(12), 1881-1885. doi: 10.1093/ptj/67.12.1881

Horstman, A. M., Dillon, E. L., Urban, R. J., & Sheffield-Moore, M. (2012). The role of androgens and estrogens on healthy aging and longevity. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 67*(11), 1140-1152. doi: 10.1093/gerona/gls068

Howe, T. E., Shea, B., Dawson, L. J., Downie, F., Murray, A., Ross, C., . . . Creed, G. (2011). Exercise for preventing and treating osteoporosis in postmenopausal women (Review) *Cochrane Database of Systematic Reviews* (pp. 1-160): The Cochrane Collaboration.

Hsieh, Y. F., Wang, T., & Turner, C. H. (1999). Viscoelastic response of the rat loading model: implications for studies of strain-adaptive bone formation. *Bone, 25*(3), 379-382. doi: http://dx.doi.org/10.1016/S8756-3282(99)00181-7

Ilona, I., Taina, A., Mirela, S., Eugenia, R., & Mihaela, Z. (2010). The role of high impact exercise in improve bone mineral density in postmenopausal women with osteopenia or osteoporosis. *Journal of Physical Education & Sport / Citius Altius Fortius, 27*(2), 110-115.

International Osteoporosis Foundation. (2015, January 29, 2016). National and Regional Osteoporosis Guidelines. Retrieved January 20, 2018, 2018, from https://www.iofbonehealth.org/facts-statistics

Jenkins, N., Black, M., Paul, E., Pasco, J. A., Kotowicz, M. A., & Schneider, H. G. (2013). Age-related reference intervals for bone turnover markers from an Australian reference population. *Bone, 55*(2), 271-276. doi: http://dx.doi.org/10.1016/j.bone.2013.04.003

Johnson, L. G., Kraemer, R. R., Haltom, R., Kraemer, G. R., Gaines, H. E., & Daniel C, V. (1997). Effects of estrogen replacement therapy on dehydroepiandrosterone, dehydroepiandrosterone sulfate, and cortisol responses to exercise in postmenopausal women. *Fertil Steril, 68*(5), 836-843. doi: 10.1016/s0015-0282(97)00369-5

Kanis, J. A. (2002). Diagnosis of osteoporosis and assessment of fracture risk. *The Lancet, 359*(9321), 1929-1936. doi: https://doi.org/10.1016/S0140-6736(02)08761-5

Kanis, J. A., Adachi, J. D., Cooper, C., Clark, P., Cummings, S. R., Diaz-Curiel, M., . . . IOF, Q. o. L. W. G. o. (2013). Standardising the descriptive epidemiology of osteoporosis: recommendations from the Epidemiology and Quality of Life Working Group of IOF. *Osteoporosis International, 24*(11), 2763-2764. doi: 10.1007/s00198-013-2413-7

Kanis, J. A., & Kanis, J. A. (1994). Assessment of fracture risk and its application to screening for postmenopausal osteoporosis: Synopsis of a WHO report. *Osteoporosis International, 4*(6), 368-381. doi: 10.1007/BF01622200

Kanis, J. A., McCloskey, E. V., Johansson, H., Cooper, C., Rizzoli, R., & Reginster, J. Y. (2013). European guidance for the diagnosis and management of osteoporosis in postmenopausal women. *Osteoporosis International, 24*(1), 23-57. doi: 10.1007/s00198-012-2074-y

Kaptoge, S., Beck, T. J., Reeve, J., Stone, K. L., Hillier, T. A., Cauley, J. A., & Cummings, S. R. (2008). Prediction of incident hip fracture risk by femur geometry variables measured by hip structural analysis in the study of osteoporotic fractures. *Journal of bone and mineral research : the official journal of the American Society for Bone and Mineral Research, 23*(12), 1892-1904. doi: 10.1359/jbmr.080802

Kato, T., Terashima, T., Yamashita, T., Hatanaka, Y., Honda, A., & Umemura, Y. (2006). Effect of low-repetition jump training on bone mineral density in young women. *Journal of Applied Physiology, 100*(3), 839-843. doi: 10.1152/japplphysiol.00666.2005

Kemmler, W., Engelke, K., & von Stengel, S. (2015). Long-Term Exercise and Bone Mineral Density Changes in Postmenopausal Women-Are There Periods of Reduced Effectiveness? *J Bone Miner Res*. doi: 10.1002/jbmr.2608

Kemmler, W., Engelke, K., Von Stengel, S., Weineck, J., Lauber, D., & Kalender, W. A. (2007). Long-term four year exercise has a positive effect on menopausal risk factors: The Erlangen fitness osteoporosis prevention study. *Journal of Strength & Conditioning Research, 21*(1), 232-239.

Kenkre, J. S., & Bassett, J. (2018). The bone remodelling cycle. *Ann Clin Biochem, 55*(3), 308-327. doi: 10.1177/0004563218759371

Kenny, A. M., & Prestwood, K. M. (2000). Osteoporosis. Pathogenesis, diagnosis, and treatment in older adults. *Rheum Dis Clin North Am, 26*(3), 569-591.

Khosla, S. (2010). Update on Estrogens and the Skeleton. *Journal of Clinical Endocrinology & Metabolism, 95*(8), 3569-3577. doi: 10.1210/jc.2010-0856

Kishimoto, K., Lynch, R. P., Reiger, J., & Yingling, V. R. (2012). Short-term jump activity on bone metabolism in female college-aged non-athletes. *Journal of Sports Science & Medicine, 11*(1), 31-38.

Kohrt, W. M., Barry, D. W., & Schwartz, R. S. (2009). Muscle forces or gravity: What predominates mechanical loading on bone? . *Medicine & Science in Sports & Exercise, 41*(11), 2050-2055.

Kontulainen, S., Sievanen, H., Kannus, P., Pasanen, M., & Vuori, I. (2003). Effect of long-term impact-loading on mass, size, and estimated strength of humerus and radius of female racquet-sports players: a peripheral quantitative computed tomography study between young and old starters and controls. *J Bone Miner Res, 18*(2), 352-359. doi: 10.1359/jbmr.2003.18.2.352

Kraemer, W. J., & Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Medicine & Science in Sports & Exercise, 36*(4), 674-688.

Krassas, G. E., & Papadopoulou, P. (2001). Oestrogen action on bone cells. *Journal of Musculoskeletal and Neuron Interaction 2*(2), 143-151.

Kritz, M. M. C., Cronin, J. P. H. D., & Hume, P. P. (2009). The Bodyweight Squat: A Movement Screen for the Squat Pattern. *Strength and Conditioning Journal, 31*(1), 76-85.

Kwak, S. K., & Kim, J. H. (2017). Statistical data preparation: management of missing values and outliers. *Korean journal of anesthesiology, 70*(4), 407-411. doi: 10.4097/kjae.2017.70.4.407

Langdahl, B., Ferrari, S., & Dempster, D. W. (2016). Bone modeling and remodeling: potential as therapeutic targets for the treatment of osteoporosis. *Therapeutic Advances in Musculoskeletal Disease, 8*(6), 225-235. doi: 10.1177/1759720X16670154

Lanyon, L. E. (1987). Functional strain in bone tissue as an objective, and controlling stimulus for adaptive bone remodelling. *Journal of Biomechanics, 20*(11–12), 1083-1093. doi: http://dx.doi.org/10.1016/0021-9290(87)90026-1

Lanyon, L. E. (1996). Using functional loading to influence bone mass and architecture: objectives, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. *Bone, 18*(1, Supplement 1), S37-S43. doi: 10.1016/8756-3282(95)00378-9

Lawton, B. A., Rose, S. B., Cormack, D. M., Stanley, J., & Dowell, A. C. (2008). The menopause symptom profile of Maori and non-Maori women in New Zealand. *Climacteric, 11*(6), 467-474. doi: doi:10.1080/13697130802351094

Leard, J. S., Cirillo, M. A., Katsnelson, E., Kimiatek, D. A., Miller, T. W., Trebincevic, K., & Garbalosa, J. C. (2007). Validity of two alternative systems for measuring vertical jump height. *Journal of Strength & Conditioning Research, 21*(4), 1296-1299.

Lees, A. (1981). Methods of impact absorption when landing from a jump. *Engineering in Medicine, 10*(4), 207-211. doi: 10.1243/emed_jour_1981_010_055_02

Lees, A., Vanrenterghem, J., & De Clercq, D. (2004). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics, 37*(12), 1929-1940. doi: http://dx.doi.org/10.1016/j.jbiomech.2004.02.021

Lenchik, L., Kiebzak, G. M., & Blunt, B. A. (2002). What is the role of serial bone mineral density measurements in patient management? *J Clin Densitom, 5 Suppl*, S29-38.

Leslie, W. D., Orwoll, E. S., Nielson, C. M., Morin, S. N., Majumdar, S. R., Johansson, H., . . . Kanis, J. A. (2014). Estimated lean mass and fat mass differentially affect femoral bone density and strength index but are not FRAX independent risk factors for fracture. *J Bone Miner Res, 29*(11), 2511-2519. doi: 10.1002/jbmr.2280

Lippuner, K., Johansson, H., Kanis, J. A., & Rizzoli, R. (2009). Remaining lifetime and absolute 10-year probabilities of osteoporotic fracture in Swiss men and women. *Osteoporosis International, 20*(7), 1131-1140. doi: http://dx.doi.org/10.1007/s00198-008-0779-8

Lusardi, M. M., Fritz, S., Middleton, A., Allison, L., Wingood, M., Phillips, E., . . . Chui, K. K. (2017). Determining Risk of Falls in Community Dwelling Older Adults: A Systematic Review and Meta-analysis Using Posttest Probability. *J Geriatr Phys Ther, 40*(1), 1-36. doi: 10.1519/jpt.0000000000000099

Ma, D., Wu, L., & He, Z. (2013). Effects of walking on the preservation of bone mineral density in perimenopausal and postmenopausal women: a systematic review and meta-analysis. *Menopause, 20*(11), 1216-1226. doi: 10.1097/gme.0000000000000100

Mansfield, E. M. (2006). Designing exercise programs to lower fracture risk in mature women. *Strength and Conditioning Journal, 28*(1), 24-29.

Markovic, G., Dizdar, D., Jukic, I., & Cardinale, M. (2004). Reliability and factorial validity of squat and countermovement jump tests. *Journal of Strength and Conditioning Research, 18*(3), 551-555.

Martyn-St James, M., & Carroll, S. (2008). Meta-analysis of walking for preservation of bone mineral density in postmenopausal women. *Bone, 43*(3), 521-531. doi: http://dx.doi.org/10.1016/j.bone.2008.05.012

Martyn-St James, M., & Carroll, S. (2009). A meta-analysis of impact exercise on postmenopausal bone loss: the case for mixed loading exercise programmes. *British Journal of Sports Medicine, 43*(12), 898-908. doi: 10.1136/bjsm.2008.052704

Martyn-St James, M., & Carroll, S. (2010). Effects of different impact exercise modalities on bone mineral density in premenopausal women: a meta-analysis. *Journal of Bone and Mineral Metabolism, 28*(3), 251-267. doi: 10.1007/s00774-009-0139-6

McArdle, W. D., Katch, F. I., & Katch, V. L. (2006). *Essentials of exercise physiology*: Lippincott Williams & Wilkins.

McKay, H., Tsang, G., Heinonen, A., MacKelvie, K., Sanderson, D., & Khan, K. M. (2005). Ground reaction forces associated with an effective elementary school based jumping intervention. *British Journal of Sports Medicine, 39*(1), 10-14. doi: 10.1136/bjsm.2003.008615

McNitt-Gray, J. L. (1993). Kinetics of the lower extremities during drop landings from three heights. *Journal of Biomechanics, 26*(9), 1037-1046. doi: http://dx.doi.org/10.1016/S0021-9290(05)80003-X

Meshkati, Z., Namazizadeh, M., Salavati, M., & Mazaheri, M. (2011). Reliability of force-platform measures of postural sway and expertise-related differences. *J Sport Rehabil, 20*(4), 442-456.

Moghadam, M., Ashayeri, H., Salavati, M., Sarafzadeh, J., Taghipoor, K. D., Saeedi, A., & Salehi, R. (2011). Reliability of center of pressure measures of postural stability in healthy older adults: effects of postural task difficulty and cognitive load. *Gait Posture, 33*(4), 651-655. doi: 10.1016/j.gaitpost.2011.02.016

Moghaddam, A., Müller, U., Roth, H. J., Wentzensen, A., Grützner, P. A., & Zimmermann, G. (2011). TRACP 5b and CTX as osteological markers of delayed fracture healing. *Injury, 42*(8), 758-764. doi: http://dx.doi.org/10.1016/j.injury.2010.11.017

Mothersole, G., Cronin, J. B., & Harris, N. K. (2014). Jump-landing program for females: Development of a systematic progression model. *Strength and Conditioning Journal, 36*(4), 52-64. doi: 10.1519/SSC.0000000000000078

Moyer, V. A. (2013). Menopausal Hormone Therapy for the Primary Prevention of Chronic Conditions: U.S. Preventive Services Task Force Recommendation Statement. *Annals of Internal Medicine, 158*(1), 47-54.

Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2012). Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. *Med Sci Sports Exerc, 44*(1), 180-189. doi: 10.1249/MSS.0b013e318228b60e

Nedergaard, A., Henriksen, K., Karsdal, M. A., & Christiansen, C. (2013). Musculoskeletal ageing and primary prevention. *Best Practice & Research Clinical Obstetrics & Gynaecology, 27*(5), 673-688. doi: http://dx.doi.org/10.1016/j.bpobgyn.2013.06.001

Nelson, H. D., Walker, M., Zakher, B., & Mitchell, J. (2012). Menopausal Hormone Therapy for the Primary Prevention of Chronic Conditions: A Systematic Review to Update the U.S. Preventive Services Task Force Recommendations. *Annals of Internal Medicine, 157*(2), 104-W-123.

Niu, K., Ahola, R., Guo, H., Korpelainen, R., Uchimaru, J., Vainionpää, A., . . . Nagatomi, R. (2010). Effect of office-based brief high-impact exercise on bone mineral density in healthy premenopausal women: the Sendai Bone Health Concept Study. *Journal of Bone and Mineral Metabolism, 28*(5), 568-577. doi: 10.1007/s00774-010-0163-6

O'Connor, J. A., Lanyon, L. E., & MacFie, H. (1982). The influence of strain rate on adaptive bone remodelling. *Journal of Biomechanics, 15*(10), 767-781. doi: http://dx.doi.org/10.1016/0021-9290(82)90092-6

Ohnaru, K., Sone, T., Tanaka, K., Akagi, K., Ju, Y.-I., Choi, H.-J., . . . Fukunaga, M. (2013). Hip structural analysis: a comparison of DXA with CT in postmenopausal Japanese women. *SpringerPlus, 2*, 331. doi: 10.1186/2193-1801-2-331

Osteoporosis New Zealand. (2018). Who is affected? Retrieved April 3, 2018, 2018, from https://osteoporosis.org.nz/osteoporosis-fractures/who-is-affected/

Palmieri, R. M., Ingersoll, C. D., Stone, M. B., & Krause, B. A. (2002). Center-of-Pressure Parameters Used in the Assessment of Postural Control. *11*(1), 51. doi: 10.1123/jsr.11.1.51

Petit, M. A., McKay, H. A., MacKelvie, K. J., Heinonen, A., Khan, K. M., & Beck, T. J. (2002). A randomized school-based jumping intervention confers site and maturity-specific benefits on bone structural properties in girls: a hip structural analysis study. *J Bone Miner Res, 17*(3), 363-372. doi: 10.1359/jbmr.2002.17.3.363

Polidoulis, I., Beyene, J., & Cheung, A. M. (2012). The effect of exercise on pQCT parameters of bone structure and strength in postmenopausal women--a systematic review and meta-analysis of randomized controlled trials. *Osteoporosis International 23*(1), 39-51. doi: 10.1007/s00198-011-1734-7

Prevrhal, S., Shepherd, J. A., Faulkner, K. G., Gaither, K. W., Black, D. M., & Lang, T. F. (2008). Comparison of DXA Hip Structural Analysis with Volumetric QCT. *Journal of Clinical Densitometry, 11*(2), 232-236. doi: http://dx.doi.org/10.1016/j.jocd.2007.12.001

Qvist, P., Christgau, S., Pedersen, B. J., Schlemmer, A., & Christiansen, C. (2002). Circadian variation in the serum concentration of C-terminal telopeptide of type I collagen (serum

CTx): effects of gender, age, menopausal status, posture, daylight, serum cortisol, and fasting. *Bone, 31*(1), 57-61. doi: http://dx.doi.org/10.1016/S8756-3282(02)00791-3

Rapuri, P. B., Gallagher, J. C., & Haynatzki, G. (2004). Endogenous Levels of Serum Estradiol and Sex Hormone Binding Globulin Determine Bone Mineral Density, Bone Remodeling, the Rate of Bone Loss, and Response to Treatment with Estrogen in Elderly Women. *The Journal of Clinical Endocrinology & Metabolism, 89*(10), 4954-4962. doi: doi:10.1210/jc.2004-0434

Richter, A., Räpple, S., Kurz, G., & Schwameder, H. (2011). Countermovement jump in performance diagnostics: Use of the correct jumping technique. *European Journal of Sport Science, 12*(3), 231-237. doi: 10.1080/17461391.2011.566369

Robling, A. G., Burr, D. B., & Turner, C. H. (2001). Recovery periods restore mechanosensitivity to dynamically loaded bone. *Journal of Experimental Biology, 204*(19), 3389-3399.

Robling, A. G., Castillo, A. B., & Turner, C. H. (2006). Biomechanical and molecular regulation of bone remodeling *Annual Review of Biomedical Engineering* (Vol. 8, pp. 455-498). Palo Alto: Annual Reviews.

Santoro, N., Taylor, E. S., & Sutton-Tyrrell, K. (2011). The SWAN Song: Study of Women's Health Across the Nation's Recurring Themes. *Obstetrics and gynecology clinics of North America, 38*(3), 417-423. doi: 10.1016/j.ogc.2011.05.001

Scheid, J. L., Toombs, R. J., Ducher, G., Gibbs, J. C., Williams, N. I., & De Souza, M. J. (2011). Estrogen and peptide YY are associated with bone mineral density in premenopausal exercising women. *Bone, 49*(2), 194-201. doi: 10.1016/j.bone.2011.04.011

Schneiders, A., Gregory, K., Karas, S., & Mündermann, A. (2016). Effect of foot position on balance ability in single-leg stance with and without visual feedback. *Journal of Biomechanics, 49*(9), 1969-1972. doi: https://doi.org/10.1016/j.jbiomech.2016.04.020

Scofield, K. L., & Hecht, S. (2012). Bone Health in Endurance Athletes: Runners, Cyclists, and Swimmers. *Current Sports Medicine Reports, 11*(6), 328-334. doi: 10.1249/JSR.0b013e3182779193

Shi, X., Deng, Y., Kang, H., Liu, M., Chen, Y.-M., & Xiao, S.-M. (2019). Association of body composition with predicted hip bone strength among Chinese postmenopausal women: a longitudinal study. *Scientific Reports, 9*(1), 5507. doi: 10.1038/s41598-019-42031-1

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin, 86*(2), 420-428. doi: 10.1037/0033-2909.86.2.420

Sipila, S., & Poutamo, J. (2003). Muscle performance, sex hormones and training in peri-menopausal and post-menopausal women. *Scand J Med Sci Sports, 13*(1), 19-25.

Siris, E. S., Miller, P. D., Barrett-Connor, E., & et al. (2001). Identification and fracture outcomes of undiagnosed low bone mineral density in postmenopausal women: Results from the national osteoporosis risk assessment. *JAMA, 286*(22), 2815-2822. doi: 10.1001/jama.286.22.2815

Snow, C. M., Williams, D. P., LaRiviere, J., Fuchs, R. K., & Robinson, T. L. (2001). Bone gains and losses follow seasonal training and detraining in gymnasts. *Calcif Tissue Int, 69*(1), 7-12.

Srinivasan, S., Weimer, D. A., Agans, S. C., Bain, S. D., & Gross, T. S. (2002). Low-Magnitude Mechanical Loading Becomes Osteogenic When Rest Is Inserted Between Each Load Cycle. *Journal of Bone and Mineral Research, 17*(9), 1613-1620. doi: 10.1359/jbmr.2002.17.9.1613

Stiles, V. H., Griew, P. J., & Rowlands, A. V. (2013). Use of accelerometry to classify activity beneficial to bone in premenopausal women. *Medicine & Science in Sports & Exercise, 45*(12), 2353-2361.

Stokes, F. J., Ivanov, P., Bailey, L. M., & Fraser, W. D. (2011). The Effects of Sampling Procedures and Storage Conditions on Short-term Stability of Blood-Based Biochemical Markers of Bone Metabolism. *Clinical Chemistry, 57*(1), 138-140.

Stone, M. H., Pierce, K. C., Sands, W. A., & Stone, M. E. (2006). Weightlifting: Program Design. *Strength & Conditioning Journal, 28*(2), 10-17.

Strong, J. E. (2004). *Effects of different jumping programs on hip and spine bone mineral density in pre-menopausal women.* (3148850 Ph.D.), Brigham Young University, Ann Arbor.

Tatangelo, G., Watts, J., Lim, K., Connaughton, C., Abimanyi-Ochom, J., Borgstrom, F., . . . Sanders, K. M. (2019). The Cost of Osteoporosis, Osteopenia, and Associated Fractures in Australia in 2017. *J Bone Miner Res, 34*(4), 616-625. doi: 10.1002/jbmr.3640

Tipton, C. M., & Medicine, A. C. o. S. (2006). *ACSM's advanced exercise physiology*: Lippincott Williams & Wilkins.

Ton, F. N., Gunawardene, S. C., Lee, H., & Neer, R. M. (2005). Effects of Low-Dose Prednisone on Bone Metabolism. *Journal of Bone and Mineral Research, 20*(3), 464-470. doi: 10.1359/JBMR.041125

Tucker, L. A., Strong, J. E., LeCheminant, J. D., & Bailey, B. W. (2014). Effect of two jumping programs on hip bone mineral density in premenopausal women: A randomized controlled trial. *American Journal of Health Promotion*. doi: 10.4278/ajhp.130430-QUAN-200

Turner, C. H. (1999). Mechanical signaling in the development of postmenopausal osteoporosis. *Lupus, 8*(5), 388-392.

Turner, C. H., & Robling, A. G. (2003). Designing exercise regimens to increase bone strength. *Exercise & Sport Sciences Reviews, 31*(1), 45-50.

Turner, C. H., & Robling, A. G. (2005). Exercises for improving bone strength. *British Journal of Sports Medicine, 39*(4), 188-189.

Turner, D. A., Khioe, R. F. S., Shepstone, L., Lenaghan, E., Cooper, C., Gittoes, N., . . . Team, t. S. S. (2018). The Cost-Effectiveness of Screening in the Community to Reduce Osteoporotic Fractures in Older Women in the UK: Economic Evaluation of the SCOOP Study. *Journal of Bone and Mineral Research, 33*(5), 845-851. doi: 10.1002/jbmr.3381

Umemura, Y., Sogo, N., & Honda, A. (2002). Effects of intervals between jumps or bouts on osteogenic response to loading. *Journal of Applied Physiology, 93*(4), 1345-1348. doi: 10.1152/japplphysiol.00358.2002

Vainionpää, A., Korpelainen, R., Leppäluoto, J., & Jämsä, T. (2005). Effects of high-impact exercise on bone mineral density: a randomized controlled trial in premenopausal women. *Osteoporosis International, 16*(2), 191-197. doi: http://dx.doi.org/10.1007/s00198-004-1659-5

Vainionpää, A., Korpelainen, R., Vihriälä, E., Rinta-Paavola, A., Leppäluoto, J., & Jämsä, T. (2006). Intensity of exercise is associated with bone density change in premenopausal women. *Osteoporosis International, 17*(3), 455-463. doi: http://dx.doi.org/10.1007/s00198-005-0005-x

van Ingen Schenau, G. J., Bobbert, M. F., & de Haan, A. (1997). Does elastic energy enhance work and efficiency in the stretch-shortening cycle? *Journal of Applied Biomechanics, 13*(4), 389.

Vanputte, C. L., Regan, J. L., & Russo, A. F. (2013) *Seeley's Essentials of Anatomy & Physiology* (8th ed., pp. 110-149). USA.

Vasikaran, S., Cooper, C., Eastell, R., Griesmacher, A., Morris, H. A., Trenti, T., & Kanis, J. A. (2011). International Osteoporosis Foundation and International Federation of Clinical Chemistry and Laboratory Medicine Position on bone marker standards in osteoporosis. *Clinical Chemistry & Laboratory Medicine, 49*(8), 1271-1274. doi: 10.1515/CCLM.2011.602

Vasikaran, S., Eastell, R., Bruyère, O., Foldes, A. J., Garnero, P., Griesmacher, A., . . . Kanis, J. A. (2011). Markers of bone turnover for the prediction of fracture risk and monitoring of osteoporosis treatment: a need for international reference standards. *Osteoporosis International, 22*(2), 391-420. doi: http://dx.doi.org/10.1007/s00198-010-1501-1

Vasikaran, S. D. (2008). Utility of biochemical markers of bone turnover and bone mineral density in management of osteoporosis. *Critical Reviews in Clinical Laboratory Sciences, 45*(2), 221-258.

Vellas, B. J., Wayne, S. J., Romero, L., Baumgartner, R. N., Rubenstein, L. Z., & Garry, P. J. (1997). One-Leg Balance Is an Important Predictor of Injurious Falls in Older Persons. *Journal of the American Geriatrics Society, 45*(6), 735-738. doi: 10.1111/j.1532-5415.1997.tb01479.x

Wang, L., Xu, X., Zhang, Y., Hao, H., Chen, L., Su, T., & Ma, Y. (2016). A model of health education and management for osteoporosis prevention. *Experimental and Therapeutic Medicine*. doi: http://dx.doi.org/10.3892/etm.2016.3822

Weaver, C. M., Gordon, C. M., Janz, K. F., Kalkwarf, H. J., Lappe, J. M., Lewis, R., . . . Zemel, B. S. (2016). The National Osteoporosis Foundation's position statement on peak bone mass development and lifestyle factors: a systematic review and implementation recommendations. *Osteoporosis International, 27*(4), 1281-1386. doi: 10.1007/s00198-015-3440-3

Weeks, B. K., & Beck, B. R. (2008). The BPAQ: a bone-specific physical activity assessment instrument. *Osteoporosis International, 19*(11), 1567-1577. doi: 10.1007/s00198-008-0606-2

Winters-Stone, K. M., Dobek, J., Nail, L. M., Bennett, J. A., Leo, M. C., Torgrimson-Ojerio, B., . . . Schwartz, A. (2013). Impact + resistance training improves bone health and body composition in prematurely menopausal breast cancer survivors: a randomized controlled trial. *Osteoporosis International, 24*(5), 1637-1646. doi: 10.1007/s00198-012-2143-2

Winters-Stone, K. M., & Snow, C. M. (2006). Site-specific response of bone to exercise in premenopausal women. *Bone, 39*(6), 1203-1209. doi: http://dx.doi.org/10.1016/j.bone.2006.06.005

Winters, K. M., & Snow, C. M. (2000). Detraining reverses positive effects of exercise on the musculoskeletal system in premenopausal women. *Journal of Bone and Mineral Research, 15*(12), 2495-2503. doi: 10.1359/jbmr.2000.15.12.2495

Winwood, P. W., Cronin, J. B., Posthumus, L. R., Finlayson, S. J., Gill, N. D., & Keogh, J. W. L. (2015). Strongman vs. traditional resistance training effects on muscular function and performance. *Journal of Strength & Conditioning Research, 29*(2), 429-439.

Wulf, G., & Dufek, J. S. (2009). Increased jump height with an external focus due to enhanced lower extremity joint kinetics. *Journal of Motor Behavior, 41*(5), 401-409. doi: 10.1080/00222890903228421

Young, W. B., Pryor, J. F., & Wilson, G. J. (1995). Effect of instructions on characteristics of countermovement and drop jump performance. *The Journal of Strength & Conditioning Research, 9*(4), 232-236.

Zhao, R., Zhao, M., & Zhang, L. (2014). Efficiency of Jumping Exercise in Improving Bone Mineral Density Among Premenopausal Women: A Meta-Analysis. *Sports Medicine, 44*(10), 1393-1402.

Zofková, I. (2008). Hormonal aspects of the muscle-bone unit. *Physiological Research, 57(Suppl. 1)*, S159-S169.

ABBREVIATIONS AND GLOSSARY

ABBREVIATIONS

AI	Adequate intake
ANOVA	Analysis of variance
BDJ	Bounce drop jump
BIA	Bioelectrical impedance analysis
BJ	Bounce jump
BMD	Bone mineral density
BMI	Body mass index
BMC	Bone mineral content
BSPAQ	Bone specific physical activity questionnaire
BTM	Bone turnover marker
BW	Body weight
CA	Cronbach's Alpha
CMDJ	Countermovement drop jump
CMJ	Countermovement jump
CSA	Cross sectional area
CVJ	Countermovement vertical jump
CT	Computed tomography
CTx	Type I Collagen C-Telopeptide
DEXA/DXA	Dual energy x-ray absorptiometry
df	Degrees of freedom
DJ	Drop jump
e.g.	For example
EMG	Electromyography
F	Fishers distribution value

FH	Forward hop
FRAX	Fracture risk assessment tool
GCT	Ground contact time
GRF	Ground reaction force
HRT	Hormone replacement therapy
HSA	Hip structural analysis
i.e.	That is
IL 1-6	Interleukin 1 and 6
IFCC	International Federation of Clinical Chemistry and Laboratory Medicine
IOF	International Osteoporosis Foundation
L1-L4	Lumbar 1 - lumbar 4 vertebrae
LH	Lateral hop
LMM	Linear mixed model
MES	Minimum effective strain
N.B.	Nota bene “note well”
NZ	New Zealand
P1NP	Procollagen Type I N-Propeptide
PAF	Peak anterior force
PAR-Q	Physical Activity Readiness Questionnaire
PLF	Peak lateral force
PMF	Peak medial force
PPF	Peak posterior force
PRF	Peak resultant force
PRFD	Peak rate of force development
PVF	Peak vertical force

QCT	Quantitative computed tomography
RANKL	Receptor activator of nuclear factor B ligand
RDI	Recommended dietary intake
reps	Repetitions
RJ	Reactive jump
RM	Repetition maximum
ROM	Range of motion
SDJ	Stride jump
SJ	Star jump
T-score	BMD score for the patient's age, sex and ethnicity
TNF-α	Tumor necrosis factor
UTPSTF	U.S. Preventive Services Task Force
VH	Vertical hop
VGRF	Vertical ground reaction force
V max	Velocity maximum
V min	Velocity minimum
WHI	Women’s Health Initiative
WHO	World Health Organisation
WI	With instruction
WO	Without instruction
X axis	Medial and lateral axis
Y axis	Anterior and posterior axis
Z axis	Vertical axis
Z-score	BMD score compared to a healthy 30-year-old adult of the same sex and ethnicity as the patient

UNITS OF MEASUREMENT

%	Percentage
BW	Body weight
BW·s^{-1}	Body weight per second
CI	Confidence interval
cm	Centimetre
cm^{2}	Centimetre squared
cm^{3}	Centimeter cubed
CV	Coefficient of variation
ES	Effect size
g·cm^{2}	Gram per centimeter squared
g.kg^{-1}	Gram per kilo of body weight
H	Hertz
ICC	Intraclass correlation coefficient
IU	International unit
kg	Kilogram
kN·s-1	Kilonewton per second
m	Meter
mg	Milligram
min	Minute
mm	Millimeter
ms	Millisecond
ms	Millisecond
N	Newton
ng.ml^{-1}	Nanogram per milliliter

°	Degrees
$ng.ml^{-1}$	nanogram per milliliter
r	Correlation coefficient
r^2	Coefficient of determination
s	Seconds
SD	Standard deviation
W	Watts
wk	Week
yr	Year

GLOSSARY

Amenorrhoea	The absence of a menstrual period in a woman of reproductive age.
Anterio-posterior force	Forces in the Y axis relative to the front and back of the body (anterior$^+$/posterior$^-$).
Anthropometry	The science of measurement applied to the human body and generally includes measurement of height, weight, and selected body and limb girths.
Basic Multicellular unit (BMU)	The region of cells on the bone surface responsible for bone remodelling.
Bilateral ground reaction force production	The force exerted on the ground from both legs.
Bilateral jump-landing	Both feet landing on the ground simultaneously.
Biomechanics	The application of the laws of mechanics to biological systems.
Body composition	The percentages of fat, bone and muscle in human bodies.

Bone	A combination of type 1 collagen bone matrix (organic) and hydroxyapatite crystals (inorganic). Two types of bone are cortical and trabecular (cancellous).
Bone cross-sectional area (femoral sites)	Equivalent to the amount of (cortical equivalent) bone surface area in the cross-section after excluding all trabecular and soft tissue spaces.
Bone cortical thickness (femoral sites)	Estimate of mean cortical thickness at femoral site.
Bone formation	Process by which cells differentiate, proliferate, mature and mineralise into osteocytes (mature bone cells).
Bone remodelling period	The average total duration of a single cycle of bone remodelling at any point on a bone surface (120-200 days).
Bone remodelling cycle	A continuous lifelong process in the skeleton where mature bone tissue is removed (resorption) and new bone tissue is formed (formation).
Bone microarchitecture	The structural geometry of bone contributing to bone strength, including width, shape and porosity.

Bone mineral content (BMC)	A measurement of bone mineral found in a specific area (g)
Bone mineral density (BMD)	The amount of bone mineral per square centimeter of bone (g/cm^2). Derived using BMC divided by area.
Bone resorption	The process by which osteoclasts break down the tissue in bones and release the minerals, resulting in a transfer of calcium from bone tissue to the blood.
Bone section modulus	A geometric index of bending strength at the bone site.
Bone turnover markers (BTM)	Bone turnover markers (BTMs) are a series of protein or protein derivative biomarkers released during bone remodelling by osteoblasts or osteoclasts.
Calcium	The most abundant mineral in the human body. Stored mostly in the teeth and bones.
Corticosteroid	Steroid medications have major effects on the metabolism of calcium, vitamin D and bone. This can lead to bone loss and osteoporosis.

Cortical bone	The solid outer shell of bone comprising of about 80% of the mature skeleton. It is typically found in the long bones and outer region of the vertebrae.
Countermovement jump (vertical jump)	The jumper starts from an upright standing position, makes a preliminary downward movement by flexing at the knees and hips, then immediately extends the knees and hips again to jump vertically up off the ground.
Drop jump	The jumper steps off a box (i.e. 20cm used in these studies), and lands with two feet.
Dual energy x-ray absorptiometry (DEXA)	A quantitative imaging technique that uses a radiation soured to measure bone mineral density.
Epidemiology	The study of patterns of health and illness and associated factors at the population level.
Femoral DEXA scan	A scan that measures three regions of interest: the femoral neck, inter-trochanter, and the greater trochanter.

Force profile	A pictorial representation (graph) of the forces involved in a jump-landing developed using excel data.
Forward hop	The jumper leaps forward from two feet to land on one foot.
Ground reaction force	The force exerted by the ground on the body in contact with it.
Histomorphometry (of bone)	The qualitative analysis of microstructure morphology and organisation of bone.
Hop	Defined as used in this study to mean leaping from two feet to land on one foot.
Hormone replacement therapy	The use of hormone therapy (tablets, patches or cream) to replace the oestrogen that your ovaries no longer make during and after menopause.
Interrelationships	The relationships between dependent and independent variables.
Jump-landing	The technique utilised by the jumper on landing.
Kinematics	The characteristics of motion from a spatial and temporal perspective

	without reference to the forces causing that motion.
Kinetics	The examination of forces acting on a system, such as a human body.
Lateral hop	The jumper leaps sideways from two feet to land on one foot.
Lever	In biomechanics, bones act as lever arms, joints act as pivots and muscles provide the effort forces to move loads.
Lumbar DEXA scan	A scan that measures the lower 4 lumbar vertebrae (L1 - L4).
Medio-lateral force	Forces in the X axis relative to the sides of the body (medial$^+$/lateral$^-$).
Mechanosensitivity	The specific response to mechanical stimulation, is common to a wide variety of cells in many different organisms ranging from bacteria to bone. Mechanical stress can modulate physiological processes at the molecular, cellular, and systemic level.
Mechanostat theory	A term describing the way in which mechanical loading influences bone structure by changing the mass (amount of bone) and architecture (its arrangement) to provide a structure

	that resists habitual loads with an economical amount of material.
Menopause	A normal condition that all women experience as they age. The term "menopause" can describe any of the changes a woman goes through either just before or after she stops menstruating, marking the end of her reproductive period.
Minimum effective strain (MES)	A hypothesis since 1964, has achieved experimental support. Strains below the MES apparently do not evoke adaptive architectural bone modelling, but those above it do.
Musculoskeletal system	Provides form, stability, and movement to the human body. It consists of the body's bones, muscles, tendons, ligaments, joints, cartilage, and other connective tissue.
Oestradiol/ Estradiol	It is the main oestrogen found in women and is used to prevent osteoporosis (bone loss) in menopausal women.
Oestrogen/ Estrogen	It has an important role in the growth and maturation of bone as well as in the regulation of bone turnover in adult bone. Oestrogen deficiency leads to increased osteoclast formation and enhanced bone resorption.

Osteoarthritis	Sometimes called degenerative joint disease or degenerative arthritis, osteoarthritis (OA) is the most common chronic condition of the joints. OA can affect any joint, but it occurs most often in knees, hips, lower back and neck, small joints of the fingers and the bases of the thumb and big toe.
Osteogenic	Derived from or made up of bone-forming tissue.
Osteogenic threshold	Forces or stresses (magnitude and rate) imposed on bone in excess of this will stimulate bone growth.
Osteoblasts	Cells which make new bone and aids its mineralisation. A bone-forming cell.
Osteoclasts	A large multinuclear cell associated with absorption and removal of bone: responsible for bone resorption.
Osteopenia	A condition where bone mineral density is lower than normal however not yet as low as osteoporosis and falls in the “T score” range of -1.1 to -2.4.
Osteoporosis	Osteoporosis is a systemic skeletal disease characterised by low bone mass and micro architectural deterioration of bone tissues,

	with a consequent increase in bone fragility and susceptibility to fracture.
Osteoporotic fracture	These fractures are a result of osteoporosis, a condition in which the bones become more fragile due to bone deterioration or low bone mass. Bones that are weaker or more fragile are at greater risk for fractures.
Peak bone mass	The amount of bone tissue in the skeleton, known as bone mass, can keep growing until the late 20s. At that point, bones have reached their maximum strength and density.
Periodisation	The variation of training stimuli over periods of time to allow for a proper progression in the exercise stress and planned periods of rest.
Pharmacological therapy	Using pharmaceutical drugs, as distinguished from therapy using surgery, radiation, movement, or other modes.
Postmenopausal	The years after menopause. As a result of a lower level of oestrogen, postmenopausal women are at increased risk for a number of health conditions, including osteoporosis.
Power	The rate at which mechanical work is performed (Power = force x distance/time).

Premenopausal	It's the time when the ovaries gradually begin to make less oestrogen. It usually starts in a woman's 40s, but can start in her 30s or even earlier.
Quantify	To determine, express, or measure the quantity of something (i.e. GRF’s).
Rate of force development (rate of strain)	Calculated by dividing peak force by the time taken to reach peak force.
Reactive jump	To jump again immediately after the initial landing (as defined in the current research).
Reliability	The extent to which an experiment, test, or measuring procedure yields the same results on repeated trials.
Resistance training	Training that uses a resistance to the force of muscular contraction.
Star jump	The jumper starts from an upright standing position, then jumps up whilst simultaneously swinging their arms and legs outwards to land in a star position, then jumping back into the starting position to finish.
Strength and conditioning coach	A coach whose job is the physical and physiological development of athletes for elite sport performance.

Strength training	The use of resistance to muscular contraction to build the strength.
Stretch shortening cycle	Stretch reflex initiated by a fast-eccentric muscle contraction followed immediately by a fast-concentric muscle action.
Stride jump	The jumper starts from an upright standing position, in a split stance with opposite arms and legs forward and back. Then jumps up whilst simultaneously swinging their arms and legs in opposite directions, and then jumping back into the starting position to finish.
Trabecular bone	Porous bone composed of an intricate, latticed network of fibrous, calcified mineral. It is typically found at points of compression, such as lumbar vertebrae, femoral head, etc. Preferentially affected by osteoporosis.
T- score	The difference between the patient's BMD and the mean young adult value of the reference population, divided by the reference standard deviation (SD). A T-score of -2 means the patient is 2 SDs below the reference population.
Unilateral ground reaction force production	The force exerted on the ground from a single leg.

Unilateral jump-landing	Landing on the ground with one foot only.
Validity	This gives an indication of how sound your research is. More specifically, validity applies to both the design and the methods of your research. Validity in data collection means that your findings truly represent the phenomenon you are claiming to measure.
Vertical hop	The jumper leaps forward from two feet to land on one foot.
Vitamin D	Vitamin D helps the body absorb calcium. Calcium and phosphate are two minerals that you must have for normal bone formation.
Unilateral ground reaction force production	The force exerted on the ground from a single leg.
Velocity	The rate of change of displacement with respect to time. Expressed as the ratio of displacement and time (d/t).
Weight-bearing exercise	These types of exercise force you to work against gravity. They include walking, jogging, climbing stairs, playing tennis, and dancing.
Z- score	The difference between the patient's BMD and the mean age-matched value of the reference population, divided by the

reference standard deviation (SD). A Z-score of - 2 means the patient is 2 SDs below the reference population (age and gender matched).

APPENDICES

Appendix 1: Abstracts of Descriptive and Experimental Chapters

Chapter 3: DO BILATERAL VERTICAL JUMPS WITH REACTIVE JUMP-LANDINGS ACHIEVE OSTEOGENIC THRESHOLDS WITH AND WITHOUT INSTRUCTION IN PREMENOPAUSAL WOMEN?

Abstract

Jumps have been investigated as a stimulus for bone development, however effects of instruction, jump type and jump-landing techniques need investigation. This study sought to identify whether ground reaction forces (GRF's) for bilateral vertical jumps (countermovement jumps and drop jumps) with reactive jump-landings (i.e. jumping immediately after initial jump-landing), with instruction and with instruction withdrawn, achieve magnitudes and rates of strain previously shown to improve bone mass among premenopausal women. Twenty-one women (Mean ± SD: 43.3 ± 5.90 years; 69.4 ± 9.60kg; 167 ± 5.50cm; 27.5 ± 8.70% body fat) performed a testing session 'with instruction' followed by a testing session performed one week later with 'instruction withdrawn'. The magnitudes (4.59 to 5.49 BW's) and rates of strain (263 to 359 $BW \cdot s^{-1}$) for the jump-landings, performed on an AMTI force plate, exceeded previously determined thresholds (> 3BW's and > $43BW \cdot s^{-1}$). Interestingly, significantly larger peak resultant forces, (↑10%; $p = 0.002$) and peak rates of force development (↑20%; $p < 0.001$) values (in relation to BW and $BW \cdot s^{-1}$, respectively) were observed for the second jump-landing (post-reactive jump). Small increases (ES = 0.22 to 0.42) in all landing forces were observed in the second jump-landing with 'instruction withdrawn'. These jumps represent a unique training stimulus for premenopausal women and achieve osteogenic thresholds thought pre-requisite for bone growth.

Keywords: bone, impact exercise, biomechanics, ground reaction forces

Chapter 4: BILATERAL MULTIDIRECTIONAL JUMPS WITH REACTIVE JUMP-LANDINGS ACHIEVE OSTEOGENIC THRESHOLDS WITH AND WITHOUT INSTRUCTION IN PREMENOPAUSAL WOMEN.

Abstract

Background Currently jump-landing ground reaction forces have only been quantified in the vertical direction as a stimulus for bone development. This study quantified the full-spectrum of jump-landing force magnitudes, body weights (BW's) and rates of strain (BW·s^{-1}) of bilateral multidirectional jumps (star jump and stride jump) with reactive jump-landings (i.e. jumping immediately after initial jump-landing) among premenopausal women. It was also of interest to quantify the influence of instruction on the magnitude and rate of the jump-landing ground reaction forces. *Methods* Twenty-one women [Mean (SD): 43.3 (5.90) yr; 69.4 (9.60) kg; 167 (5.50) cm; 27.5 (8.70) % body fat] performed a jump testing session 'with instruction' followed by a jump testing session performed one week later with 'instruction withdrawn'. *Findings* The resultant magnitudes (3.90 to 5.38, BW's) and rates of strain (192 to 329, BW·s^{-1}) for the jump-landings, performed on an AMTI force plate, exceeded previously determined osteogenic thresholds (> 3BW's and > 43BW·s^{-1}, respectively). An instruction effect was observed for resultant (↑8% and ↑12%; $P \leq .01$) and vertical (↑8% and ↑7%; $P \leq .01$) ground reaction force's (N and BW, respectively) indicating learning/practice effects for these exercises. A jump-landing effect was observed, with larger peak rates of strain (↑29%; $P < .0001$, BW·s^{-1}) and peak forces (↑12% to ↑48%; $P \leq .01$, BW) for the second jump-landing (post-reactive jump). *Interpretation* These multidirectional bilateral jumps represent a unique training stimulus for premenopausal women and achieve osteogenic thresholds thought pre-requisite for bone growth and could be utilised in the development of osteogenic exercise programmes.

Keywords: Bone, impact exercise, jump-landing, ground reaction forces.

Chapter 5: MULTIDIRECTIONAL HOP-LANDINGS EXCEED OSTEOGENIC THRESHOLDS WITH AND WITH INSTRUCTION WITHDRAWN IN PREMENOPAUSAL WOMEN

Abstract

The purpose of this study was to quantify the full spectrum of ground reaction forces and influence of instruction associated with vertical, forward and lateral hop landings in premenopausal women. Bilateral jump-landings have previously been the focus in this population with forces quantified primarily in the vertical direction. Twenty-one women [Mean (SD): 43.3 (5.90) yr; 69.4 (9.60) kg; 167 (5.50) cm; 27.5 (8.70) % body fat] performed a testing session 'with instruction' followed by a testing session performed one week later with 'instruction withdrawn'. The resultant magnitudes (4.02 to 4.93 body weights, BW's) and rates of strain (237 to 319, body weights per second, BW/s), exceeded previously determined jump-landings thresholds (>3BW's and >43BW/s, respectively) that have achieved bone gains in this population. Jump-type effects were observed, with larger peak vertical and resultant forces (↑10% to ↑14%; $p \leq .001$, BW) produced for the vertical hop. Significant differences ($p \leq .001$) were detected for hop landings across the full spectrum of ground reaction force's (19% to 93%) suggesting that each landing type provides a different type of force distribution as required to optimise bone stimulation. These multidirectional hop-landings represent a unique training stimulus for premenopausal women and exceed osteogenic thresholds thought pre-requisite for bone growth.

Keywords: Bone, impact exercise, unilateral, ground reaction forces.

Chapter 6: THE DEVELOPMENT OF A LONGITUDINAL OSTEOGENIC PERIODISED JUMP-LANDING PROGRAMME FOR PREMENOPAUSAL WOMEN.

Abstract

The purpose of this research was to develop a longitudinal periodised osteogenic jump-landing programme for pre-menopausal women. Previously quantified jump-landing force data (from bilateral and unilateral, multidirectional jumps and hops) were utilised whilst integrating current bone health guidelines, a bone-specific stress stimulus rating system, research and concepts of best practice strength and conditioning. To provide an adaptive bone response the programme considers: a) magnitude and rate of strain; b) distribution patterns of strain; c) loading cycles; d) duration; and, e) recovery. The programme needs to be; i) site specific, ii) safe, iii) easy to administer, iv) cost effective, and v) be performed in the home setting.

Keywords: Bone; impact exercise; periodised, quantified

Chapter 7: A TEST RETEST RELIABILITY STUDY OF BONE MINERAL DENSITY AND BODY COMPOSITION MEASURES USING DEXA (DUAL ENERGY X-RAY ABSORPTIOMETRY)

Abstract

Purpose The purpose of this study was to determine the precision and reliability of a dual energy x-ray absorptiometry (DEXA) device for assessing bone mineral density (BMD), hip geometry and body composition in premenopausal women. Test-retest reliability of DEXA was determined in conjunction with a 12-month bone health intervention to determine the reliability for measurements of key variables and therefore define the smallest worthwhile change. *Method* Seventeen woman (age, 32.3 ± 7.70y; body mass, 69.1 ± 23.2kg; height, 166.5 ± 5.90cm; body fat, 27.5 ± 6.70%) received two DEXA scans within a 7-day period using the same machine and performed by the same technician. *Results* Significant correlations ($p < 0.001$) were observed for all measures and reliability was excellent for all body composition measures (ICC's = 0.92 to 1.00; CV's = 0.32 to 1.23%). Significant correlations ($p < 0.001$) were observed for all measures and reliability was excellent for all left hip measures (ICC's = 0.83 to 1.00; CV's = 0.64 to 2.13%). Significant correlations ($p < 0.001$) were observed for all measures and reliability was excellent for all lumbar spine measures (ICC's = 0.94 to 1.00; CV's = 0.56 to 1.87). *Conclusion* The excellent reliability results reported for BMD, hip geometry and body composition support the use of DEXA to assess the therapeutic effectiveness of an exercise intervention to be used for osteoporosis prevention in premenopausal women.

Key Words: precision, premenopausal, bone health, osteoporosis prevention

Chapter 8: THE CHRONIC EFFECTS OF A QUANTIFIED JUMP-LANDING PROGRAMME ON BONE HEALTH, BODY COMPOSITION AND PERFORMANCE PARAMETERS IN PREMENOPAUSAL WOMEN.

Abstract

The primary purpose of this study was to determine the effects of a 12-month quantified jump-landing program on bone remodelling at clinically relevant sites in premenopausal women. Secondary measures of interest included; lower body explosive power, muscle reactivity, balance performance parameters and body composition. A longitudinal controlled trial was implemented to determine the effect of utilizing previously quantified jumps and hops with specific cues provided for jump-landings. Fifty-seven women (age, 42.4 ± 5.50y; body mass, 70.2 ± 11.5kg; height, 165.4 ± 0.10cm; body fat, 31.5 ± 6.20%) were assigned to a jump (JL) or control (CON) group. The JL performed periodized jumping-landing exercises up to five times per week for 12-months. Performance testing and dual energy x-ray absorptiometry (DXA) was performed at baseline, 3, 6, 9 and 12 months. Linear mixed model regression analysis was used to determine if differences existed between the JL and CON. Significant group main effects ($P<0.01$) in favour of the JL (↑0.41 - ↑3.72%) were observed for bone mineral density and bone mineral content at the femoral neck, total hip and lumbar spine. Significant group main effects ($P<0.01$) for cross-sectional area, cortical thickness and section modulus at the femoral narrow neck were also in favour of the JL (↑2.78 - ↑3.84%). For ground contact time, improvements in the JL over the CON between baseline and 12-months were apparent (↑21.9% vs ↓8.86%) with significant group and time effects ($P<0.01$) being observed. Group main effects that approached significance were towards the JL for vertical jump (↑7.54% vs ↓0.24%). A longitudinal quantified periodized jump-landing program performed 2-3 mins/day, 4-5 times a week is osteogenically effective in improving bone strength at clinically relevant lower body sites associated with osteoporosis in premenopausal women. Improvements observed in muscle reactivity and explosive strength indicate additional musculoskeletal adaptations associated with the jump-landing program.

Keywords: Bone health, impact exercise, reactive jump-landing, bone-mineral density, osteoporosis prevention.

Appendix 2: Ethics Approval Forms

TAIORANGAHAU
Pacific Coast Applied Research Centre

BAY OF PLENTY POLYTECHNIC
Private Bag 12001 Tauranga 3143 New Zealand
Ph 07 544 0920 Fax 07 544 2386 Email info@boppoly.ac.nz
0800 BOP POLY www.boppoly.ac.nz

BAY OF PLENTY POLYTECHNIC
TAURANGA
Te Kuratini o Poike

15 September 2014

Tracey Clissold
School of Applied Science

Dear Tracey

Research Proposal - The design and implementation of osteogenic exercise programmes for premenopausal women (*R14/18*)

Thank you for your application for funding which was considered by the Research Committee on 11 September 2014. The Research Committee has supported and approved your project. The funding approved for your project was $4,750.00 plus GST as requested.

When accessing your research funds, the following procedures should be followed:

- **To purchase goods and equipment** – Please request order numbers from Julie Bradley. All invoices and expense claims need to be sent through Julie for signing off.
  If you are purchasing capital asset items over $1,000 your order should be requested through Finance (Christine Dean).
  The project code for charging research expenses for this project is 0000151 – 02 – 200 – xxxx.

- **To hire research assistants** – your Manager should complete a New Employee Start/Change form (available on the Hub)

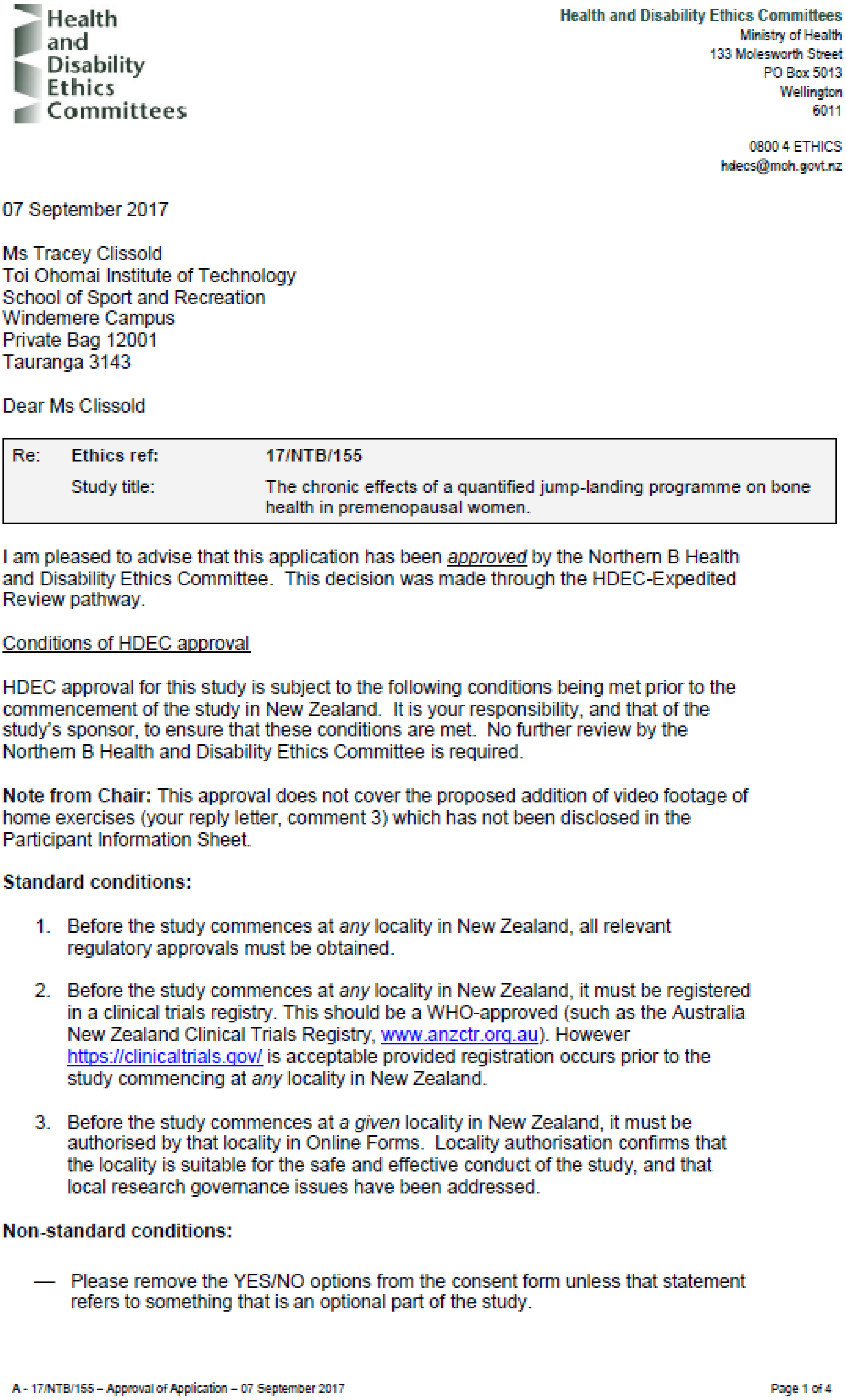
- **To use BoPP employees outside their normal hours for research** – This does not require another contract. A timesheet should be filled out for the hours they have worked on the research project

Congratulations and best wishes for the successful conduct and completion of this work.

Yours sincerely

Heather Hamerton
Chair
Research Committee

Eke Pānuku
Reaching our potential together



Health and Disability Ethics Committees

Health and Disability Ethics Committees
Ministry of Health
133 Molesworth Street
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6011

0800 4 ETHICS
hdecs@moh.govt.nz

07 September 2017

Ms Tracey Clissold
Toi Ohomai Institute of Technology
School of Sport and Recreation
Windemere Campus
Private Bag 12001
Tauranga 3143

Dear Ms Clissold

Re:	**Ethics ref:**	**17/NTB/155**
	Study title:	The chronic effects of a quantified jump-landing programme on bone health in premenopausal women.

I am pleased to advise that this application has been *approved* by the Northern B Health and Disability Ethics Committee. This decision was made through the HDEC-Expedited Review pathway.

Conditions of HDEC approval

HDEC approval for this study is subject to the following conditions being met prior to the commencement of the study in New Zealand. It is your responsibility, and that of the study's sponsor, to ensure that these conditions are met. No further review by the Northern B Health and Disability Ethics Committee is required.

Note from Chair: This approval does not cover the proposed addition of video footage of home exercises (your reply letter, comment 3) which has not been disclosed in the Participant Information Sheet.

Standard conditions:

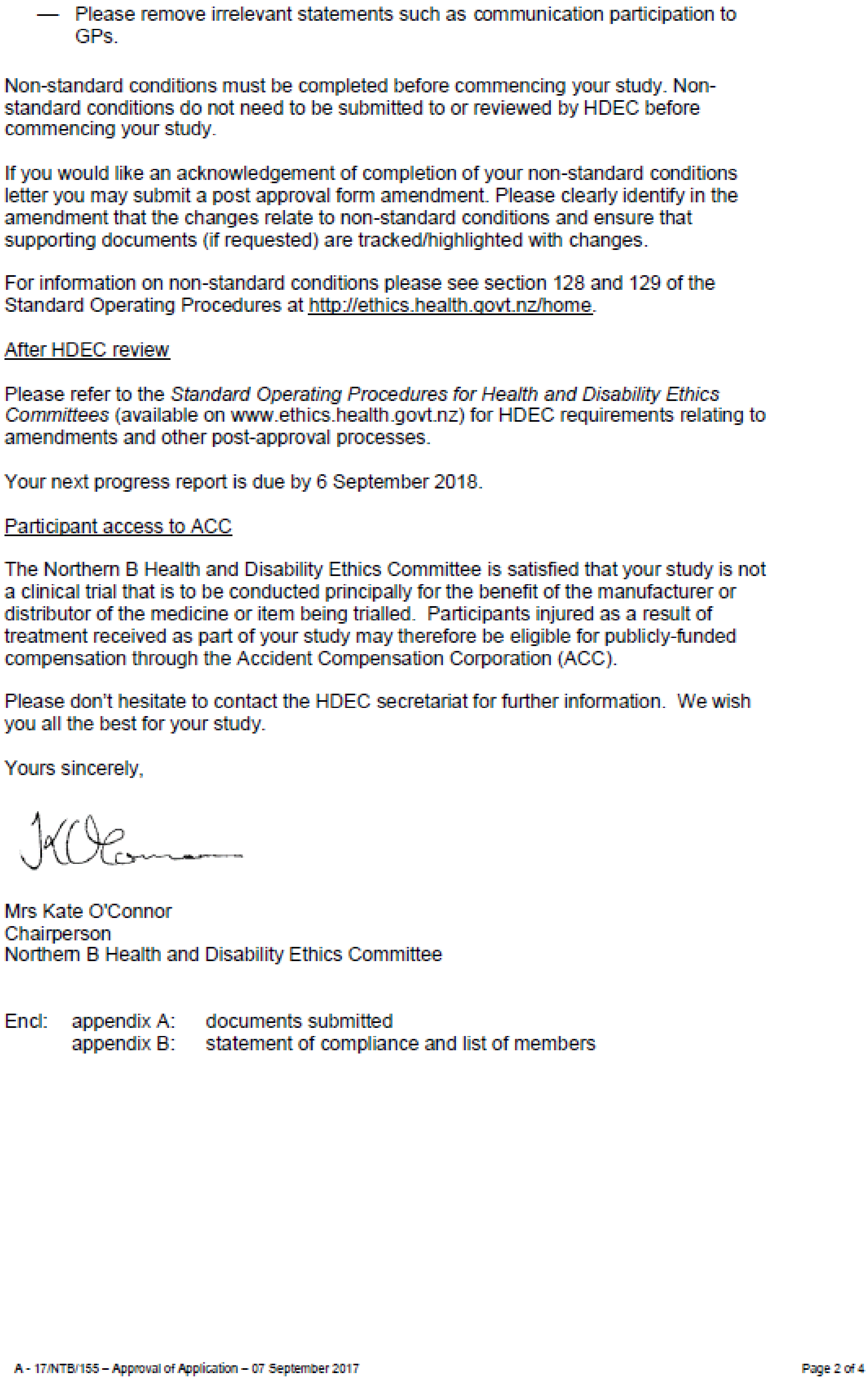
1. Before the study commences at *any* locality in New Zealand, all relevant regulatory approvals must be obtained.

2. Before the study commences at *any* locality in New Zealand, it must be registered in a clinical trials registry. This should be a WHO-approved (such as the Australia New Zealand Clinical Trials Registry, www.anzctr.org.au). However https://clinicaltrials.gov/ is acceptable provided registration occurs prior to the study commencing at *any* locality in New Zealand.

3. Before the study commences at *a given* locality in New Zealand, it must be authorised by that locality in Online Forms. Locality authorisation confirms that the locality is suitable for the safe and effective conduct of the study, and that local research governance issues have been addressed.

Non-standard conditions:

— Please remove the YES/NO options from the consent form unless that statement refers to something that is an optional part of the study.



- Please remove irrelevant statements such as communication participation to GPs.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by HDEC before commencing your study.

If you would like an acknowledgement of completion of your non-standard conditions letter you may submit a post approval form amendment. Please clearly identify in the amendment that the changes relate to non-standard conditions and ensure that supporting documents (if requested) are tracked/highlighted with changes.

For information on non-standard conditions please see section 128 and 129 of the Standard Operating Procedures at http://ethics.health.govt.nz/home.

After HDEC review

Please refer to the *Standard Operating Procedures for Health and Disability Ethics Committees* (available on www.ethics.health.govt.nz) for HDEC requirements relating to amendments and other post-approval processes.

Your next progress report is due by 6 September 2018.

Participant access to ACC

The Northern B Health and Disability Ethics Committee is satisfied that your study is not a clinical trial that is to be conducted principally for the benefit of the manufacturer or distributor of the medicine or item being trialled. Participants injured as a result of treatment received as part of your study may therefore be eligible for publicly-funded compensation through the Accident Compensation Corporation (ACC).

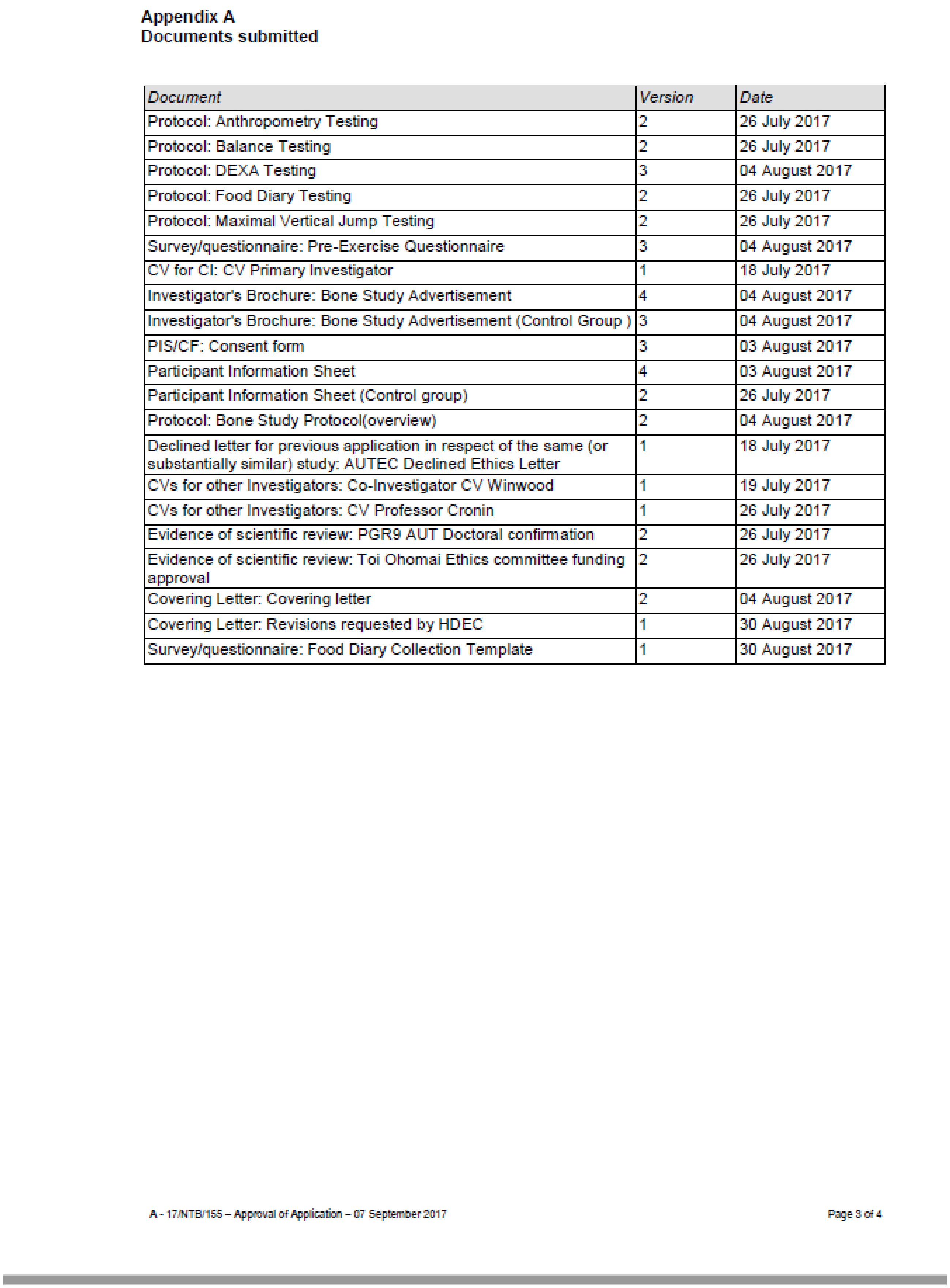
Please don't hesitate to contact the HDEC secretariat for further information. We wish you all the best for your study.

Yours sincerely,

Mrs Kate O'Connor
Chairperson
Northern B Health and Disability Ethics Committee

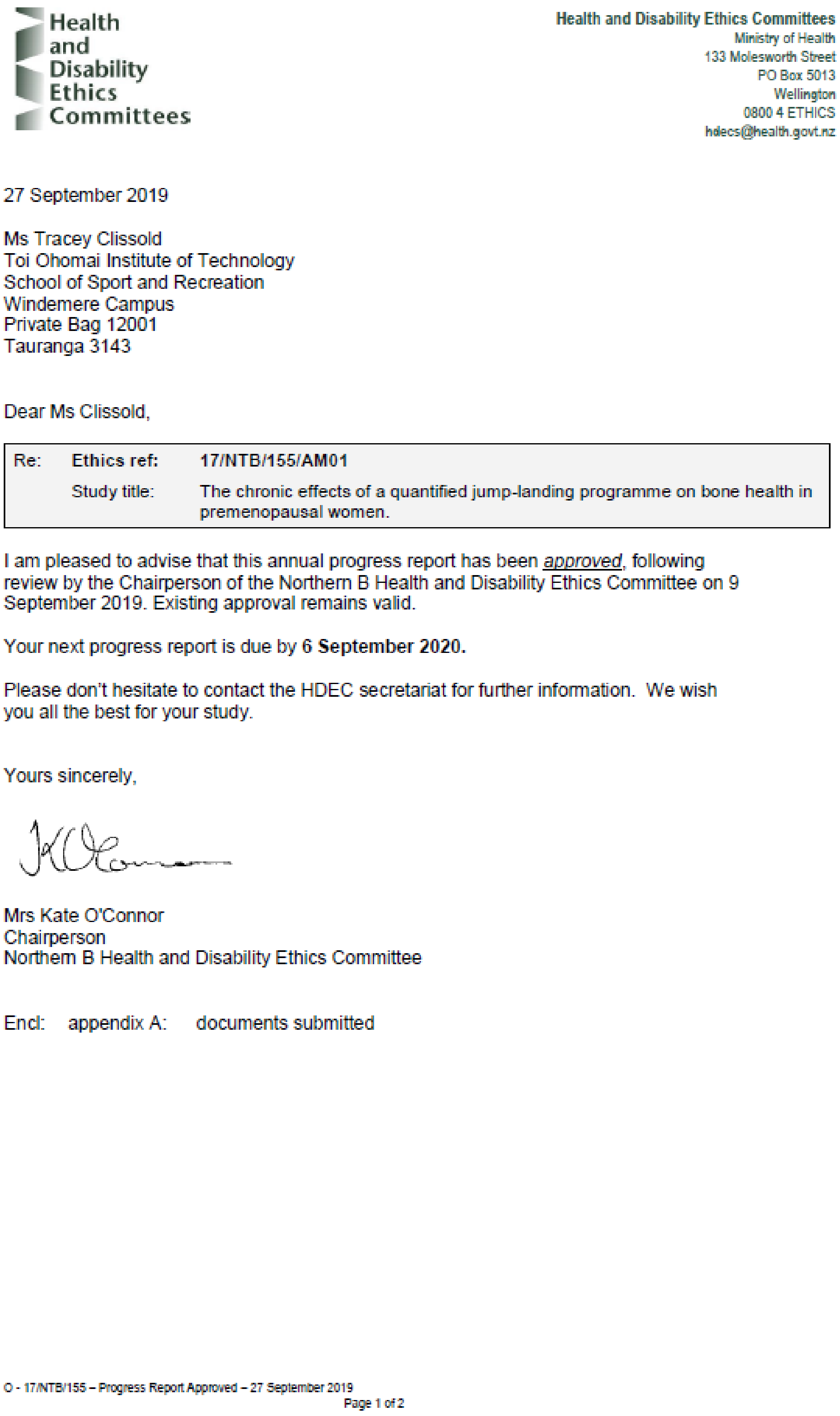
Encl: appendix A: documents submitted
appendix B: statement of compliance and list of members

A - 17/NTB/155 – Approval of Application – 07 September 2017 Page 2 of 4



Appendix A
Documents submitted

Document	*Version*	*Date*
Protocol: Anthropometry Testing	2	26 July 2017
Protocol: Balance Testing	2	26 July 2017
Protocol: DEXA Testing	3	04 August 2017
Protocol: Food Diary Testing	2	26 July 2017
Protocol: Maximal Vertical Jump Testing	2	26 July 2017
Survey/questionnaire: Pre-Exercise Questionnaire	3	04 August 2017
CV for CI: CV Primary Investigator	1	18 July 2017
Investigator's Brochure: Bone Study Advertisement	4	04 August 2017
Investigator's Brochure: Bone Study Advertisement (Control Group)	3	04 August 2017
PIS/CF: Consent form	3	03 August 2017
Participant Information Sheet	4	03 August 2017
Participant Information Sheet (Control group)	2	26 July 2017
Protocol: Bone Study Protocol(overview)	2	04 August 2017
Declined letter for previous application in respect of the same (or substantially similar) study: AUTEC Declined Ethics Letter	1	18 July 2017
CVs for other Investigators: Co-Investigator CV Winwood	1	19 July 2017
CVs for other Investigators: CV Professor Cronin	1	26 July 2017
Evidence of scientific review: PGR9 AUT Doctoral confirmation	2	26 July 2017
Evidence of scientific review: Toi Ohomai Ethics committee funding approval	2	26 July 2017
Covering Letter: Covering letter	2	04 August 2017
Covering Letter: Revisions requested by HDEC	1	30 August 2017
Survey/questionnaire: Food Diary Collection Template	1	30 August 2017



Health
and
Disability
Ethics
Committees

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27 September 2019

Ms Tracey Clissold
Toi Ohomai Institute of Technology
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Windemere Campus
Private Bag 12001
Tauranga 3143

Dear Ms Clissold,

Re:	**Ethics ref:**	**17/NTB/155/AM01**
	Study title:	The chronic effects of a quantified jump-landing programme on bone health in premenopausal women.

I am pleased to advise that this annual progress report has been *approved*, following review by the Chairperson of the Northern B Health and Disability Ethics Committee on 9 September 2019. Existing approval remains valid.

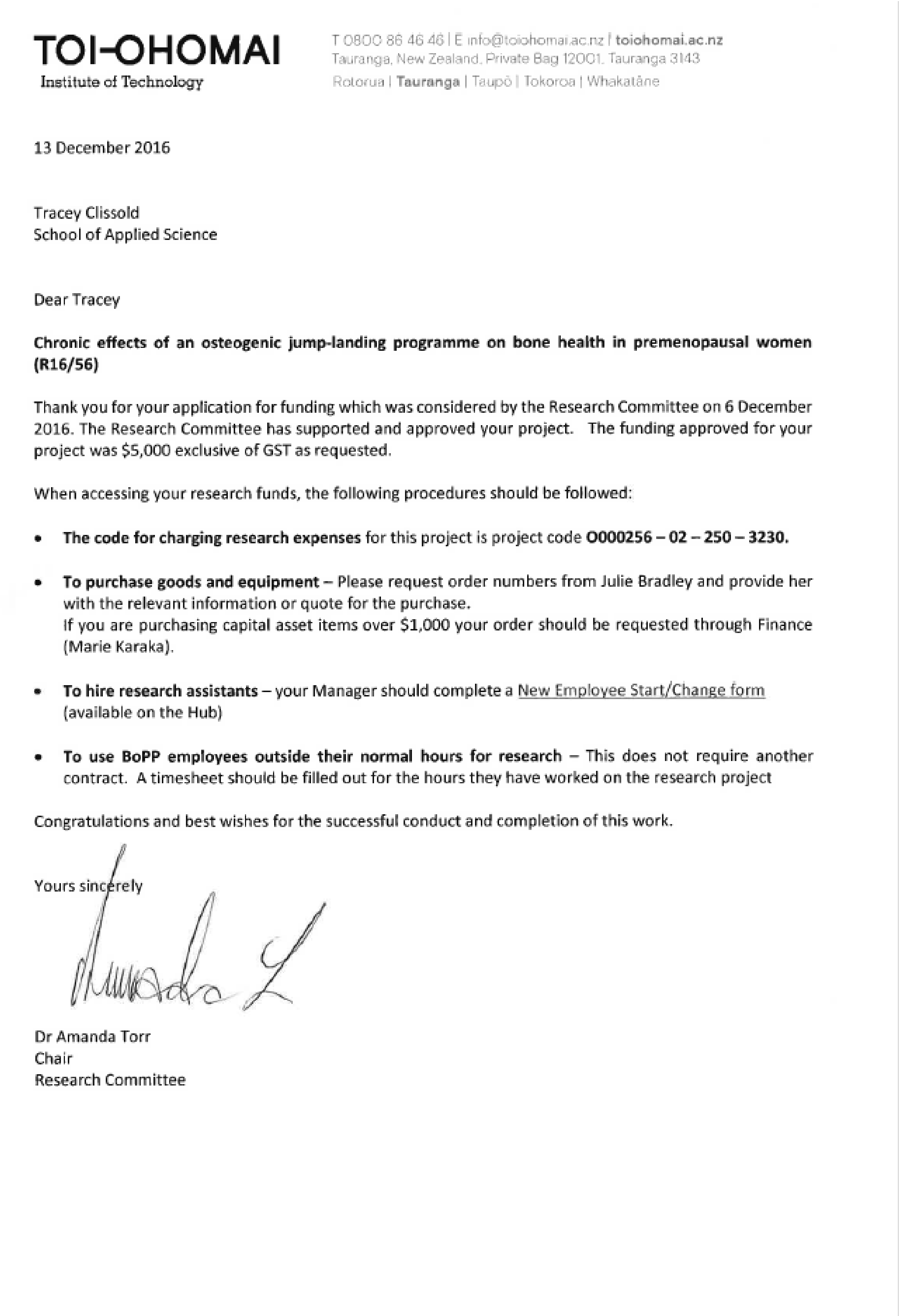
Your next progress report is due by **6 September 2020.**

Please don't hesitate to contact the HDEC secretariat for further information. We wish you all the best for your study.

Yours sincerely,

Mrs Kate O'Connor
Chairperson
Northern B Health and Disability Ethics Committee

Encl: appendix A: documents submitted



TOI-OHOMAI
Institute of Technology

T 0800 86 46 46 | E info@toiohomai.ac.nz | toiohomai.ac.nz
Tauranga, New Zealand, Private Bag 12001, Tauranga 3143
Rotorua | **Tauranga** | Taupō | Tokoroa | Whakatāne

13 December 2016

Tracey Clissold
School of Applied Science

Dear Tracey

Chronic effects of an osteogenic jump-landing programme on bone health in premenopausal women (R16/56)

Thank you for your application for funding which was considered by the Research Committee on 6 December 2016. The Research Committee has supported and approved your project. The funding approved for your project was $5,000 exclusive of GST as requested.

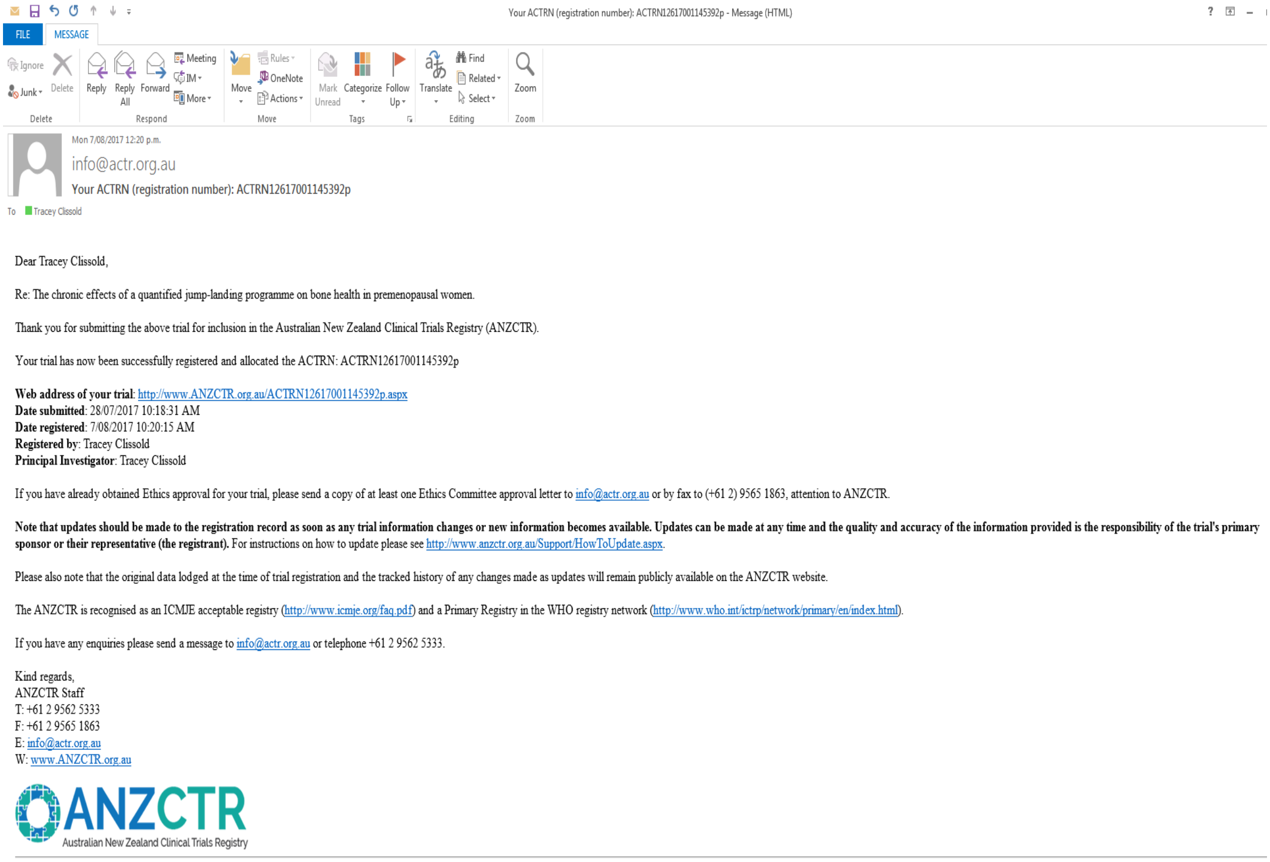
When accessing your research funds, the following procedures should be followed:

- **The code for charging research expenses** for this project is project code **O000256 – 02 – 250 – 3230.**
- **To purchase goods and equipment** – Please request order numbers from Julie Bradley and provide her with the relevant information or quote for the purchase.
  If you are purchasing capital asset items over $1,000 your order should be requested through Finance (Marie Karaka).
- **To hire research assistants** – your Manager should complete a New Employee Start/Change form (available on the Hub)
- **To use BoPP employees outside their normal hours for research** – This does not require another contract. A timesheet should be filled out for the hours they have worked on the research project

Congratulations and best wishes for the successful conduct and completion of this work.

Yours sincerely

Dr Amanda Torr
Chair
Research Committee



Your ACTRN (registration number): ACTRN12617001145392p - Message (HTML)

Mon 7/08/2017 12:20 p.m.

info@actr.org.au

Your ACTRN (registration number): ACTRN12617001145392p

To Tracey Clissold

Dear Tracey Clissold,

Re: The chronic effects of a quantified jump-landing programme on bone health in premenopausal women.

Thank you for submitting the above trial for inclusion in the Australian New Zealand Clinical Trials Registry (ANZCTR).

Your trial has now been successfully registered and allocated the ACTRN: ACTRN12617001145392p

Web address of your trial: http://www.ANZCTR.org.au/ACTRN12617001145392p.aspx
Date submitted: 28/07/2017 10:18:31 AM
Date registered: 7/08/2017 10:20:15 AM
Registered by: Tracey Clissold
Principal Investigator: Tracey Clissold

If you have already obtained Ethics approval for your trial, please send a copy of at least one Ethics Committee approval letter to info@actr.org.au or by fax to (+61 2) 9565 1863, attention to ANZCTR.

Note that updates should be made to the registration record as soon as any trial information changes or new information becomes available. Updates can be made at any time and the quality and accuracy of the information provided is the responsibility of the trial's primary sponsor or their representative (the registrant). For instructions on how to update please see http://www.anzctr.org.au/Support/HowToUpdate.aspx.

Please also note that the original data lodged at the time of trial registration and the tracked history of any changes made as updates will remain publicly available on the ANZCTR website.

The ANZCTR is recognised as an ICMJE acceptable registry (http://www.icmje.org/faq.pdf) and a Primary Registry in the WHO registry network (http://www.who.int/ictrp/network/primary/en/index.html).

If you have any enquiries please send a message to info@actr.org.au or telephone +61 2 9562 5333.

Kind regards,
ANZCTR Staff
T: +61 2 9562 5333
F: +61 2 9565 1863
E: info@actr.org.au
W: www.ANZCTR.org.au

Appendix 3a. Participant Information Letter and Consent Form (Study’s 1, 2 and 3)

Information for Participants

Participant Information Sheet

Participant Information Sheet 31/08/16

To quantify and the osteogenic benefit of jumping exercises with and without instructions.

An Invitation

My name is Tracey Clissold. I would like to invite you to participate in a study that will investigate the ground reaction forces for a selection of jumping and hopping exercises shown to benefit bone.

Your participation is voluntary and will provide an opportunity to investigate parameters of bone health considered important during the critical premenopausal period. You may withdraw from the study at any time prior to the completion of data collection with no adverse consequences. The goal of the researchers is to have the results of this study published in a peer-reviewed journal and presented at a national conference. The data collected for this study may also be used in a future study.

What is the purpose of this research?

Osteoporosis is a silent epidemic responsible for bone fractures in 56% of NZ woman from 60 years of age. Resistance exercise programmes are a way of preventing and reducing osteoporosis and have the advantage of being an efficient, safe and inexpensive way of improving bone strength.

The purpose of this study is to quantify the ground reaction forces associated with a countermovement jump and other jumping and hopping exercises, combined with a reactive jump, after one session of instruction in premenopausal women.

Am I eligible to participate in this research?

You are invited to participate in this study if you meet our eligibility requirements. To be included you must:

- Be female.
- Be between the ages of 30 and 55 years (with a regular menstrual cycle).
- Be in good health, free of injury and chronic illness.

What will happen in this research?

You will be required to participate in two testing sessions scheduled one week apart, and a familiarisation session scheduled several days prior to the first testing session. You will maintain your normal activity and diet regimen for the duration of the study. Testing involved in the study will take place in the Bay of Plenty Polytechnic Sports Science laboratory located in Te Pare a Ruahine (Aquatic Centre). These procedures include performing a variety of jumping exercises, getting weighed, having your body fat percentage measured and filling out questionnaires. In addition, you will be required to wear an accelerometer device for the 7 days between testing sessions to collect information about your habitual activity levels.

Familiarisation & Pretesting Data collection:

The exercise intervention and anthropometric testing will be done at the Bay of Plenty Aquatic and Fitness Centre and Sports Science laboratory.

Pre-testing data collection:

1. Height & Weight
2. Total tissue mass, lean mass and fat mass (Bioelectric Impedance Analysis)
3. Muscle girths (thigh, calf, upper arm)
4. Peak power using maximal vertical jump (Force platform and Vertec).
5. Physical Activity Readiness Questionnaire (PAR-Q)
6. Written Informed Consent

Measurement of your height, weight and body composition:

Your body weight will be measured without shoes using a calibrated scale, while your height will be measured with a stadiometer. Your body composition will be estimated using Bioelectrical Impedance Analysis (BIA). You will stand on the foot electrodes with bare feet whilst simultaneously holding the hand electrodes. This machine measures the resistance of the low-level electrical current to your body tissues, and it can determine the amount of fat and lean body mass on your body from this measurement. This test will take approximately 2 - 3 minutes to complete. BIA is a non-invasive completely pain-free technique for determining body composition using low voltage electrical currents which are not detectable. The researchers will ensure safety during the use of this equipment and warn participants that they cannot use this equipment if they have metal implants or a pacemaker.

Health and Training History Questionnaires:

You will be asked to fill out a questionnaire regarding your health/medical history and your exercise training history. This will take approximately 15 - 20 minutes for you to complete. You do not have to answer all the questions. You will have the opportunity to see the questionnaires before signing this consent form.

Familiarisation Protocol:

After completing the assessment of body composition and other measurements you will be familiarised with the jumping protocol which will be used in this study. This will occur after the collection of pre-testing information. The jumping protocol will require you to perform a standardised warm-up consisting of cycling for 5 minutes followed by 5 minutes of dynamic movement exercises, such as marching. After warming up you will rest for 5 minutes and then perform a series of different jumps. For example, the counter movement jump in which you squat down and jump up as quickly as possible, followed by another jump for maximum height. After completing these jumps, you will rest for 5 minutes. After resting for 5 minutes you will perform a maximal vertical jump in which you squat down and then jump as high as possible. Instruction will be given on how to perform the various jumping activities.

Jumping Session Data Collection (1 & 2):

Each participant will perform no more than 10 repetitions for each of the jumping activities. The order of the different jump tests will be randomly assigned but the basic procedure for testing will be similar to the familiarisation session.

Peak and mean vertical ground reaction forces (BW) and rate of force application (BW/sec) using force platform and g forces using accelerometer devices for the selected exercises will be collected.

Video footage may be collected for some participants for some aspects of the jump sessions. Each participant will wear several accelerometer devices in a variety of positions for all jumps, to determine reliability.

Each session is preceded by 5 - 10 minutes of warm-up and mobilisation exercises, participants will warm down and stretch to complete the session.

You will come into the laboratory on three occasions for no more than 2hr for the familiarisation session and 1 hour for each jumping session to complete the following:

1. Familiarisation session & baseline data collection (no more than 2 hours).
2. Jumping session 1 (approx. 1 hour).
3. Jumping session 2 (approx. 1 hour).

In addition, participants will be required to wear an accelerometer device for the 7-day period between testing sessions to collect data about habitual activity levels. Please see the separate accelerometer information sheet.

What are the benefits of my participation in this research?

By participating in this study, you will help increase our knowledge about preventative health care management that in the long term has the potential to reduce the direct and indirect costs of osteoporosis to the health sector. The proposed studies will inform practice and facilitate the development of educational resources. It is envisaged that the evidence from these studies will provide a unique approach for the management of bone health and the development of safe and effective training practices with additional health benefits. In addition, you will benefit from this study as you will have your body fat, girths, and strength and power levels measured. In return for your participation, you will receive a complete report of your scores on the tests and procedures and information about the results from this study.

What are the discomforts and risks and how will they be alleviated?

The following factors have been identified and discussed:

1. Anthropometry testing:

Bioelectrical Impedance Analysis (BIA) is a non-invasive completely pain-free technique for determining body composition using low voltage electrical currents which are not detectable. The primary researcher will ensure safety during the use of this equipment and warn participants they cannot use this equipment if they have metal implants or a pacemaker.

2. The actual jump testing: will carry minimal risk, as exercises selected are initially achieving the minimal threshold identified as producing osteogenic benefit to bone. All testing will be preceeded by warm up and mobilisation exercises, and these same exercises will be used to warm down the athlete (to minimise any chance of post exercise muscle soreness).

3. The questionnaires: used during pre-screening may provide questions to the participants which some potentially could find personal in nature. However, surveys will be self-administered, and will only be identified by the participant's encoded number, not by personally identifiable information. We encourage you to answer all questions in the screening questionnaires as accurately as possible. However, we acknowledge that some questions may make you may feel uncomfortable or embarrassed. Please be reassured that you do not need to answer any question that you feel uncomfortable with.

We encourage you to discuss any queries or concerns that you may have with the researchers and remind you that, up to the completion of data collection, you are able to withdraw from the study for any reason.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

Your privacy will be maintained and conflicts of interest avoided by the following procedures:

- All electronic information will be kept strictly confidential on a password protected computer.
- All written information will be kept in a single file and held in a locked storage cupboard.
- Information about you (i.e. name, training schedule, place of residence) will not be disclosed in written or electronic format utilised for conference presentations or reports.

What are the costs of participating in this research?

The only cost to you in this research is your valuable time and effort.

What opportunity do I have to consider this invitation?

It is the researcher’s intention to collect data for the jumping interventions before the Christmas break (Friday December 5 –Monday December 15). Therefore, there is only a short time frame for you to consider participating in the study. Please discuss any queries, including cultural needs, you may have about the study with the researchers and remember your participation is voluntary and, up to the completion of data collection you may withdraw from the study without any adverse consequences of any kind.

How do I agree to participate in this research?

If your eligibility is confirmed during the screening and baseline phases and you would like to participate in the study, please read and sign the consent form and hand it back to Tracey Clissold.

Whom do I contact for further information about this research?

Researcher: Tracey Clissold
tracey.clissold@boppoly.ac.nz 0212097022, 0800BOPPOLY ext.8681

Research Supervisor: Dr Paul Winwood
paul.winwood@boppoly.ac.nz 0800BOPPOLY ext.8580

Approved by the Bay of Plenty Polytechnic Research Committee on 11 September 2014

Consent Form

Project title: **To quantify and the osteogenic benefit of jumping exercises with and without instructions.**

Project Supervisor: Dr Paul Winwood paul.winwood@boppoly.ac.nz
Researcher: Tracey Clissold tracey.clissold@boppoly.ac.nz

Please tick (√)

○ I have read and understood the information provided about this research project in the Information Sheet.

○ I have had an opportunity to ask questions and to have them answered.

○ I understand that my data will be recorded during testing for research purposes only.

○ I understand that I may withdraw myself or any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.

○ I am not suffering from any illness, high blood pressure, or injury that impairs my physical performance to perform resistance training.

○ I understand that my participation in this study is confidential and that no material, which could identify me, will be used in any reports on this study.

○ I have been verbally informed and fully understand the procedures and potential risks of the tests in which I am a subject.

○ I understand that my participation in this study is confidential and that no material, which could identify me, will be used in any reports on this study.

○ I agree to take part in this research.

○ I consent to the indefinite storage of my data (tick one): Yes ○ No ○

○ I consent to be contacted in future in the case of a follow up study (tick one): Yes ○ No ○

○ I wish to receive a copy of the report from the research (tick one): Yes ○ No ○

Participant's Signature: ……………………………………………………………………………………

Participant's name: ……………………………………………………………………………………

Participants Contact Details:
……………………………………………………………………………………………

……………………………………………………………………………………………

Date: ……………………………………………

Approved by the Bay of Plenty Polytechnic Research Committee on 11 September 2014

Note: The Participant should retain a copy of this form.

Appendix 3b. Participant Information Letter and Consent Form (Study's 5 and 6)

TOI-OHOMAI Institute of Technology | AUT UNIVERSITY SPORT+ RECREATION

Participant Information Sheet

Study title: Bone health in premenopausal women	
Locality: Tauranga	**Ethics committee ref.**: 17/NTB/155
Lead investigator: Tracey Clissold	**Contact phone number**: 021 2097022

You are invited to take part in a study starting in November 2017. Whether or not you take part is your choice. If you don't want to take part, you don't have to give a reason. If you do want to take part now, but change your mind later, you can pull out of the study at any time.

This Participant Information Sheet will help you decide if you'd like to take part. It sets out why we are doing the study, what your participation would involve, what the benefits and risks to you might be, and what would happen after the study ends. We will go through this information with you and answer any questions you may have. You do not have to decide today whether or not you will participate in this study. Before you decide you may want to talk about the study with other people, such as family, whānau, friends, or healthcare providers. Feel free to do this.

If you agree to take part in this study, you will be asked to sign the Consent Form on the last page of this document. You will be given a copy of both the Participant Information Sheet and the Consent Form to keep.

This document is 8 pages long, including the Consent Form. Please make sure you have read and understood all the pages.

WHAT IS THE PURPOSE OF THE STUDY?

My name is Tracey Clissold and I teach on the AUT Bachelor of Sport and Recreation at Toi Ohomai Institute of Technology at Windemere campus. My goal is to have the results of this study published in a peer-reviewed journal and presented at national and international conferences. This research will also contribute towards an AUT Doctoral qualification for the primary researcher. Research scholarships from Toi Ohomai and AUT have been awarded to enable this research to take place.

The purpose of this study is to determine the effects of a jump-landing programme on bone health in premenopausal women for a period of 12 months. The measurement of bone mineral density and bone geometry, will provide an opportunity to determine the time course of the bones response to factors which contribute to overall bone strength and fracture resistance. Researchers have shown exercise regimes involving impact forces to be a powerful bone stimulus resulting in mineralisation in areas where the stress is applied, however specific protocols to optimise bone health are currently lacking.

You will be assigned into either the training (doing the jump-landing programme) or control (maintain normal activity levels) groups (based on your willingness to participate in the daily jump-landing programme (in your own home), and attend jump-landing group classes (at Toi Ohomai campuses) regularly. The purpose of the control group is to track the normal age-related changes occurring to bone and provide baseline measures for the study. Evidence from this study has potential to inform future exercise recommendations used to improve bone health during the critical premenopausal period, and both reduce and delay the incidence of osteoporotic fracture in the years post menopause.

Any questions or concerns regarding the nature of this project should be notified in the first instance to the Coordinating Investigator, Tracey Clissold, tracey.clissold@toiohomai.ac.nz (07) 557 8681, or 021 2097022

Approved by the Health and Disability Ethics Committee on *September 7, 2017*. Reference number 17/NTB/155.

WHAT WILL MY PARTICIPATION IN THE STUDY INVOLVE?

You are invited to participate in this study if you meet our eligibility requirements. To be included you must:

- Be female.
- Be between the ages of 30 and 50 years (with a regular menstrual cycle).
- Not be pregnant.
- Be in good health, free of injury and chronic illness (including not having a recent or current musculoskeletal injury, osteoarthritis and any condition of impaired balance or coordination).
- Not currently (or in the past 12 months), engaged in regular physical activity involving impact exercise.

All Participants: You will be required to attend five testing sessions scheduled at baseline, 3, 6, 9 and 12 months (approx. 1 hour). Testing will take place in the Sports Science laboratory, DEXA clinic and "Fun House" located in the Aquatic Centre at Toi Ohomai Institute of Technology.

Testing procedures are detailed below and will be made available to participants on request. You will be asked to maintain your normal activity and diet regimen for the duration of the study.

1. Height and Weight: During the familiarisation session participants will fill in pre-screening questionnaires and have their height measured in bare feet, using a wall mounted stadiometer. Weight will be measured using scales.

2. Jump height: The Vertec Yardstick, a portable device used to measure vertical jump height, will be used to determine baseline jumping ability. Participants will be encouraged to touch the highest rung of the Vertec device.

3. Balance: Balance test (i.e. the Stork), using a balance force plate, will be used to measure baseline and progressive improvement in balance throughout the course of the study.

4. Food Diary: A 3-day food diary (including 2-week days and 1 weekend day), will be used to measure dietary status at baseline. This will involve writing down everything you eat and drink for a period of 3 days. You will be asked to provide descriptions of food (brands, cooking method etc), and amounts (standard household measures, cups, tsp, Tbs etc). Food diary collection sheets and an information sheet to outline the procedure will be provided. Dietary assessment software will be used to determine average estimated energy intake and calcium intake, from food, fluids and supplements. Supplemental calcium may be provided to ensure the recommended dietary intake of 1000mg is achieved for all participants.

5. Training Diaries and Activity Logs: You will be required to complete training diaries that will be uploaded to a group spreadsheet to be accessed online. Activity logs will be completed to determine activity levels. All templates will be provided.

6. Bone Mineral Density (BMD) and Body Composition (DEXA): Bone mineral density will be measured at the proximal femur (neck and trochanter), and lumbar spine (L1 - L4) using DEXA scanning. This scanning procedure will involve lying still in a supine position on the scanner for 15 - 20 minutes. This will allow for scanning for BMD and body composition to be performed. The amount of radiation used for this scanning is extremely small; less than one-tenth the dose of a standard chest x-ray, and less than a day's exposure to natural radiation. The measurements will be carried out by licensed technicians.

Summary of testing during 12-month study:

Name of test	How often?	How much time?	What's the cost?
1. Weight and Height	5 times (at the start, 3, 6, 9 and 12 months).	2 minutes	No cost
2. Jump Height	5 times (at the start, 3, 6, 9 and 12 months).	2 - 3 minutes	No cost
3. Balance	5 times. At the start, 3, 6, 9 and 12 months	2 - 3 minutes	No cost
4. Food Diary (3-day)	3 times. At the start, 6, and 12 months	10 - 15 minutes (each day)	No cost
5. Activity Diary	3 times. At the start, 6, and 12 months	5 - 10 minutes (each day)	No cost
6. Bone Density	3 times. At the start, 6, and 12 months	15 - 20 minutes	No cost

Texts & Facebook

Communication will be maintained via phone calls, text messages and emails, with participants encouraged to contact the researcher any time about any concerns or issues they might have. The use of social media (i.e. Facebook) will be an option to provide social interaction among participants.

The Jump-Landing Programme (Treatment group only):

You will be required to participate in two familiarisation training sessions where you will get to practice proper technique for each of the jumps (1 hour). In addition, you will be required to attend weekly group exercise sessions (jump-landing classes) (20 - 30 min) and perform the brief jump-landing programme five times each week in your own home (15 - 20 min).

The training programme will include combinations made from the following jumps; 1) countermovement jump, 2) drop jump, 3) star jump, 4) stride jump, 5) vertical hop, 6) lateral hop, and 7) forward hop. It is proposed that this programme will increase in number of ground contacts and technical difficulty in a safe progressive manner over the 12-month period. You will be required to perform the daily (5 times/ week), jump-landing programme (in your own homes), and attend jump-landing group classes regularly (ideally weekly).

The jump-landing exercise programme is expected to take about 20 minutes to complete including a brief warm up and cool down, and can be performed at a time and place that suits you. Two of the exercises you will be performing are shown in the picture below, including; the countermovement jump (on left), and 20cm (standard step height) drop jump (on right).

WHAT ARE THE POSSIBLE BENEFITS AND RISKS OF THIS STUDY?

By participating in this study, you will help increase our knowledge about preventative health care management that in the long term has the potential to reduce the direct and indirect costs of osteoporosis to the health sector. In addition, you will benefit from this study as you will have your body composition, leg strength, diet and bone mineral density measured. You will receive a complete report of your test results and information about the results from this study.

We are confident that all testing and jumping will be safe with minimal discomfort or risk, however we encourage you to discuss any queries or concerns that you may have with the researchers and remind you that, up to the completion of data collection, you are able to withdraw from the study for any reason.

WHO PAYS FOR THE STUDY?

There will be no costs incurred by the participants, just your time and effort!

WHAT IF SOMETHING GOES WRONG?

If you were injured in this study, which is unlikely, you would be eligible for compensation from ACC just as you would be if you were injured in an accident at work or at home. You will have to lodge a claim with ACC, which may take some time to assess. If your claim is accepted, you will receive funding to assist in your recovery. If you have private health or life insurance, you may wish to check with your insurer that taking part in this study won’t affect your cover.

WHAT ARE MY RIGHTS?

Your participation is voluntary and will provide an opportunity to investigate bone health during the critical premenopausal period. You may withdraw from the study at any time prior to the completion of data collection with no adverse consequences.

In return for your participation, you will receive a complete report of your test results and information about the results from this study. All data will be safely stored in the researchers locked office and any data used for research purposes will be de-identified, to maintain strict confidentiality.

WHAT HAPPENS AFTER THE STUDY OR IF I CHANGE MY MIND?

Individual results will be provided to participants and a report of the findings (with de-identified data) will be communicated to the participants. An academic publication from the findings will also be sought.

Research findings will be used to develop resources and workshops for study participants, the wider Institutions (Toi Ohomai Institute of Technology and Auckland University of Technology), and the communities via Regional Sports Trusts. Media exposure will also be organised to spread the information to a wider audience.

Your privacy will be maintained and conflicts of interest avoided by the following procedures:

- ➢ All electronic information will be kept strictly confidential on a password protected computer.
- ➢ All written information will be kept in a single file and held in a locked storage cupboard.
- ➢ Information about you (i.e. name, training schedule, place of residence) will not be disclosed in written or electronic format utilised for conference presentations or reports.

WHO DO I CONTACT FOR MORE INFORMATION OR IF I HAVE CONCERNS?

If you have any questions, concerns or complaints about the study at any stage, you can contact:

Tracey Clissold (Coordinating Investigator)
0212097022
tracey.clissold@toiohomai.ac.nz

If you want to talk to someone who isn’t involved with the study, you can contact an independent health and disability advocate on:

Phone: 0800 555 050
Fax: 0800 2 SUPPORT (0800 2787 7678)
Email: advocacy@hdc.org.nz

For Maori health support please contact : Dr Ana Morrison (ana.morrison@toiohomai.ac.nz)

You can also contact the health and disability ethics committee (HDEC) that approved this study on:

Phone:	0800 4 ETHICS
Email:	hdecs@moh.govt.nz

TOI-OHOMAI Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Consent Form

* If you need an INTERPRETER, please tell us and we will do our best to provide one.

Please tick to indicate you consent to the following:

I have read, or have had read to me in my first language, and I understand the Participant Information Sheet.	Yes ☐	No ☐
I have been given sufficient time to consider whether or not to participate in this study.	Yes ☐	No ☐
I have had the opportunity to use a legal representative, whanau/ family support or a friend to help me ask questions and understand the study.	Yes ☐	No ☐
I am satisfied with the answers I have been given regarding the study and I have a copy of this consent form and information sheet.	Yes ☐	No ☐
I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time.	Yes ☐	No ☐
I consent to the research staff collecting and processing my information, including information about my health.	Yes ☐	No ☐
If I decide to withdraw from the study, I agree that the information collected about me up to the point when I withdraw may continue to be processed.	Yes ☐	No ☐
I understand that there may be risks associated with DXA testing in the event of becoming pregnant. I undertake to inform my partner of the risks and to take responsibility for the prevention of pregnancy.	Yes ☐	No ☐
I agree to an approved auditor appointed by the New Zealand Health and Disability Ethic Committees, or any relevant regulatory authority or their approved representative reviewing my relevant medical records for the sole purpose of checking the accuracy of the information recorded for the study.	Yes ☐	No ☐
I understand that my participation in this study is confidential and that no material, which could identify me personally, will be used in any reports on this study.	Yes ☐	No ☐
I understand the compensation provisions in case of injury during the study.	Yes ☐	No ☐

I know who to contact if I have any questions about the study in general.	Yes ☐	No ☐
I understand my responsibilities as a study participant.	Yes ☐	No ☐
I wish to receive a summary of the results from the study.	Yes ☐	No ☐

Declaration by participant:
I hereby consent to take part in this study.

Participant’s name: ______________________________

Signature: ____________________ Date: ____________________

Declaration by member of research team:

I have given a verbal explanation of the research project to the participant, and have answered the participant’s questions about it.

I believe that the participant understands the study and has given informed consent to participate.

Researcher’s name: ______________________________

Signature: ____________________ Date: ____________________

Appendix 4a: Pre-exercise Questionnaire (Study's 1, 2 and 3)

Pre –Exercise Questionnaire

(Adapted from the Bay of Plenty Polytechnics pre-screen questionnaire)

Personal Information:
Note: All the following information will be treated with the strictest of confidence and is being collected as part of this research only.

If you require a photocopy of this pre-exercise questionnaire please indicate: circle. Yes/No

Name	Age*
Email contact	Phone

Emergency contact person and phone number

Doctor's name and phone number

Medical History:

Are you currently on any prescribed medication?

No

Yes (please specify)

Do you have any current or recent injuries (eg. muscle, joint or bone) that may affect your ability to take part in this research study?

No

Yes (please specify)

____

Do you suffer from any of the following - Neck, back, knee or ankle pain?

No

Yes (please specify)

____

Do you, or have you ever had any of the following?
(Please indicate by circling)

Respiratory problems (asthma, bronchitis)

Diabetes

Stroke Circulatory problems

Anaemia

Hernia

Heart trouble (pain or tightness in chest)

Epilepsy

Blood pressure problems

Dizziness or fainting

Rheumatic fever

Are there any conditions not listed above that you would like to mention?

No

Yes (please specify)

____

Fitness Profile:

Briefly describe any planned physical activity you participate in each week.

______________________________type of activity (hours)

______________________________type of activity (hours)

______________________________type of activity (hours)

Pre-screening tests: (Taken by researcher)

Height* ___________________________cm

Current weight* ___________________________kg's

BMI ___________________________

Blood pressure ___________________________mmHg

Body fat percentage*___________________________ %

Note: Fields with a * will be entered into the participants' data and the mean values of all participants will be recorded in the final report

Appendix 4b. Pre-exercise Questionnaire (Study's 5 and 6)

TOI-OHOMAI
Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Pre –Exercise Questionnaire

(Adapted from Toi Ohomai Aquatic Centre Pre-Exercise Questionnaire)

Personal Information:

Note: All the following information will be treated with the strictest of confidence and is being collected as part of this research only.

If you require a photocopy of this pre-exercise questionnaire please indicate: circle. Yes/No

Name ______________________________ Age* ______________

Email contact ______________________________ Phone ______________

Emergency contact person and phone number ______________________________

Doctor's name and phone number ______________________________

Medical History:

Are you currently on any prescribed medication?

No

Yes (please specify)

____

Do you have any current or recent injuries (eg. muscle, joint or bone) that may affect your ability to take part in this research study?

No

Yes (please specify)

____

Do you suffer from any of the following - Neck, back, knee or ankle pain?

No

Yes (please specify)

____

Are you pregnant?

No

Yes

Do you, or have you ever had any of the following? (Please indicate by circling)

Respiratory problems (asthma, bronchitis)

Diabetes

Stroke Circulatory problems

Anaemia

Hernia

Heart trouble (pain or tightness in chest)

Epilepsy

Blood pressure problems

Dizziness or fainting

Rheumatic fever

Are there any conditions not listed above that you would like to mention?

No

Yes (please specify)

____

Fitness Profile:

Briefly describe any planned physical activity you participate in each week.

______________________________type of activity (hours)

______________________________type of activity (hours)

_______________________________type of activity (hours)

Pre-screening tests: (Taken by researcher)

Height* _____________________________cm

Current weight* _____________________________kg’s

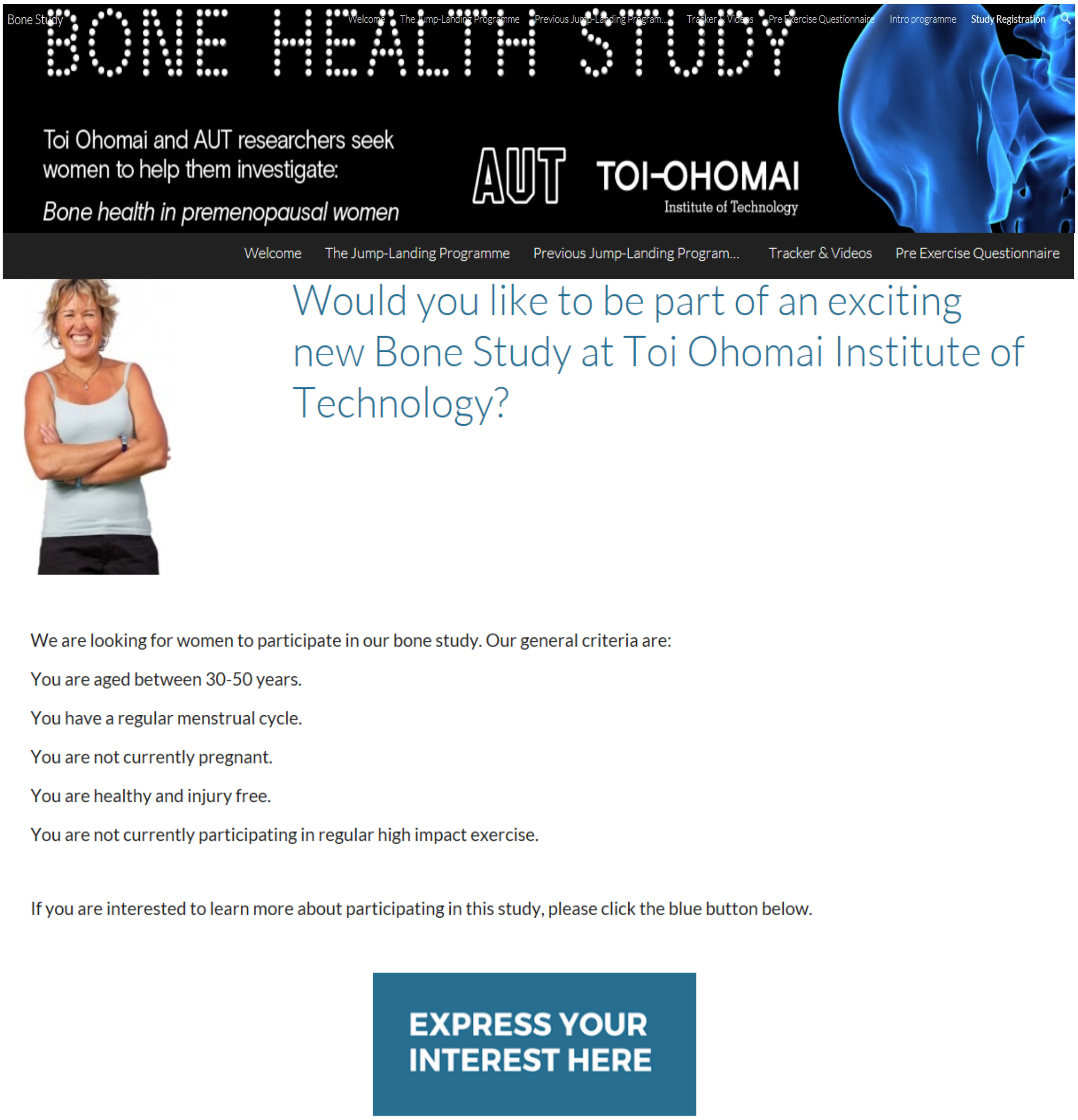
BMI* _____________________________

Blood pressure _____________________________mmHg

Body fat percentage*_____________________________ %

Note: Fields with a ***** will be entered into the participants’ data and the mean values of all participants will be recorded in the final report

Appendix 4c. Online Expression of Interest and Registration Form (Study's 5 and 6)



Toi Ohomai and AUT researchers seek women to help them investigate:

Bone health in premenopausal women

Would you like to be part of an exciting new Bone Study at Toi Ohomai Institute of Technology?

We are looking for women to participate in our bone study. Our general criteria are:

You are aged between 30-50 years.

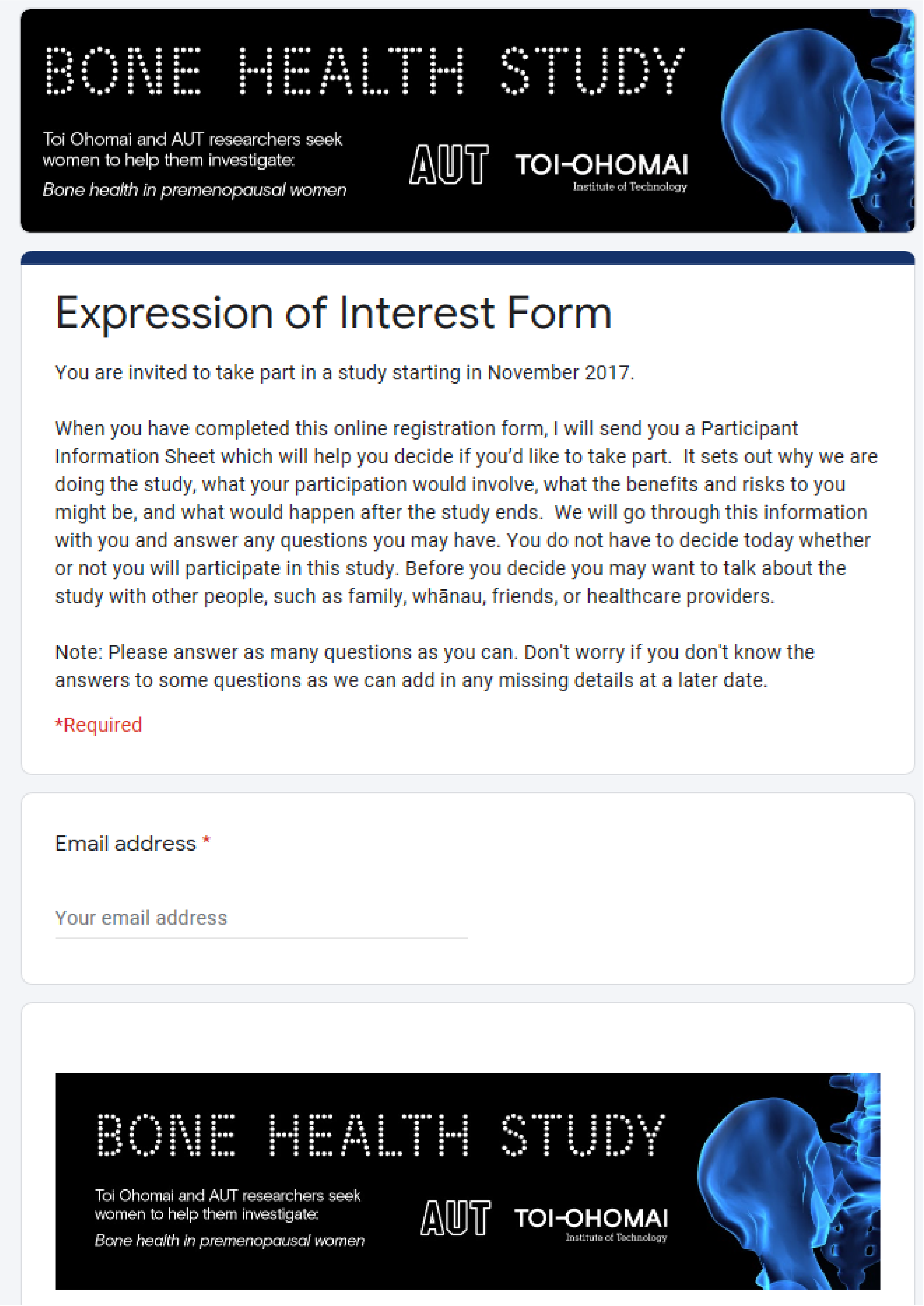
You have a regular menstrual cycle.

You are not currently pregnant.

You are healthy and injury free.

You are not currently participating in regular high impact exercise.

If you are interested to learn more about participating in this study, please click the blue button below.



Expression of Interest Form

You are invited to take part in a study starting in November 2017.

When you have completed this online registration form, I will send you a Participant Information Sheet which will help you decide if you'd like to take part. It sets out why we are doing the study, what your participation would involve, what the benefits and risks to you might be, and what would happen after the study ends. We will go through this information with you and answer any questions you may have. You do not have to decide today whether or not you will participate in this study. Before you decide you may want to talk about the study with other people, such as family, whānau, friends, or healthcare providers.

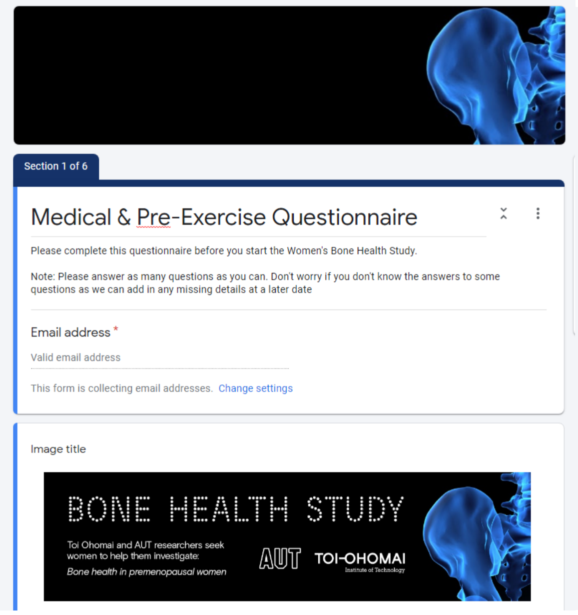
Note: Please answer as many questions as you can. Don't worry if you don't know the answers to some questions as we can add in any missing details at a later date.

*Required

Email address *

Your email address

Appendix 4d. Online Medical and Pre-exercise Questionnaire (Study's 5 and 6)



Section 1 of 6

Medical & Pre-Exercise Questionnaire

Please complete this questionnaire before you start the Women's Bone Health Study.

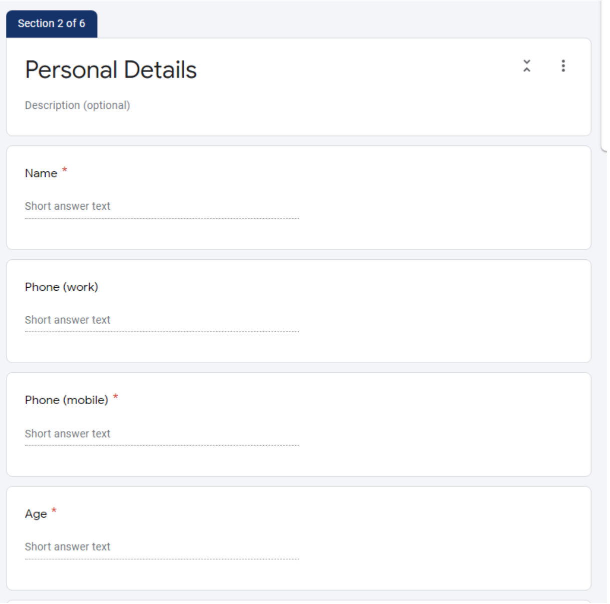
Note: Please answer as many questions as you can. Don't worry if you don't know the answers to some questions as we can add in any missing details at a later date

Email address *

Valid email address

This form is collecting email addresses. Change settings

Image title



Section 2 of 6

Personal Details

Description (optional)

Name *

Short answer text

Phone (work)

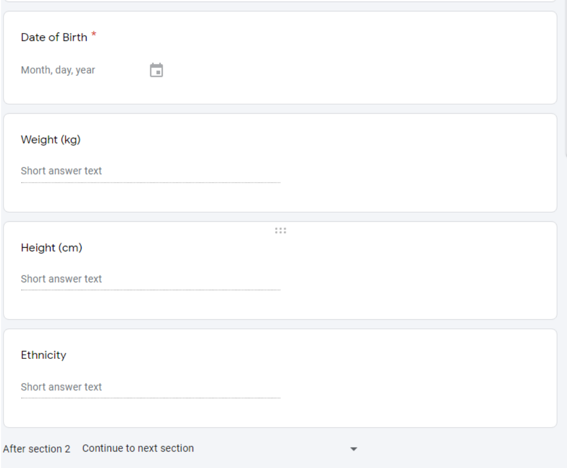
Short answer text

Phone (mobile) *

Short answer text

Age *

Short answer text



Date of Birth *

Month, day, year

Weight (kg)

Short answer text

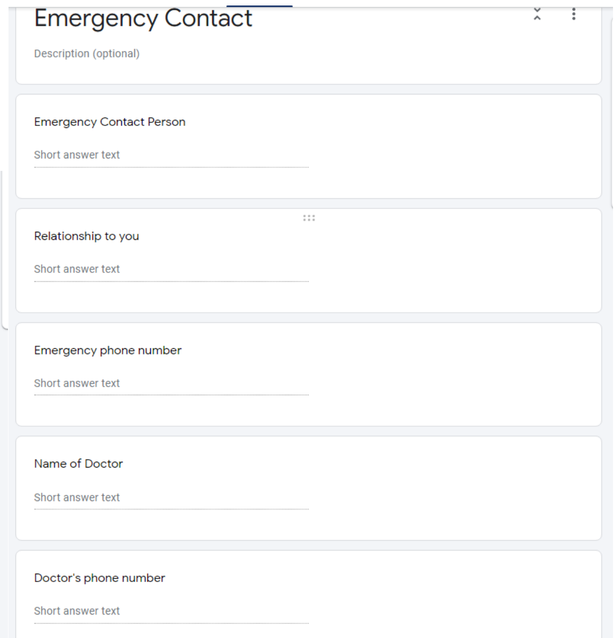
Height (cm)

Short answer text

Ethnicity

Short answer text

After section 2 Continue to next section



Emergency Contact

Description (optional)

Emergency Contact Person

Short answer text

Relationship to you

Short answer text

Emergency phone number

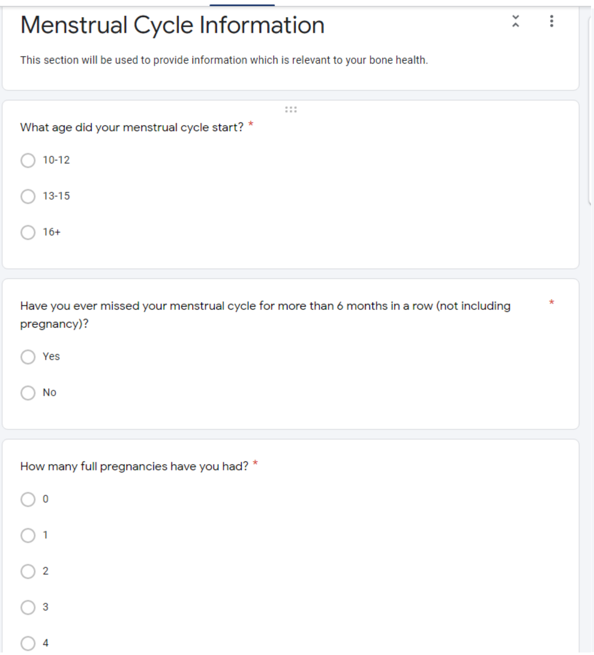
Short answer text

Name of Doctor

Short answer text

Doctor's phone number

Short answer text



Menstrual Cycle Information

This section will be used to provide information which is relevant to your bone health.

What age did your menstrual cycle start? *

○ 10-12

○ 13-15

○ 16+

Have you ever missed your menstrual cycle for more than 6 months in a row (not including pregnancy)? *

○ Yes

○ No

How many full pregnancies have you had? *

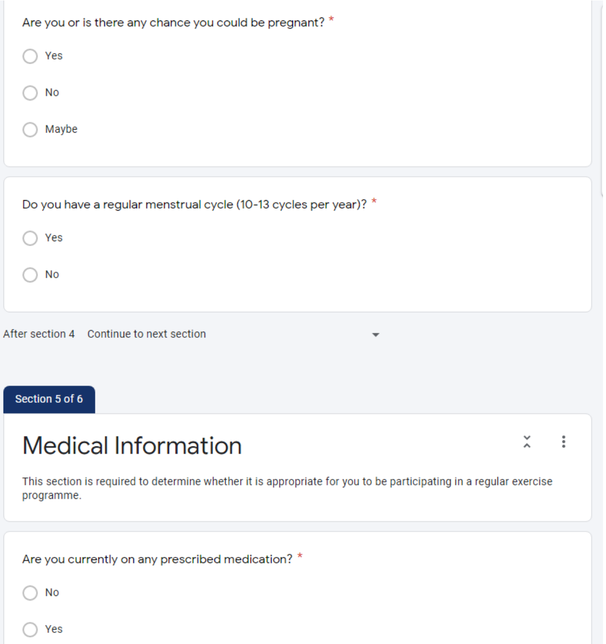
○ 0

○ 1

○ 2

○ 3

○ 4



Are you or is there any chance you could be pregnant? *

○ Yes

○ No

○ Maybe

Do you have a regular menstrual cycle (10-13 cycles per year)? *

○ Yes

○ No

After section 4 Continue to next section

Section 5 of 6

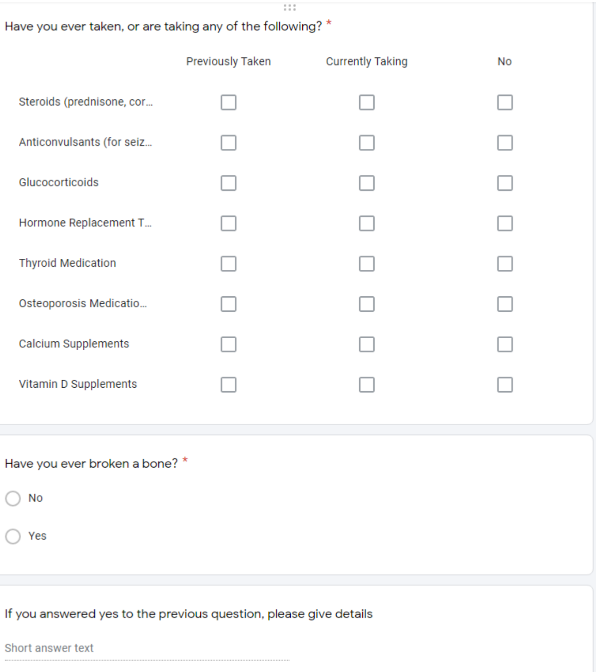
Medical Information

This section is required to determine whether it is appropriate for you to be participating in a regular exercise programme.

Are you currently on any prescribed medication? *

○ No

○ Yes



Have you ever taken, or are taking any of the following? *

	Previously Taken	Currently Taking	No
Steroids (prednisone, cor…	☐	☐	☐
Anticonvulsants (for seiz…	☐	☐	☐
Glucocorticoids	☐	☐	☐
Hormone Replacement T…	☐	☐	☐
Thyroid Medication	☐	☐	☐
Osteoporosis Medicatio…	☐	☐	☐
Calcium Supplements	☐	☐	☐
Vitamin D Supplements	☐	☐	☐

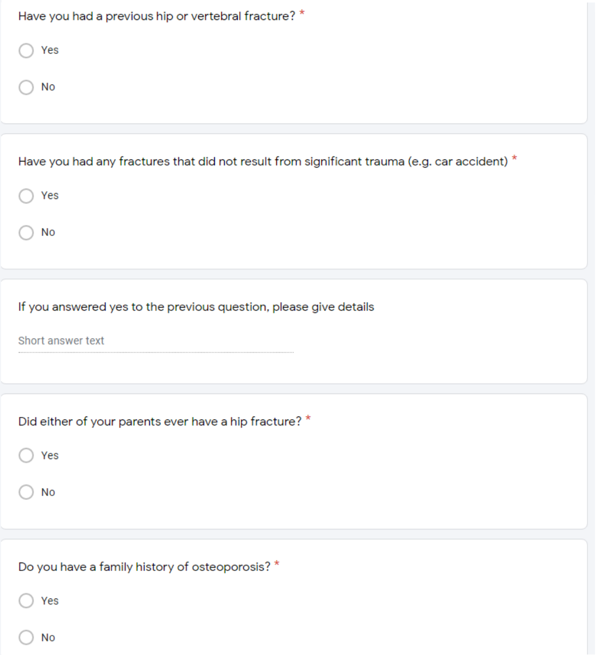
Have you ever broken a bone? *

○ No

○ Yes

If you answered yes to the previous question, please give details

Short answer text



Have you had a previous hip or vertebral fracture? *

○ Yes

○ No

Have you had any fractures that did not result from significant trauma (e.g. car accident) *

○ Yes

○ No

If you answered yes to the previous question, please give details

Short answer text

Did either of your parents ever have a hip fracture? *

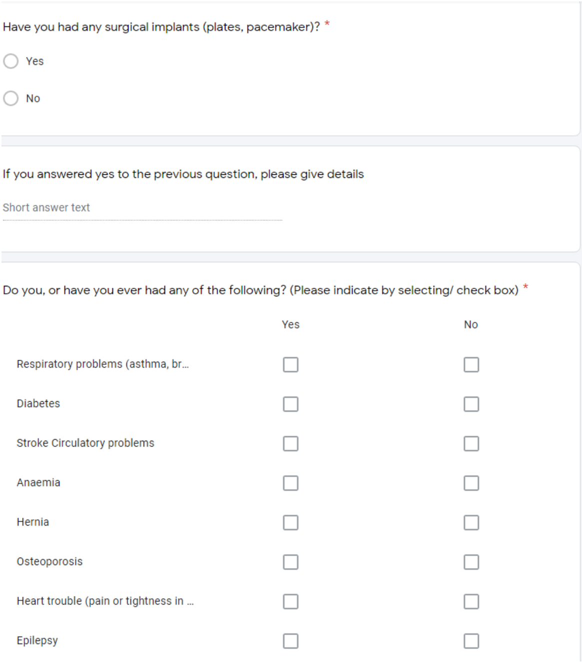
○ Yes

○ No

Do you have a family history of osteoporosis? *

○ Yes

○ No



Have you had any surgical implants (plates, pacemaker)? *

○ Yes

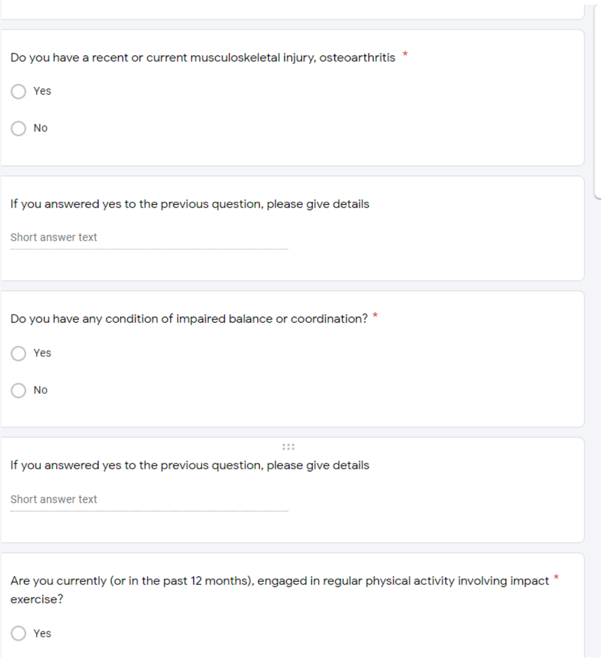
○ No

If you answered yes to the previous question, please give details

Short answer text

Do you, or have you ever had any of the following? (Please indicate by selecting/ check box) *

	Yes	No
Respiratory problems (asthma, br...	☐	☐
Diabetes	☐	☐
Stroke Circulatory problems	☐	☐
Anaemia	☐	☐
Hernia	☐	☐
Osteoporosis	☐	☐
Heart trouble (pain or tightness in ...	☐	☐
Epilepsy	☐	☐



Do you have a recent or current musculoskeletal injury, osteoarthritis *

○ Yes

○ No

If you answered yes to the previous question, please give details

Short answer text

Do you have any condition of impaired balance or coordination? *

○ Yes

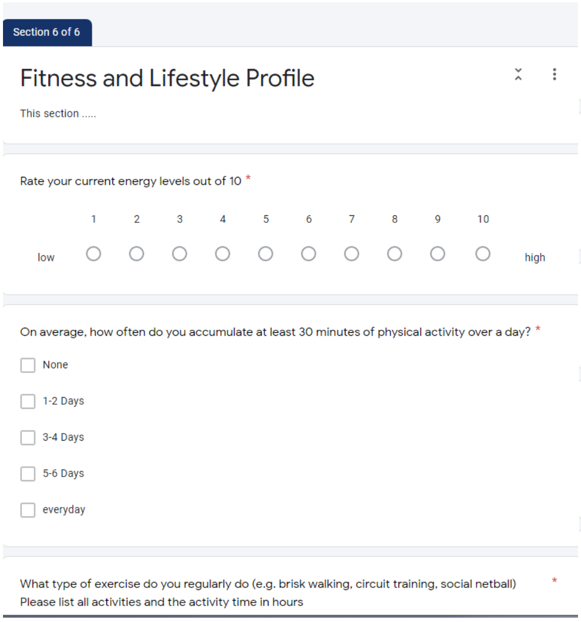
○ No

If you answered yes to the previous question, please give details

Short answer text

Are you currently (or in the past 12 months), engaged in regular physical activity involving impact exercise? *

○ Yes



Section 6 of 6

Fitness and Lifestyle Profile

This section .....

Rate your current energy levels out of 10 *

	1	2	3	4	5	6	7	8	9	10	
low	○	○	○	○	○	○	○	○	○	○	high

On average, how often do you accumulate at least 30 minutes of physical activity over a day? *

☐ None

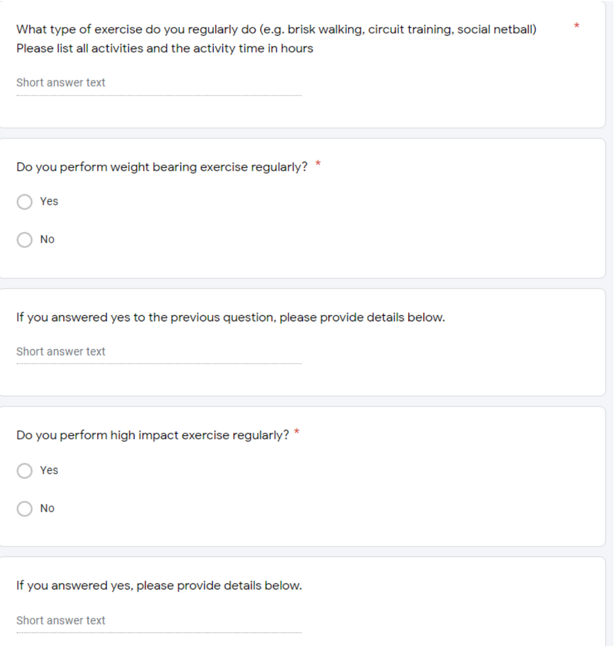
☐ 1-2 Days

☐ 3-4 Days

☐ 5-6 Days

☐ everyday

What type of exercise do you regularly do (e.g. brisk walking, circuit training, social netball) Please list all activities and the activity time in hours *



What type of exercise do you regularly do (e.g. brisk walking, circuit training, social netball) Please list all activities and the activity time in hours *

Short answer text

Do you perform weight bearing exercise regularly? *

○ Yes

○ No

If you answered yes to the previous question, please provide details below.

Short answer text

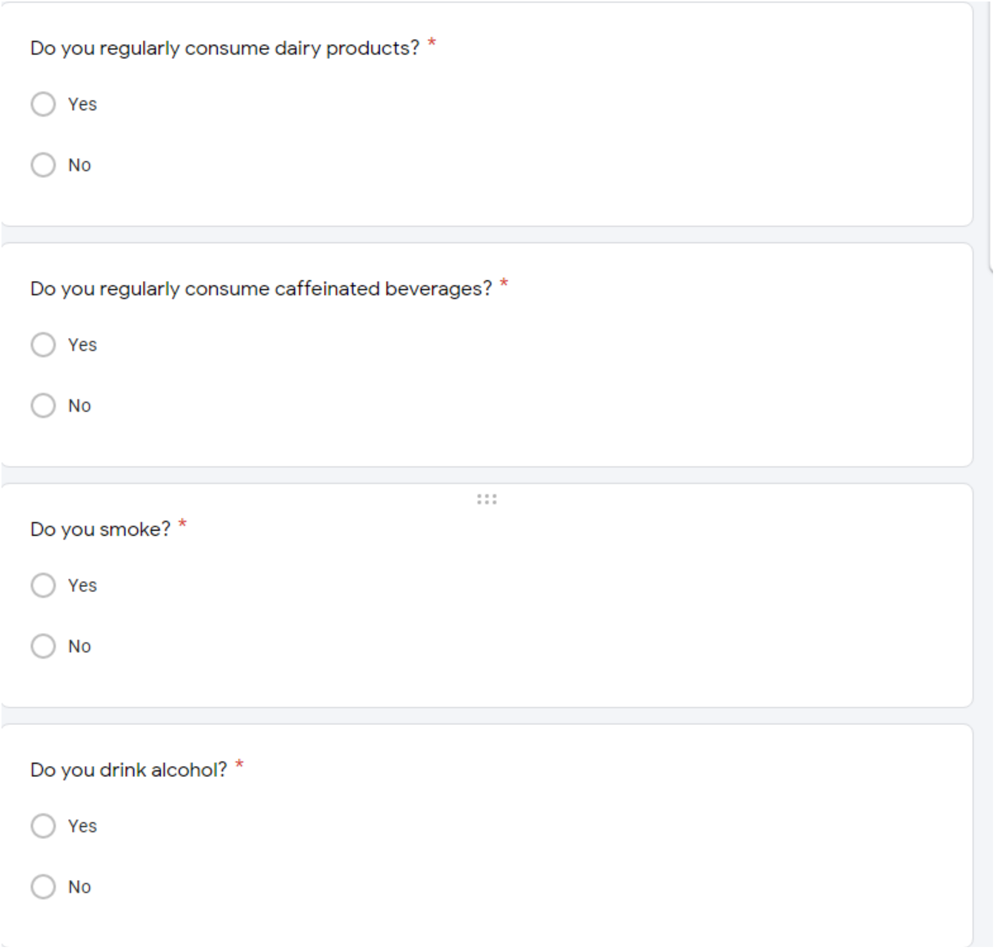
Do you perform high impact exercise regularly? *

○ Yes

○ No

If you answered yes, please provide details below.

Short answer text



Do you regularly consume dairy products? *

○ Yes

○ No

Do you regularly consume caffeinated beverages? *

○ Yes

○ No

Do you smoke? *

○ Yes

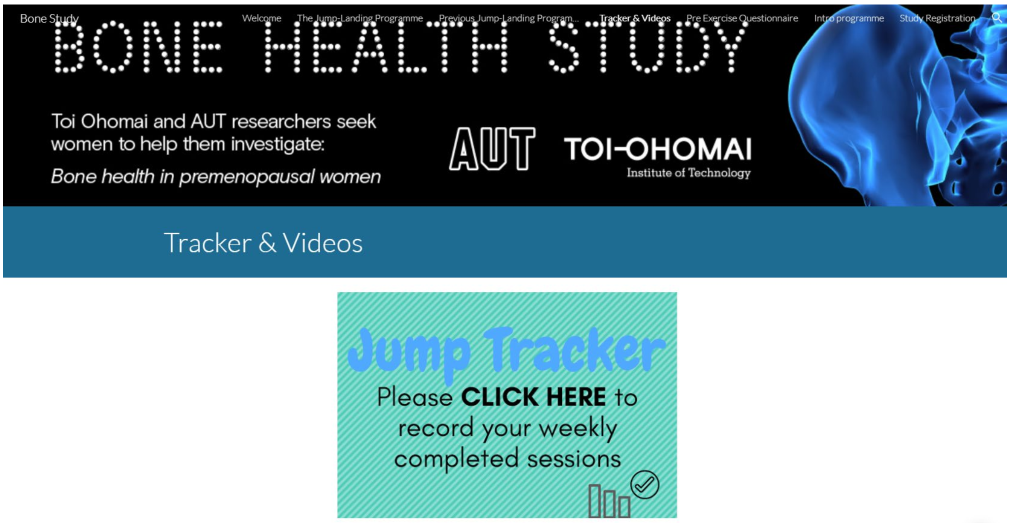
○ No

Do you drink alcohol? *

○ Yes

○ No

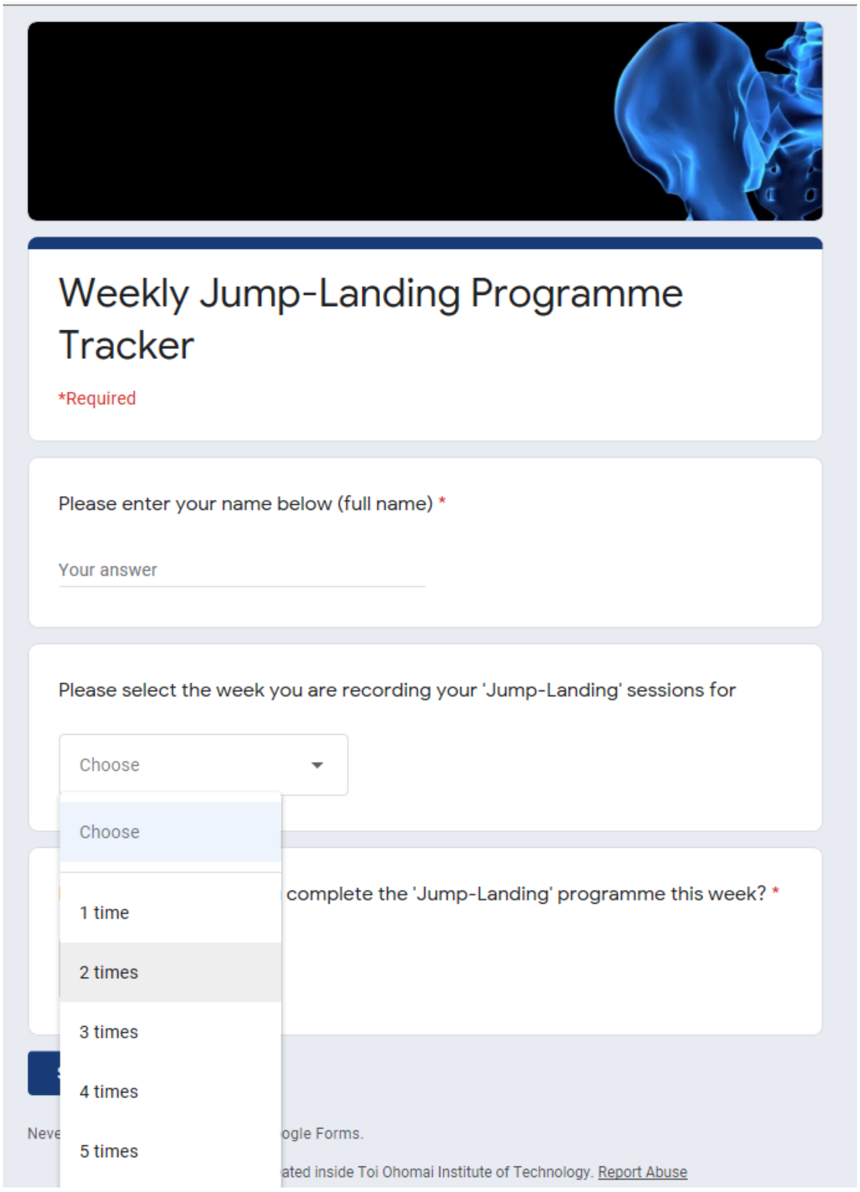
Appendix 4e. Online Weekly Jump Tracker Questionnaire (Study 6)



Toi Ohomai and AUT researchers seek women to help them investigate:

Bone health in premenopausal women

Please **CLICK HERE** to record your weekly completed sessions



Weekly Jump-Landing Programme Tracker

*Required

Please enter your name below (full name) *

Your answer

Please select the week you are recording your 'Jump-Landing' sessions for

Choose

Choose

1 time

2 times

3 times

4 times

5 times

complete the 'Jump-Landing' programme this week? *

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ated inside Toi Ohomai Institute of Technology. Report Abuse

Appendix 4f. Adherence Questionnaire (at 3 months and 9 months) Jump Group (Study 6)

‘Jumping for our Bones’: Quick Questions after 3 months (Jump Group)

1. Was it easy to remember do the required jump sessions each week?
   YES NO SOMETIMES (Circle one)

2. If YES…what was your strategy?

   ____

3. If NO…what was your main reason?

   ____

4. How would you describe doing the jumps?
   ACHIEVABLE CHALLENGING DIFFICULT (Circle one)

5. Did the regular emails help you to achieve the required jumping sessions each week?

   YES NO (Circle one)

6. Would you be happy to receive text messages to remind you to do the jumping sessions?
   YES NO (Circle one)

7. If YES…How often… DAILY (Number of sessions)…WEEKLY (Circle one)

8. Would you be happy to join a Facebook group with all the jumping participants?
   YES NO (Circle one)

9. Have you changed the way/amount of exercise you are doing since starting the study? Briefly describe.

   ____

10. Have you changed your nutrition since you started the study? Briefly describe.

    ____

11. Has the DEXA scan motivated you to stay in the study?

    YES NO (Circle one)

‘Jumping for our Bones’: Quick Questions after 9 months (Jump Group)

Was it easy to remember do the required jump sessions each week?

YES **NO** **SOMETIMES** (Circle one)

1. If **YES**…what was your strategy?

   ____

2. If **NO**…what was your main reason?

   ____

3. How would you describe doing the jumps?
   ACHIEVABLE **CHALLENGING** **DIFFICULT** (Circle one)

4. Did the regular emails help you to achieve the required jumping sessions each week?
   YES **NO** (Circle one)

5. Would you be happy to receive text messages to remind you to do the jumping sessions? **This is planned for the last 3 months!**

   YES **NO** (Circle one)

6. If **YES**…How often… **DAILY** (Number of sessions)…**WEEKLY** (Circle one)

7. **A)** Did you join the Bone Study Facebook group?
   YES **NO** (Circle one)

   B) Did the Facebook page help you to achieve the required jumping sessions each week?
   YES **NO** (Circle one)

8. Have you changed the way/amount of exercise you are doing in the past 3 months? Briefly describe.

   ____

9. Have you changed your nutrition in the past 3 months? Briefly describe.

   ____

10. Does the DEXA scan motivate you to stay in the study?
    YES **NO** (Circle one)

Appendix 4g. Adherence Questionnaire (Control Group) (Study 6)

‘Jumping for our Bones’: Quick Questions (Control Group)

1. Have you changed the way/amount of exercise you are doing in the last 3 months? Briefly describe.

   ____

2. Have you changed your nutrition in the last 3 months? Briefly describe.

   ____

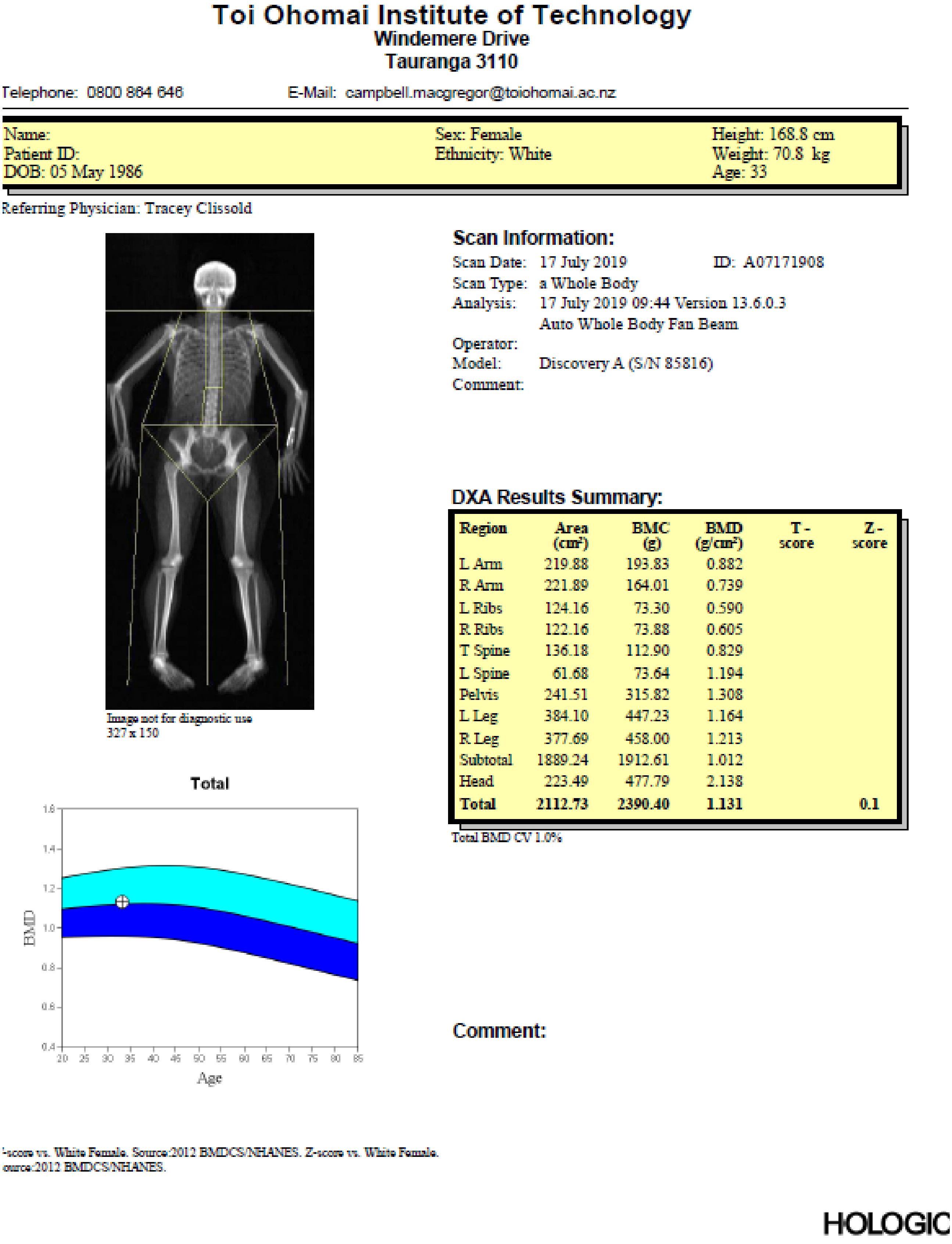
3. Does the DEXA scan continue to motivate you to stay in the study?

   YES **NO** (Circle one)

4. Would you recommend a DEXA scan to other people?

   YES **NO** (Circle one)

Appendix 5: Sample DEXA Report



Toi Ohomai Institute of Technology

Windemere Drive
Tauranga 3110

Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:
Patient ID:
DOB: 05 May 1986

Sex: Female
Ethnicity: White

Height: 168.8 cm
Weight: 70.8 kg
Age: 33

Referring Physician: Tracey Clissold

Scan Information:

Scan Date: 17 July 2019 ID: A07171908
Scan Type: a Whole Body
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Auto Whole Body Fan Beam
Operator:
Model: Discovery A (S/N 85816)
Comment:

Image not for diagnostic use
327 x 150

DXA Results Summary:

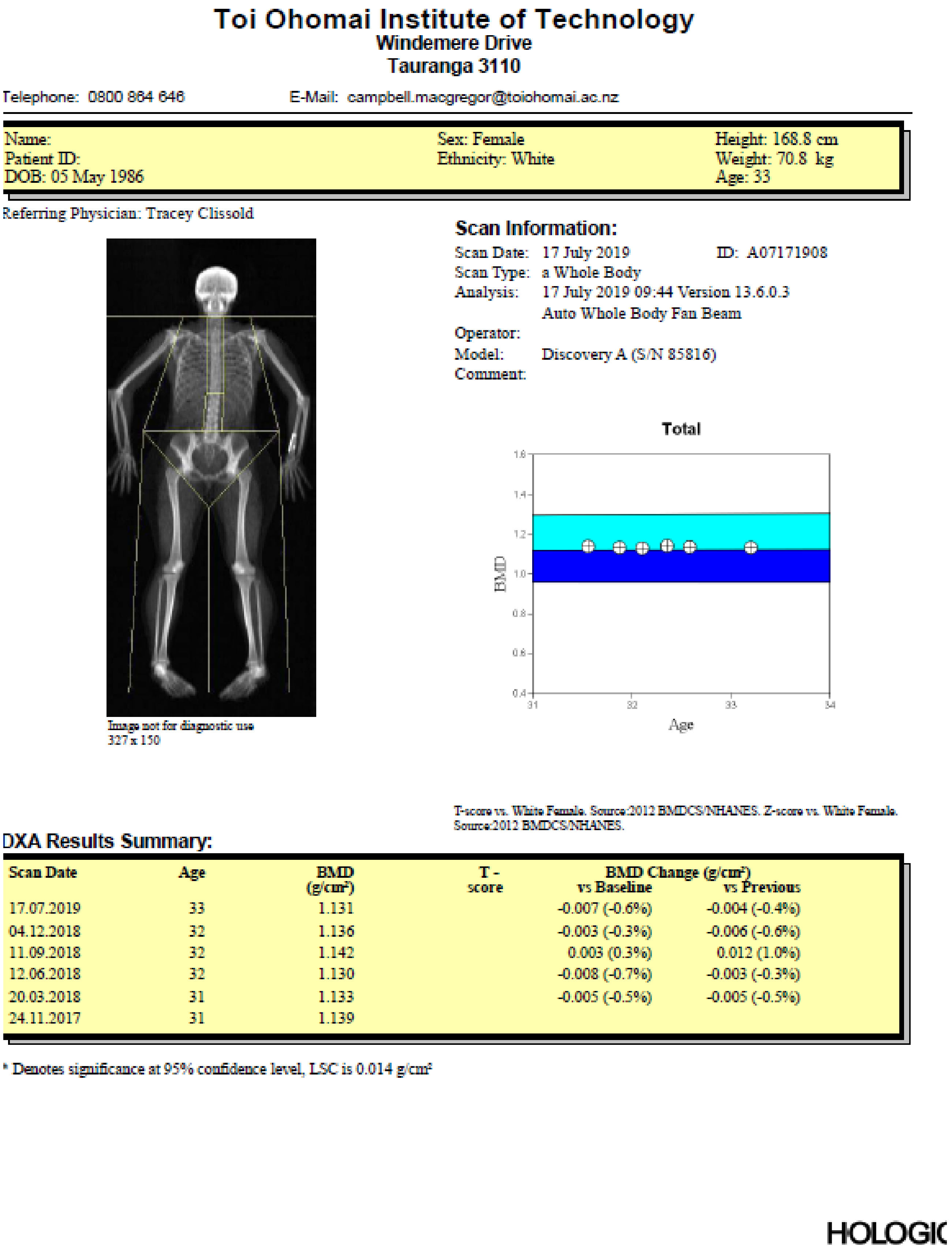
Region	Area (cm²)	BMC (g)	BMD (g/cm²)	T - score	Z - score
L Arm	219.88	193.83	0.882		
R Arm	221.89	164.01	0.739		
L Ribs	124.16	73.30	0.590		
R Ribs	122.16	73.88	0.605		
T Spine	136.18	112.90	0.829		
L Spine	61.68	73.64	1.194		
Pelvis	241.51	315.82	1.308		
L Leg	384.10	447.23	1.164		
R Leg	377.69	458.00	1.213		
Subtotal	1889.24	1912.61	1.012		
Head	223.49	477.79	2.138		
Total	**2112.73**	**2390.40**	**1.131**		**0.1**

Total BMD CV 1.0%

Comment:

-score vs. White Female. Source:2012 BMDCS/NHANES. Z-score vs. White Female.
ource:2012 BMDCS/NHANES.

HOLOGIC



Toi Ohomai Institute of Technology

Windemere Drive
Tauranga 3110

Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

Referring Physician: Tracey Clissold

Image not for diagnostic use
327 x 150

Scan Information:

Scan Date: 17 July 2019 ID: A07171908
Scan Type: a Whole Body
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Auto Whole Body Fan Beam
Operator:
Model: Discovery A (S/N 85816)
Comment:

T-score vs. White Female. Source:2012 BMDCS/NHANES. Z-score vs. White Female. Source:2012 BMDCS/NHANES.

DXA Results Summary:

Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	BMD Change (g/cm²) vs Previous
17.07.2019	33	1.131		-0.007 (-0.6%)	-0.004 (-0.4%)
04.12.2018	32	1.136		-0.003 (-0.3%)	-0.006 (-0.6%)
11.09.2018	32	1.142		0.003 (0.3%)	0.012 (1.0%)
12.06.2018	32	1.130		-0.008 (-0.7%)	-0.003 (-0.3%)
20.03.2018	31	1.133		-0.005 (-0.5%)	-0.005 (-0.5%)
24.11.2017	31	1.139			

* Denotes significance at 95% confidence level, LSC is 0.014 g/cm²

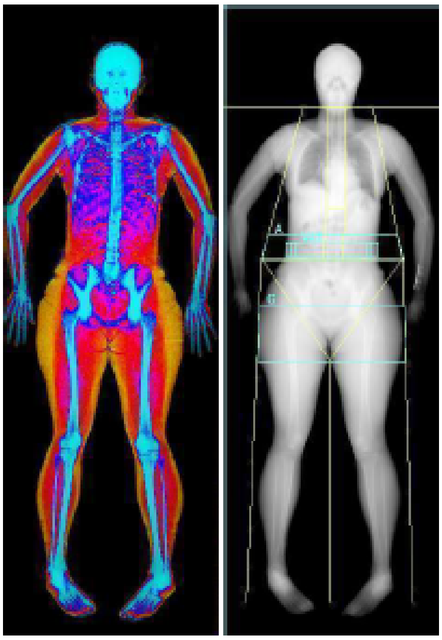
HOLOGIC

Toi Ohomai Institute of Technology

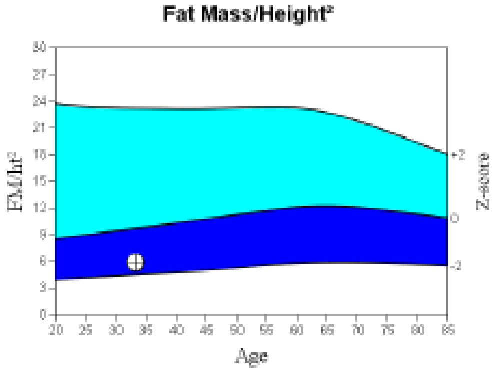
Windemere Drive
Tauranga 3110

Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

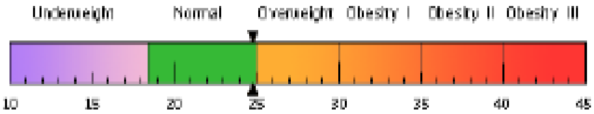


Images not for diagnostic use



Source: NHANES White Female.

World Health Organization Body Mass Index Classification
BMI = 24.8 WHO Classification Normal



BMI has some limitations and an actual diagnosis of overweight or obesity should be made by a health professional. Obesity is associated with heart disease, certain types of cancer, type 2 diabetes, and other health risks. The higher a person's BMI is above 25, the greater their weight-related risks.

Body Composition Results

Region	Fat Mass (g)	Lean + BMC (g)	Total Mass (g)	% Fat	%Fat Percentile YN	%Fat Percentile AM
L Arm	933	2892	3825	24.4	4	3
R Arm	1035	2820	3854	26.8	8	6
Trunk	6007	25524	31532	19.1	5	4
L Leg	3948	9630	13578	29.1	3	3
R Leg	4008	9765	13773	29.1	3	2
Subtotal	15931	50631	66562	23.9	4	3
Head	988	3198	4187	23.6		
Total	**16919**	**53830**	**70749**	**23.9**	**3**	**3**
Android (A)	882	3138	4020	21.9		
Gynoid (G)	3702	8639	12342	30.0		

Scan Date: 17 July 2019 ID: A07171908
Scan Type: a Whole Body
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Auto Whole Body Fan Beam
Operator:
Model: Discovery A (S/N 85816)
Comment:

Adipose Indices

Measure	Result	Percentile YN	Percentile AM
Total Body % Fat	23.9	3	3
Fat Mass/Height² (kg/m²)	**5.94**	**16**	**11**
Android/Gynoid Ratio	0.73		
% Fat Trunk/% Fat Legs	0.65	21	15
Trunk/Limb Fat Mass Ratio	0.61	15	9
Est. VAT Mass (g)	216		
Est. VAT Volume (cm³)	233		
Est. VAT Area (cm²)	44.7		

Lean Indices

Measure	Result	Percentile YN	Percentile AM
Lean/Height² (kg/m²)	18.1	88	85
Appen. Lean/Height² (kg/m²)	8.37	93	91

Est. VAT = Estimated Visceral Adipose Tissue
YN = Young Normal
AM = Age Matched

BAR1209 - NHANES BCA calibration

HOLOGIC

Toi Ohomai Institute of Technology

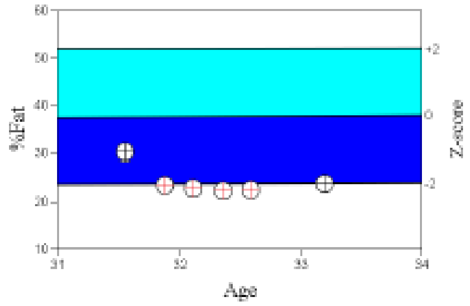
Windemere Drive
Tauranga 3110

Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

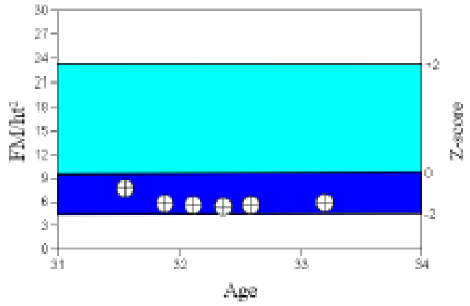
Referring Physician: Tracey Clissold

Total Body % Fat



Source: 2008 NHANES White Female

Fat Mass/Height²



Source: NHANES White Female

Total Body % Fat Results

Scan Date	Age	%Fat (%)	Percentile YN	Percentile AM	Change vs Baseline	Change vs Previous
17.07.2019	33	23.9	3	3	-6.2	1.4
04.12.2018	32	22.5	2	2	-7.6	0.3
11.09.2018	32	22.3	2	1	-7.9	-0.5
12.06.2018	32	22.8	2	2	-7.4	-0.7
20.03.2018	31	23.5	3	2	-6.7	-6.7
24.11.2017	31	30.2	20	16		

Fat Mass/Height² Results

Scan Date	Age	FM/ht² (kg/m²)	Percentile YN	Percentile AM	Change vs Baseline	Change vs Previous
17.07.2019	33	5.94	16	11	-1.8	0.3
04.12.2018	32	5.62	13	9	-2.1	0.2
11.09.2018	32	5.37	11	7	-2.4	-0.2
12.06.2018	32	5.57	13	9	-2.2	-0.3
20.03.2018	31	5.85	16	11	-1.9	-1.9
24.11.2017	31	7.73	37	31		

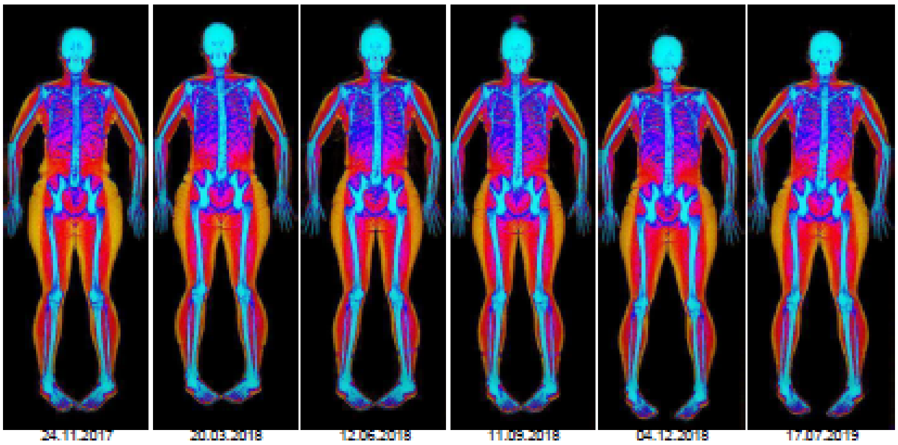
Total Fat Mass Results

Scan Date	Age	Fat Mass (g)	Change/Month vs Baseline	Change/Month vs Previous	Change vs Baseline	Change vs Previous
17.07.2019	33	16919	-259	124	-5102	914
04.12.2018	32	16005	-490	255	-6016	697
11.09.2018	32	15308	-702	-191	-6713	-565
12.06.2018	32	15873	-936	-285	-6148	-786
20.03.2018	31	16659	-1407	-1407	-5362	-5362
24.11.2017	31	22021				

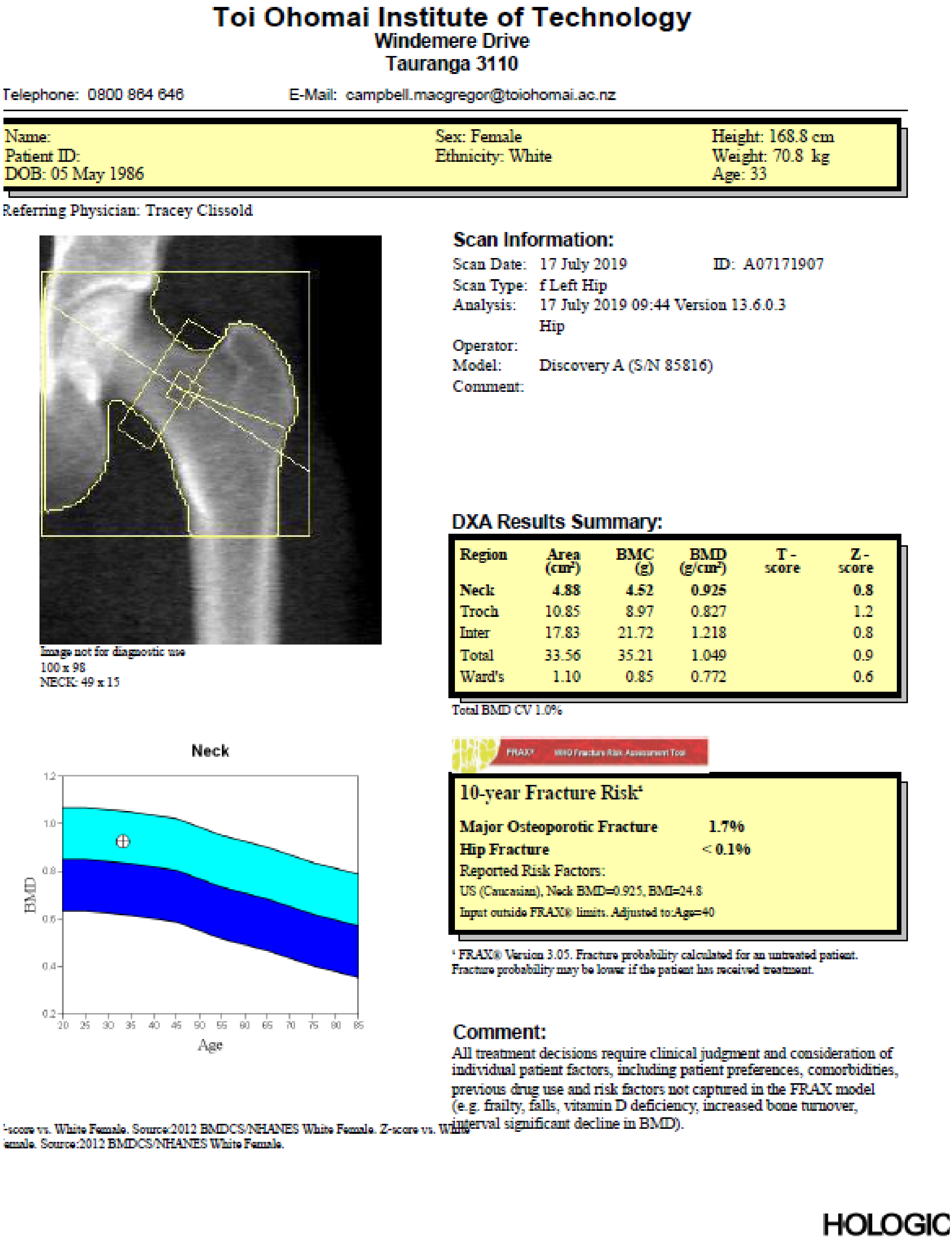
Total Lean Mass Results

Scan Date	Age	Lean (g)	Change/Month vs Baseline	Change/Month vs Previous	Change vs Baseline	Change vs Previous
17.07.2019	33	51439	146	-168	2873	-1233
04.12.2018	32	52672	334	599	4106	1633
11.09.2018	32	51039	259	-143	2473	-422
12.06.2018	32	51461	441	-172	2895	-475
20.03.2018	31	51936	884	884	3370	3370
24.11.2017	31	48566				

YN = Young Normal AM = Age Matched



Images not for diagnostic use



Toi Ohomai Institute of Technology

Windemere Drive
Tauranga 3110

Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

Referring Physician: Tracey Clissold

Image not for diagnostic use
100 x 98
NECK: 49 x 15

Scan Information:

Scan Date: 17 July 2019 ID: A07171907
Scan Type: f Left Hip
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Hip
Operator:
Model: Discovery A (S/N 85816)
Comment:

DXA Results Summary:

Region	Area (cm²)	BMC (g)	BMD (g/cm²)	T - score	Z - score
Neck	**4.88**	**4.52**	**0.925**		**0.8**
Troch	10.85	8.97	0.827		1.2
Inter	17.83	21.72	1.218		0.8
Total	33.56	35.21	1.049		0.9
Ward's	1.10	0.85	0.772		0.6

Total BMD CV 1.0%

Neck

10-year Fracture Risk[1]

Major Osteoporotic Fracture **1.7%**
Hip Fracture **< 0.1%**
Reported Risk Factors:
US (Caucasian), Neck BMD=0.925, BMI=24.8
Input outside FRAX® limits. Adjusted to:Age=40

[1] FRAX® Version 3.05. Fracture probability calculated for an untreated patient. Fracture probability may be lower if the patient has received treatment.

Comment:

All treatment decisions require clinical judgment and consideration of individual patient factors, including patient preferences, comorbidities, previous drug use and risk factors not captured in the FRAX model (e.g. frailty, falls, vitamin D deficiency, increased bone turnover, interval significant decline in BMD).

-score vs. White Female. Source:2012 BMDCS/NHANES White Female. Z-score vs. White
emale. Source:2012 BMDCS/NHANES White Female.

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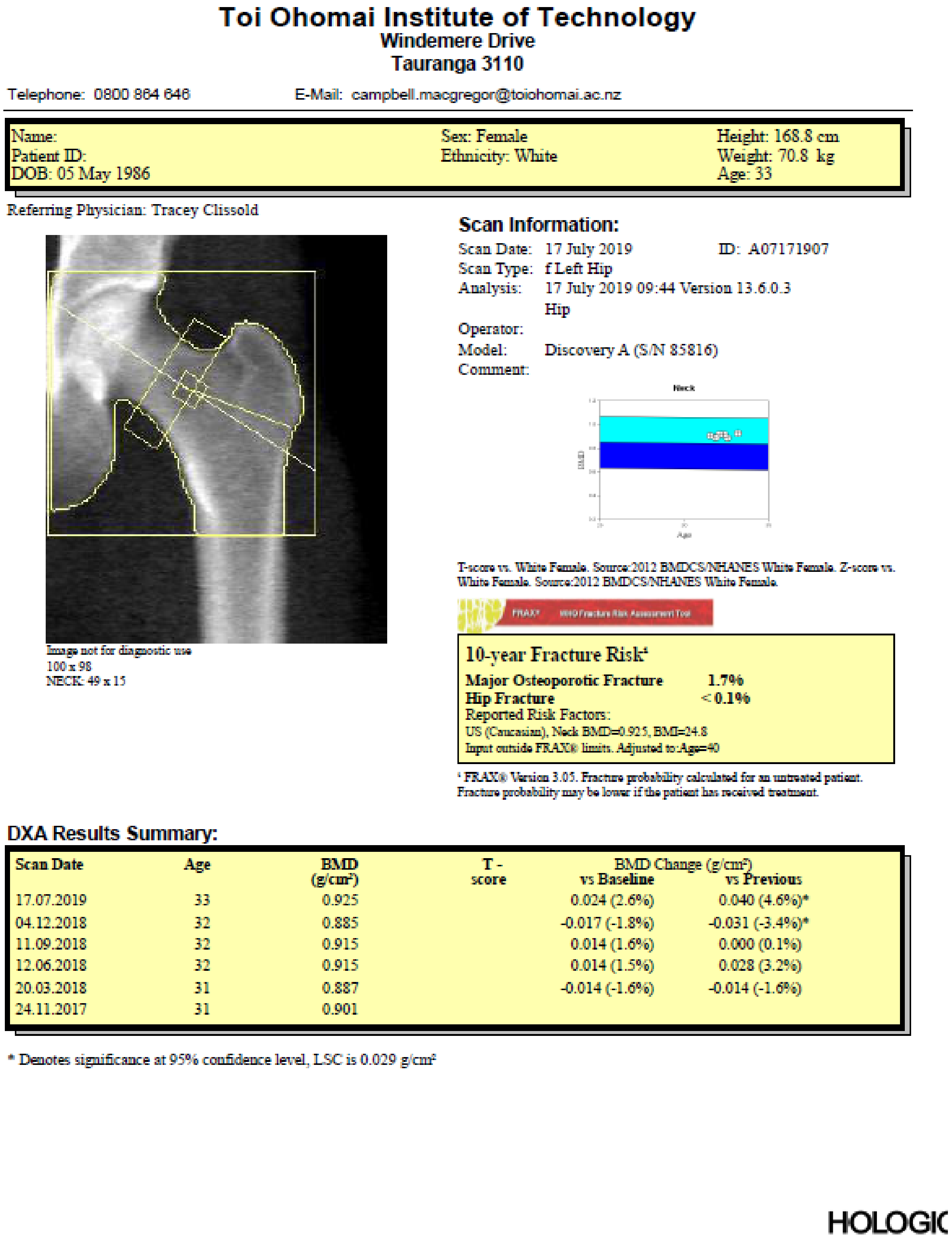

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DOB: 05 May 1986		Age: 33

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Image not for diagnostic use
100 x 98
NECK: 49 x 15

Scan Information:

Scan Date: 17 July 2019 ID: A07171907
Scan Type: f Left Hip
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Hip
Operator:
Model: Discovery A (S/N 85816)
Comment:

T-score vs. White Female. Source:2012 BMDCS/NHANES White Female. Z-score vs. White Female. Source:2012 BMDCS/NHANES White Female.

10-year Fracture Risk[1]

Major Osteoporotic Fracture	**1.7%**
Hip Fracture	**< 0.1%**

Reported Risk Factors:
US (Caucasian), Neck BMD=0.925, BMI=24.8
Input outside FRAX® limits. Adjusted to:Age=40

[1] FRAX® Version 3.05. Fracture probability calculated for an untreated patient. Fracture probability may be lower if the patient has received treatment.

DXA Results Summary:

Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	BMD Change (g/cm²) vs Previous
17.07.2019	33	0.925		0.024 (2.6%)	0.040 (4.6%)*
04.12.2018	32	0.885		-0.017 (-1.8%)	-0.031 (-3.4%)*
11.09.2018	32	0.915		0.014 (1.6%)	0.000 (0.1%)
12.06.2018	32	0.915		0.014 (1.5%)	0.028 (3.2%)
20.03.2018	31	0.887		-0.014 (-1.6%)	-0.014 (-1.6%)
24.11.2017	31	0.901			

* Denotes significance at 95% confidence level, LSC is 0.029 g/cm²

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Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

Name:
Patient ID:
DOB: 05 May 1986

Sex: Female
Ethnicity: White

Height: 168.8 cm
Weight: 70.8 kg
Age: 33

Referring Physician: Tracey Clissold

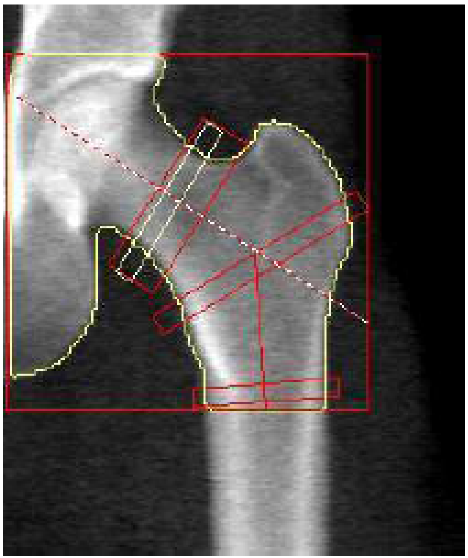

Image not for diagnostic use
100 x 98

Scan Information:

Scan Date: 17 July 2019 ID: A07171907
Scan Type: f Left Hip
Analysis: 17 July 2019 09:44 Version 13.6.0.3
Hip
Operator:
Model: Discovery A (S/N 85816)
Comment:

HSA™ Results Summary:

Region	Sub Peri. Width(cm)	Endo Cort. Width(cm)	CSA (cm^2)	CSMI (cm^4)	Z (cm^3)	Cort. Thick (cm)	BR
NN	3.12	2.68	3.34	2.59	1.57	0.22	7.5
IT	5.31	4.41	6.11	15.25	5.18	0.45	6.6
FS	3.33	2.26	4.68	4.34	2.49	0.53	3.3

Neck Shaft Angle: 127°

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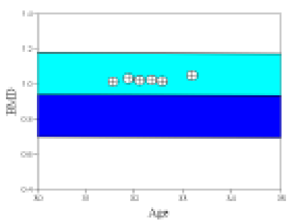
Telephone: 0800 864 646 E-Mail: campbell.macgregor@toiohomai.ac.nz

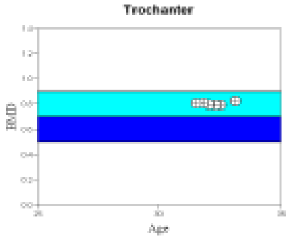
Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

DXA Results Summary:



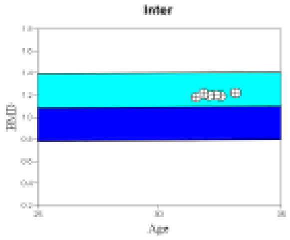
Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	vs Previous
17.07.2019	33	1.049		0.034 (3.4%)*	0.031 (3.0%)*
04.12.2018	32	1.018		0.004 (0.3%)	-0.007 (-0.7%)
11.09.2018	32	1.025		0.011 (1.1%)	0.003 (0.3%)
12.06.2018	32	1.022		0.008 (0.7%)	-0.011 (-1.0%)
20.03.2018	31	1.033		0.018 (1.8%)	0.018 (1.8%)
24.11.2017	31	1.015			

* Denotes significance at 95% confidence level, LSC is 0.027 g/cm²



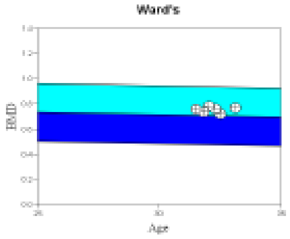
Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	vs Previous
17.07.2019	33	0.827		0.020 (2.5%)*	0.034 (4.3%)*
04.12.2018	32	0.793		-0.014 (-1.7%)	-0.002 (-0.2%)
11.09.2018	32	0.794		-0.012 (-1.5%)	-0.003 (-0.4%)
12.06.2018	32	0.797		-0.010 (-1.2%)	-0.016 (-2.0%)
20.03.2018	31	0.814		0.007 (0.8%)	0.007 (0.8%)
24.11.2017	31	0.807			

* Denotes significance at 95% confidence level, LSC is 0.018 g/cm²



Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	vs Previous
17.07.2019	33	1.218		0.037 (3.1%)*	0.025 (2.1%)
04.12.2018	32	1.193		0.011 (1.0%)	-0.005 (-0.4%)
11.09.2018	32	1.198		0.017 (1.4%)	0.003 (0.2%)
12.06.2018	32	1.196		0.014 (1.2%)	-0.018 (-1.5%)
20.03.2018	31	1.213		0.032 (2.7%)*	0.032 (2.7%)*
24.11.2017	31	1.182			

* Denotes significance at 95% confidence level, LSC is 0.025 g/cm²



Scan Date	Age	BMD (g/cm²)	T - score	BMD Change (g/cm²) vs Baseline	vs Previous
17.07.2019	33	0.772		0.013 (1.7%)	0.050 (6.9%)*
04.12.2018	32	0.722		-0.036 (-4.8%)	-0.041 (-5.4%)
11.09.2018	32	0.763		0.004 (0.6%)	-0.021 (-2.6%)
12.06.2018	32	0.783		0.025 (3.3%)	0.045 (6.1%)
20.03.2018	31	0.739		-0.020 (-2.6%)	-0.020 (-2.6%)
24.11.2017	31	0.759			

* Denotes significance at 95% confidence level, LSC is 0.045 g/cm²

T-score vs. White Female. Source:2012 BMDCS/NHANES White Female. Z-score vs. White Female. Source:2012 BMDCS/NHANES White Female.

Scan Type: f Left Hip - A07171907

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Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

Referring Physician: Tracey Clissold

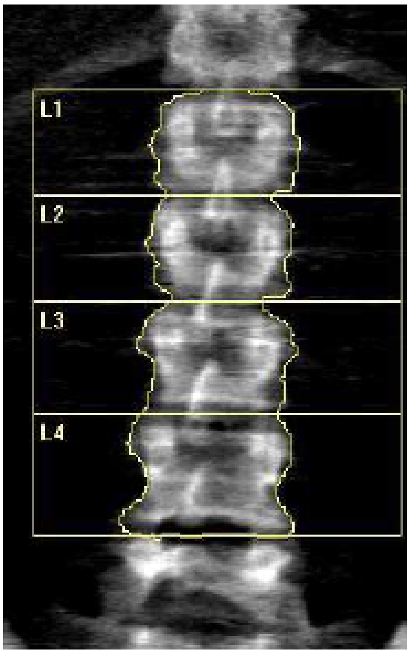


Image not for diagnostic use
116 x 140

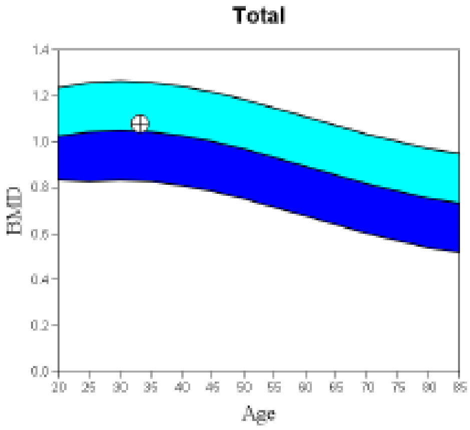
Scan Information:

Scan Date: 17 July 2019 ID: A07171906
Scan Type: f Lumbar Spine
Analysis: 17 July 2019 09:45 Version 13.6.0.3
Spine
Operator:
Model: Discovery A (S/N 85816)
Comment:

DXA Results Summary:

Region	Area (cm²)	BMC (g)	BMD (g/cm²)	T - score	Z - score
L1	13.83	15.20	1.100		1.0
L2	13.78	15.84	1.150		1.1
L3	15.18	17.10	1.127		0.4
L4	18.66	18.19	0.975		-0.7
Total	**61.44**	**66.34**	**1.080**		**0.3**

Total BMD CV 1.0%



Comment:

T-score vs. White Female. Source:2012 BMDCS/Hologic Z-score vs. White Female. Source:2012 BMDCS/Hologic

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Windemere Drive
Tauranga 3110

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Name:	Sex: Female	Height: 168.8 cm
Patient ID:	Ethnicity: White	Weight: 70.8 kg
DOB: 05 May 1986		Age: 33

Referring Physician: Tracey Clissold

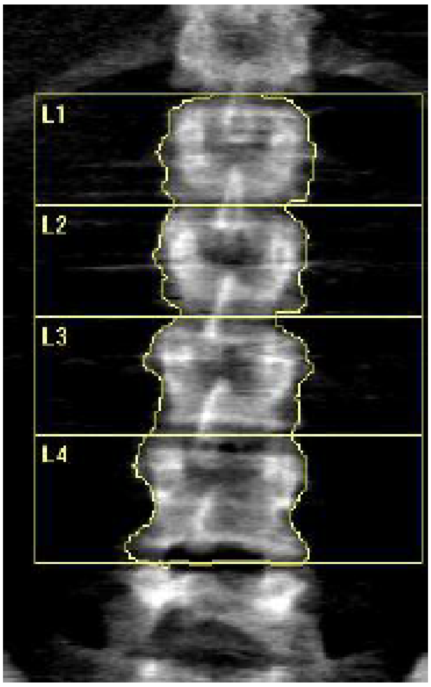
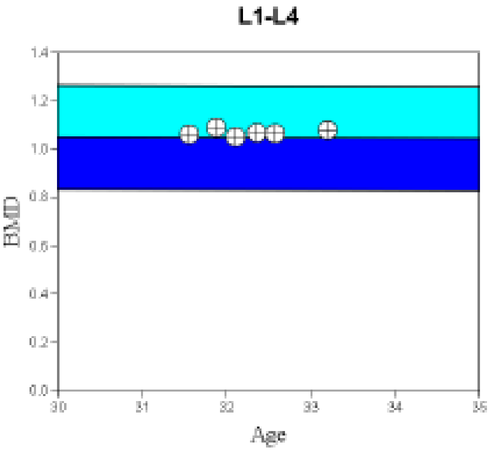


Image not for diagnostic use
116 x 140

Scan Information:

Scan Date: 17 July 2019 ID: A07171906
Scan Type: f Lumbar Spine
Analysis: 17 July 2019 09:45 Version 13.6.0.3
Spine
Operator:
Model: Discovery A (S/N 85816)
Comment:



T-score vs. White Female. Source:2012 BMDCS/Hologic Z-score vs. White Female. Source:2012 BMDCS/Hologic

DXA Results Summary: L1-L4

Scan Date	Age	BMD (g/cm^2)	T - score	BMD Change (g/cm^2) vs Baseline	BMD Change (g/cm^2) vs Previous
17.07.2019	33	1.080		0.020 (1.9%)	0.016 (1.5%)
04.12.2018	32	1.063		0.004 (0.4%)	-0.003 (-0.3%)
11.09.2018	32	1.067		0.007 (0.7%)	0.017 (1.6%)
12.06.2018	32	1.050		-0.010 (-0.9%)	-0.040 (-3.7%)*
20.03.2018	31	1.090		0.030 (2.9%)*	0.030 (2.9%)*
24.11.2017	31	1.059			

* Denotes significance at 95% confidence level, LSC is 0.022 g/cm^2

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Appendix 6a. Jump-landing Programme Infographic (weeks 9-12)

Jump Programme

1

What jumps are we doing for the next 4 weeks?

The Countermovement jump + Stride Jump

2

How many times do we perform the programme each week?

4X

3

How many jumps do we do each session?

8 CMJ+8 Stride jumps

(this means 32 jump-landings)

* Countermovement jump = CMJ

4

How do we perform the jumps?

Perform 4 MAXIMAL jumps at a time (1 set), and perform 2 sets of each jump in the session.

* see the 4-week programme for detail

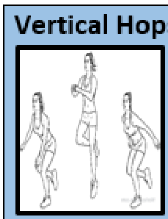
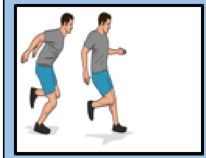
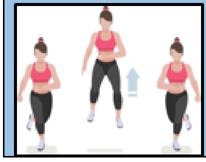
5

How much rest do we have?

Take a couple of seconds between each jump, and around 30 seconds between each set.

Appendix 6b. Jump-landing Weekly Overview Programme (weeks 48 - 52)

The Jump-Landing Programme (PHASE 4):
PUT THIS ON YOUR WALL/FRIDGE (Tick box each day you perform the jumps)

Jump Type	Freq (times per week)	Sets x Reps x Rest	Week (49-52)	1	2	3	4	5
Vertical Hops *  **Forward Leaps ****  **Lateral Leaps***** 	**4-5x**	**2 x 7** Vertical Hop **2 x 7** Forward Leap **2 x 7** Lateral Leap _*1 set for each leg_ **2-5 sec** Between each jump/hop **30 sec** Between each set	**Week 49** Nov 26-2					
			Week 46 Dec 3-9					
			Week 47 Dec 10-16					
			Week 48 Dec 17-23					

Nov 26 – Dec 23

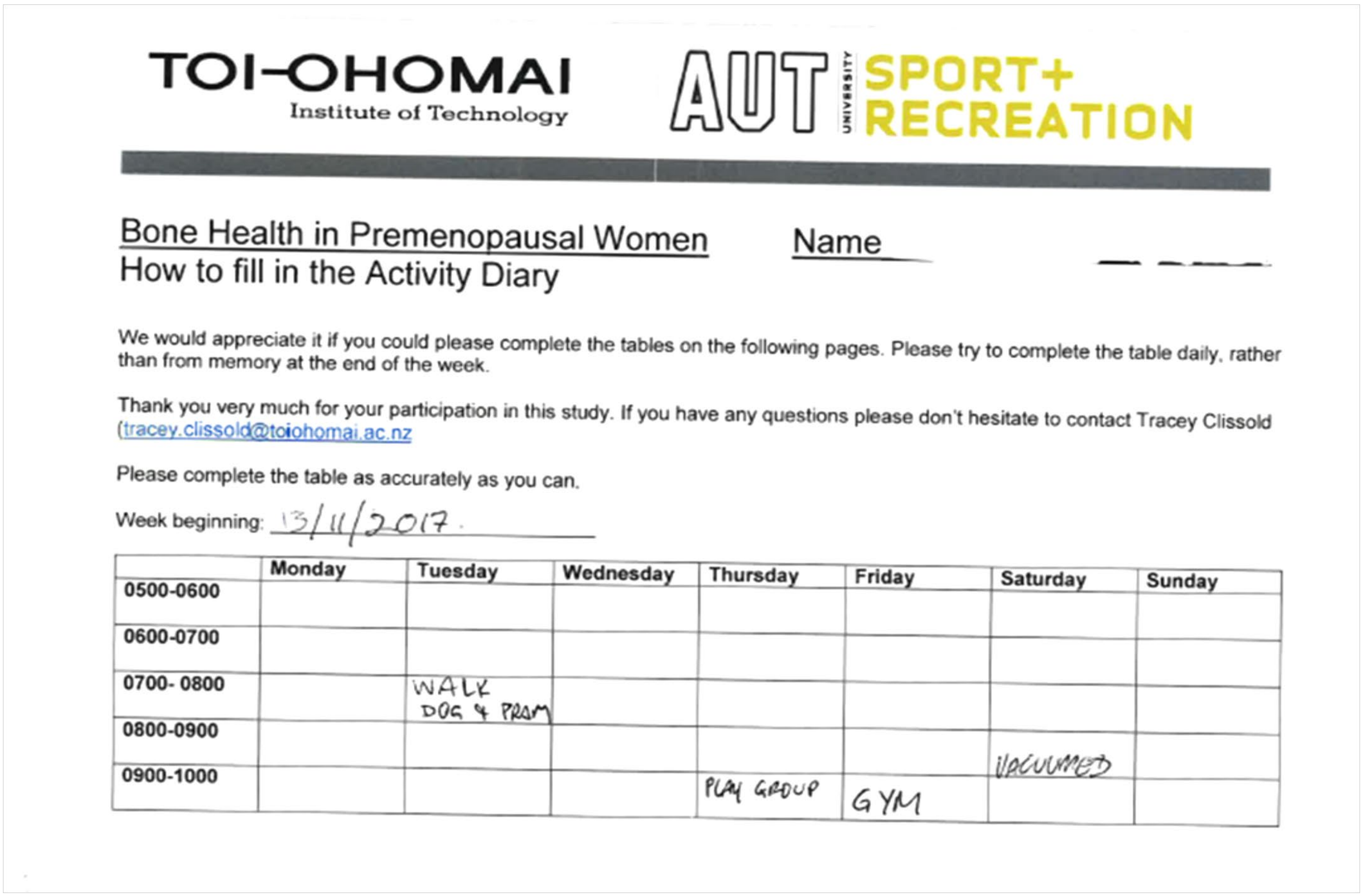
*** Vertical Hop Instructions:
1. Stand on one leg, and as you lower down you will simultaneously swing your arms down.
2. Then quickly jump upwards and forwards, with arms also swinging in the upwards direction.
3. Then land on the same leg.

** Forward Leap Instructions:
1. Stand on one leg, and as you lower down you will simultaneously swing your arms down.
2. Then quickly jump upwards and forwards, with arms also swinging in the upwards direction.
3. Then land on the opposite leg.

** Lateral Leap Instructions:
1. Stand on one leg, and as you lower down you will simultaneously swing your arms down.
2. Then quickly jump upwards and sideways, with arms also swinging in the upwards direction.
3. Then land on the opposite leg.

All hops & leaps need to be performed using both legs (right and left sides).

Appendix 7. Sample Activity Diary



TOI-OHOMAI Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Bone Health in Premenopausal Women

How to fill in the Activity Diary

Name [redacted]

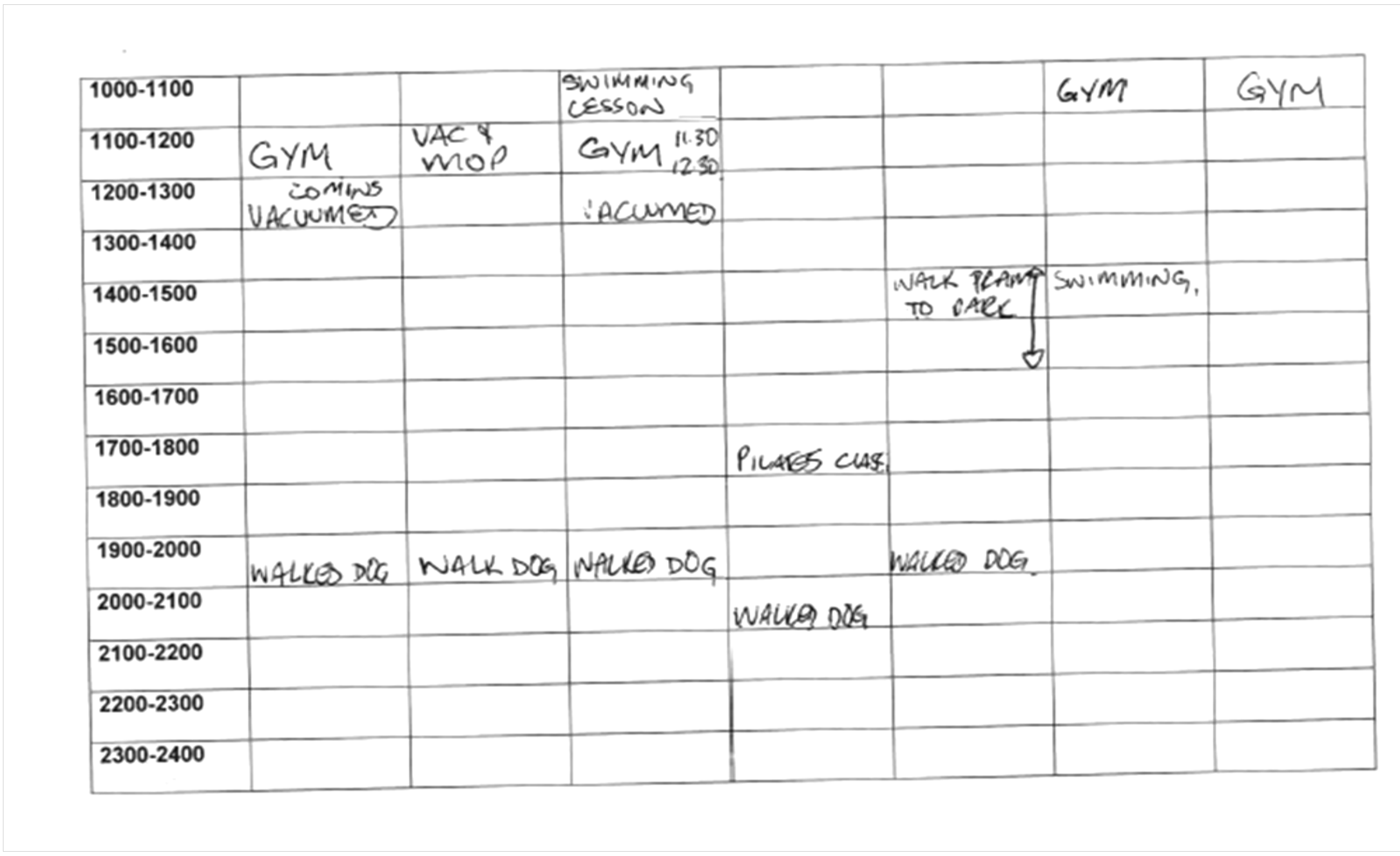
We would appreciate it if you could please complete the tables on the following pages. Please try to complete the table daily, rather than from memory at the end of the week.

Thank you very much for your participation in this study. If you have any questions please don't hesitate to contact Tracey Clissold (tracey.clissold@toiohomai.ac.nz

Please complete the table as accurately as you can.

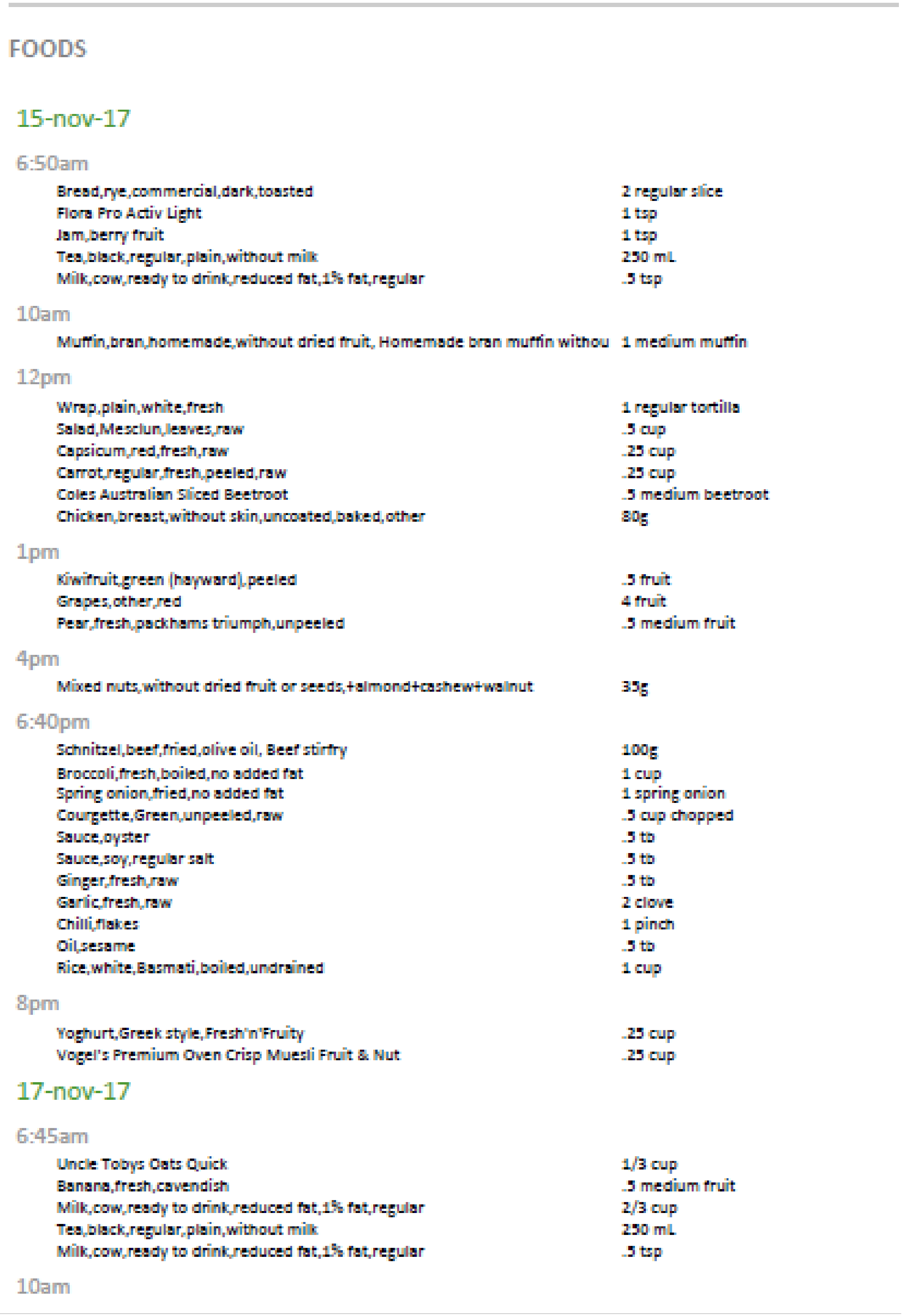
Week beginning: 13/11/2017.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0500-0600							
0600-0700							
0700- 0800		WALK DOG & PRAM					
0800-0900						VACUUMED	
0900-1000				PLAY GROUP	GYM		



1000-1100			SWIMMING LESSON			GYM	GYM
1100-1200	GYM	VAC & MOP	GYM 11.30 12.30				
1200-1300	COMINS VACUUMED		VACUUMED				
1300-1400							
1400-1500					WALK PRAM TO PARK ↓	SWIMMING,	
1500-1600							
1600-1700							
1700-1800				PILATES CLASS			
1800-1900							
1900-2000	WALKED DOG	WALK DOG	WALKED DOG		WALKED DOG		
2000-2100				WALKED DOG			
2100-2200							
2200-2300							
2300-2400							

Appendix 8. Sample Participant 3-Day Food Diary and Foodworks Report



FOODS

15-nov-17

6:50am

Bread,rye,commercial,dark,toasted	2 regular slice
Flora Pro Activ Light	1 tsp
Jam,berry fruit	1 tsp
Tea,black,regular,plain,without milk	250 mL
Milk,cow,ready to drink,reduced fat,1% fat,regular	.5 tsp

10am

Muffin,bran,homemade,without dried fruit, Homemade bran muffin withou	1 medium muffin

12pm

Wrap,plain,white,fresh	1 regular tortilla
Salad,Mesclun,leaves,raw	.5 cup
Capsicum,red,fresh,raw	.25 cup
Carrot,regular,fresh,peeled,raw	.25 cup
Coles Australian Sliced Beetroot	.5 medium beetroot
Chicken,breast,without skin,uncoated,baked,other	80g

1pm

Kiwifruit,green (hayward),peeled	.5 fruit
Grapes,other,red	4 fruit
Pear,fresh,packhams triumph,unpeeled	.5 medium fruit

4pm

Mixed nuts,without dried fruit or seeds,+almond+cashew+walnut	35g

6:40pm

Schnitzel,beef,fried,olive oil, Beef stirfry	100g
Broccoli,fresh,boiled,no added fat	1 cup
Spring onion,fried,no added fat	1 spring onion
Courgette,Green,unpeeled,raw	.5 cup chopped
Sauce,oyster	.5 tb
Sauce,soy,regular salt	.5 tb
Ginger,fresh,raw	.5 tb
Garlic,fresh,raw	2 clove
Chilli,flakes	1 pinch
Oil,sesame	.5 tb
Rice,white,Basmati,boiled,undrained	1 cup

8pm

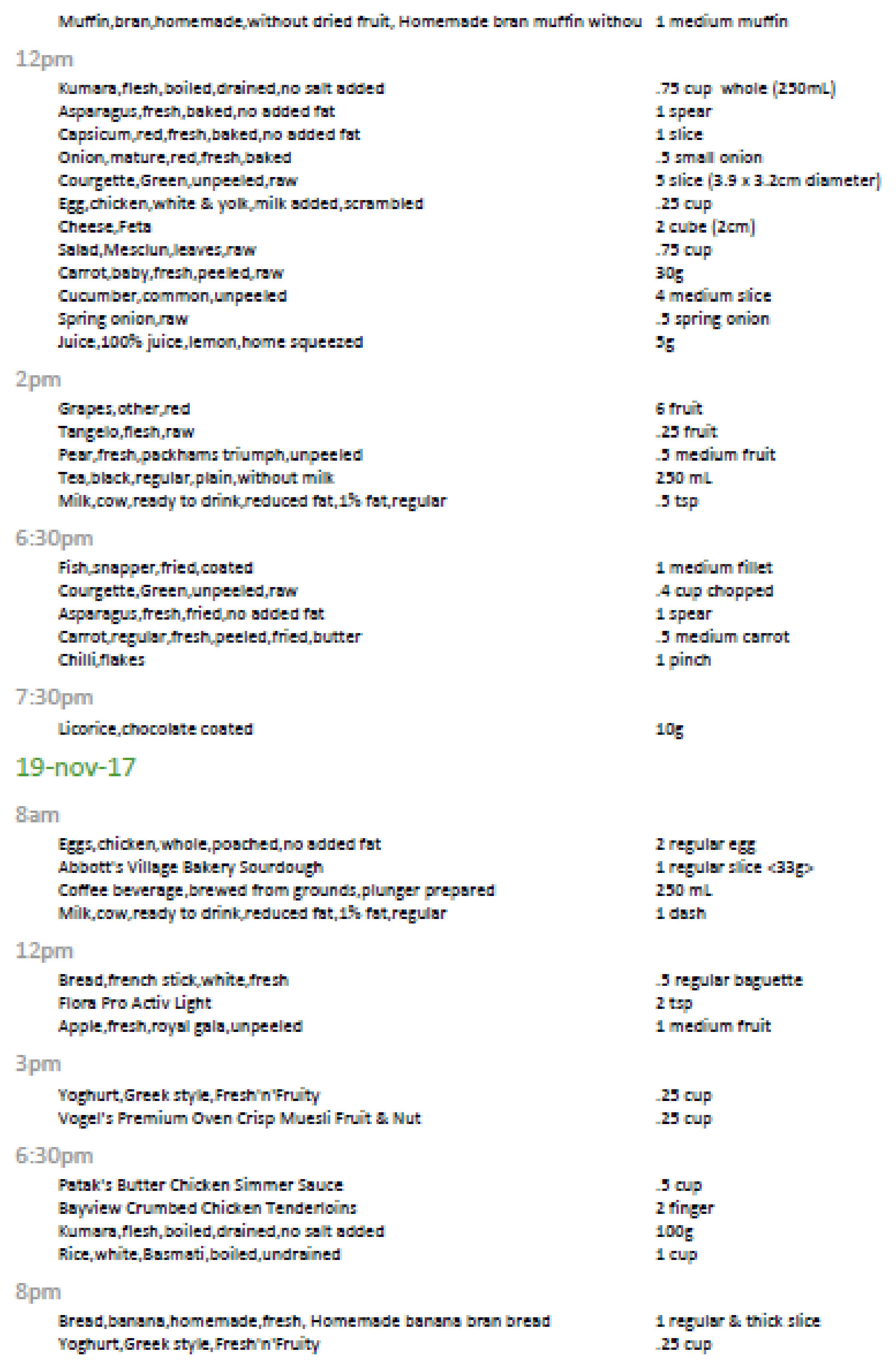
Yoghurt,Greek style,Fresh'n'Fruity	.25 cup
Vogel's Premium Oven Crisp Muesli Fruit & Nut	.25 cup

17-nov-17

6:45am

Uncle Tobys Oats Quick	1/3 cup
Banana,fresh,cavendish	.5 medium fruit
Milk,cow,ready to drink,reduced fat,1% fat,regular	2/3 cup
Tea,black,regular,plain,without milk	250 mL
Milk,cow,ready to drink,reduced fat,1% fat,regular	.5 tsp

10am



Muffin,bran,homemade,without dried fruit, Homemade bran muffin withou	1 medium muffin

12pm

Kumara,flesh,boiled,drained,no salt added	.75 cup whole (250mL)
Asparagus,fresh,baked,no added fat	1 spear
Capsicum,red,fresh,baked,no added fat	1 slice
Onion,mature,red,fresh,baked	.5 small onion
Courgette,Green,unpeeled,raw	5 slice (3.9 x 3.2cm diameter)
Egg,chicken,white & yolk,milk added,scrambled	.25 cup
Cheese,Feta	2 cube (2cm)
Salad,Mesclun,leaves,raw	.75 cup
Carrot,baby,fresh,peeled,raw	30g
Cucumber,common,unpeeled	4 medium slice
Spring onion,raw	.5 spring onion
Juice,100% juice,lemon,home squeezed	5g

2pm

Grapes,other,red	6 fruit
Tangelo,flesh,raw	.25 fruit
Pear,fresh,packhams triumph,unpeeled	.5 medium fruit
Tea,black,regular,plain,without milk	250 mL
Milk,cow,ready to drink,reduced fat,1% fat,regular	.5 tsp

6:30pm

Fish,snapper,fried,coated	1 medium fillet
Courgette,Green,unpeeled,raw	.4 cup chopped
Asparagus,fresh,fried,no added fat	1 spear
Carrot,regular,fresh,peeled,fried,butter	.5 medium carrot
Chilli,flakes	1 pinch

7:30pm

Licorice,chocolate coated	10g

19-nov-17

8am

Eggs,chicken,whole,poached,no added fat	2 regular egg
Abbott's Village Bakery Sourdough	1 regular slice <33g>
Coffee beverage,brewed from grounds,plunger prepared	250 mL
Milk,cow,ready to drink,reduced fat,1% fat,regular	1 dash

12pm

Bread,french stick,white,fresh	.5 regular baguette
Flora Pro Activ Light	2 tsp
Apple,fresh,royal gala,unpeeled	1 medium fruit

3pm

Yoghurt,Greek style,Fresh'n'Fruity	.25 cup
Vogel's Premium Oven Crisp Muesli Fruit & Nut	.25 cup

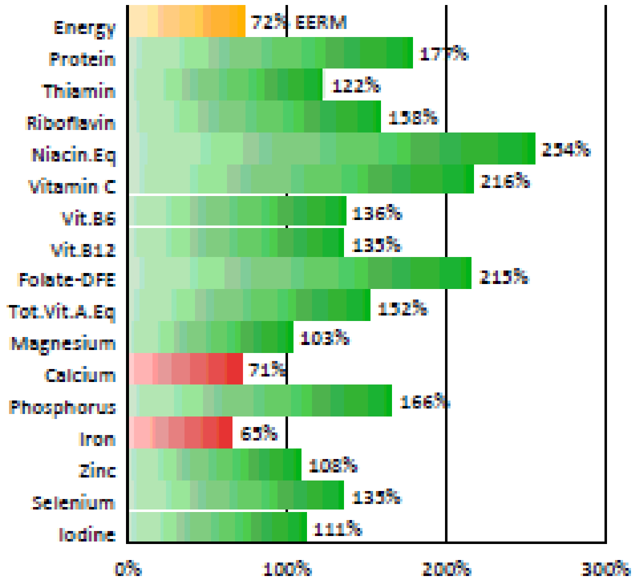
6:30pm

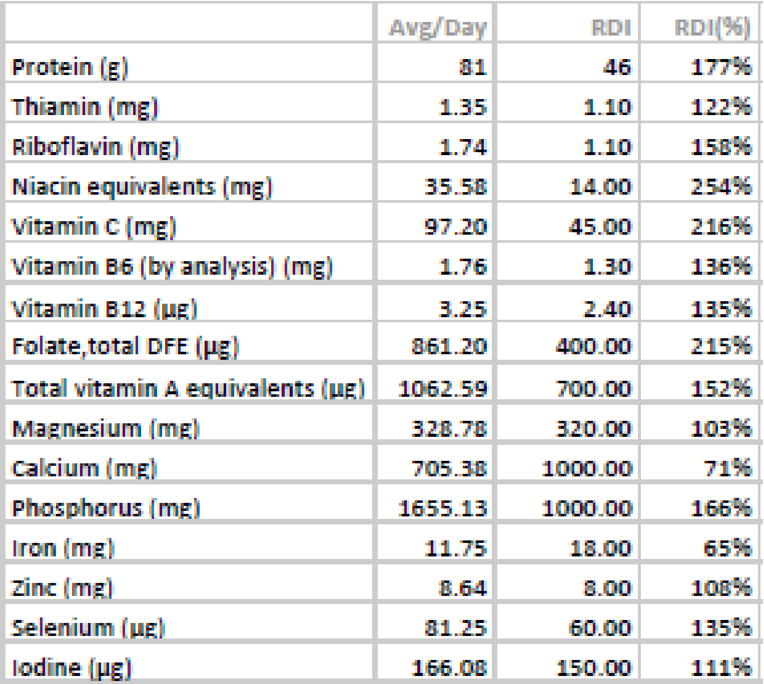
Patak's Butter Chicken Simmer Sauce	.5 cup
Bayview Crumbed Chicken Tenderloins	2 finger
Kumara,flesh,boiled,drained,no salt added	100g
Rice,white,Basmati,boiled,undrained	1 cup

8pm

Bread,banana,homemade,fresh, Homemade banana bran bread	1 regular & thick slice
Yoghurt,Greek style,Fresh'n'Fruity	.25 cup

RECOMMENDED DIETARY INTAKES (RDI)

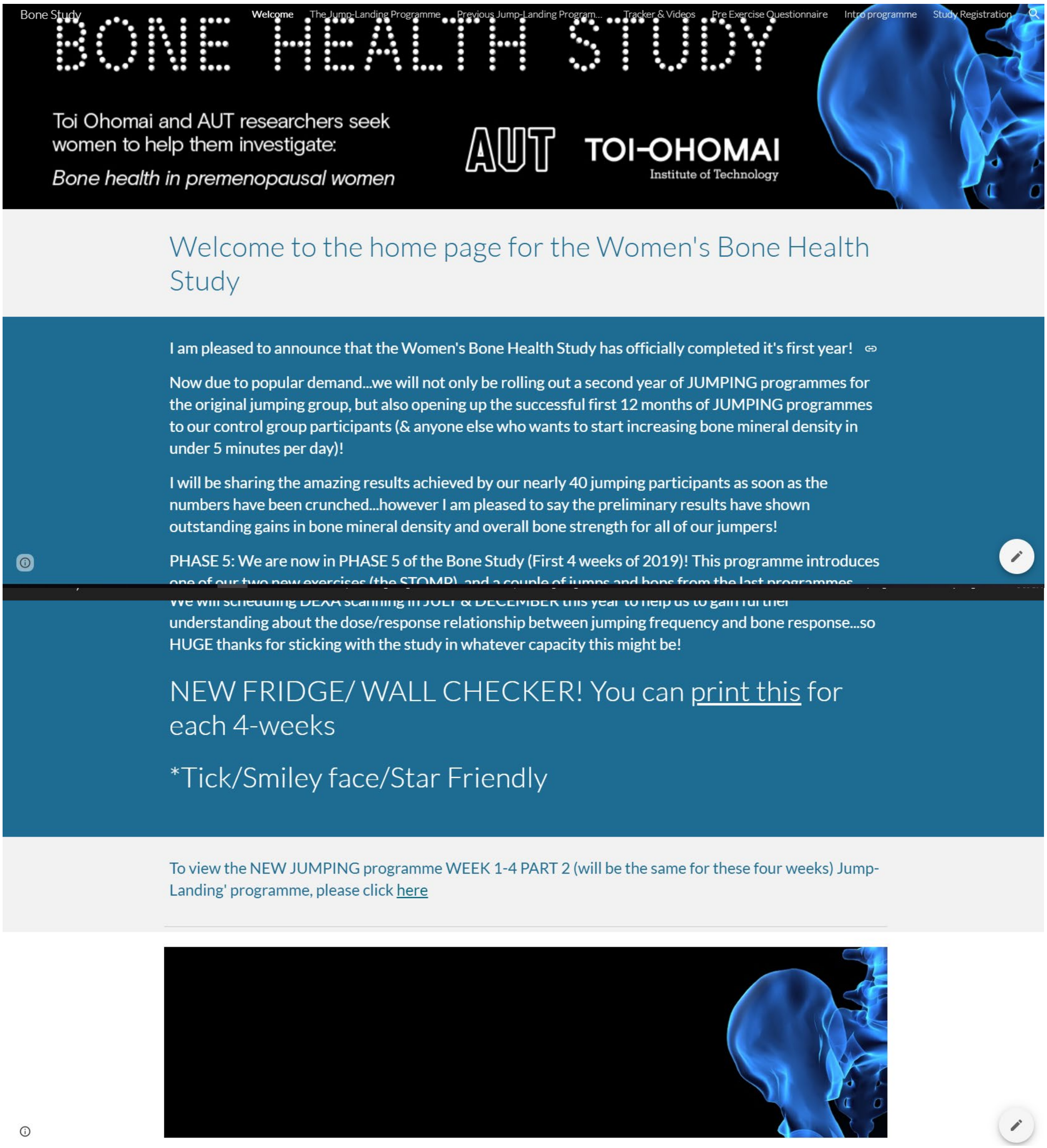




	Avg/Day	RDI	RDI(%)
Protein (g)	81	46	177%
Thiamin (mg)	1.35	1.10	122%
Riboflavin (mg)	1.74	1.10	158%
Niacin equivalents (mg)	35.58	14.00	254%
Vitamin C (mg)	97.20	45.00	216%
Vitamin B6 (by analysis) (mg)	1.76	1.30	136%
Vitamin B12 (µg)	3.25	2.40	135%
Folate,total DFE (µg)	861.20	400.00	215%
Total vitamin A equivalents (µg)	1062.59	700.00	152%
Magnesium (mg)	328.78	320.00	103%
Calcium (mg)	705.38	1000.00	71%
Phosphorus (mg)	1655.13	1000.00	166%
Iron (mg)	11.75	18.00	65%
Zinc (mg)	8.64	8.00	108%
Selenium (µg)	81.25	60.00	135%
Iodine (µg)	166.08	150.00	111%

NRVs based on: Female, 43 years, 60.7 kg, 164.5 cm, Heavy Activity

Appendix 9. Bone Study Website



BONE HEALTH STUDY

Toi Ohomai and AUT researchers seek women to help them investigate:

Bone health in premenopausal women

Welcome to the home page for the Women's Bone Health Study

I am pleased to announce that the Women's Bone Health Study has officially completed it's first year!

Now due to popular demand...we will not only be rolling out a second year of JUMPING programmes for the original jumping group, but also opening up the successful first 12 months of JUMPING programmes to our control group participants (& anyone else who wants to start increasing bone mineral density in under 5 minutes per day)!

I will be sharing the amazing results achieved by our nearly 40 jumping participants as soon as the numbers have been crunched...however I am pleased to say the preliminary results have shown outstanding gains in bone mineral density and overall bone strength for all of our jumpers!

PHASE 5: We are now in PHASE 5 of the Bone Study (First 4 weeks of 2019)! This programme introduces one of our two new exercises (the STOMP) and a couple of jumps and hops from the last programmes

We will scheduling DEXA scanning in JULY & DECEMBER this year to help us to gain further understanding about the dose/response relationship between jumping frequency and bone response...so HUGE thanks for sticking with the study in whatever capacity this might be!

NEW FRIDGE/ WALL CHECKER! You can print this for each 4-weeks

*Tick/Smiley face/Star Friendly

To view the NEW JUMPING programme WEEK 1-4 PART 2 (will be the same for these four weeks) Jump-Landing' programme, please click here

Appendix 10. Sample Jump Tracker Reports

Jump Tracker

Week 8 Update!

Well done! Go you!

Keep up the good work logging your sessions each week!

Jump videos
For jump technique demonstrations head to the jump tracker and videos **web page**!

Goal for Week 9

4 Sessions

...including the new STRIDE jump!

Jump Tracker

Week 8 Update!

...almost there!

Keep up the good work logging your sessions each week!

Jump videos
For jump technique demonstrations head to the jump tracker and videos **web page**!

Goal for Week 9

4 Sessions

...including the new STRIDE jump!

Jump Tracker

Update
Week 12

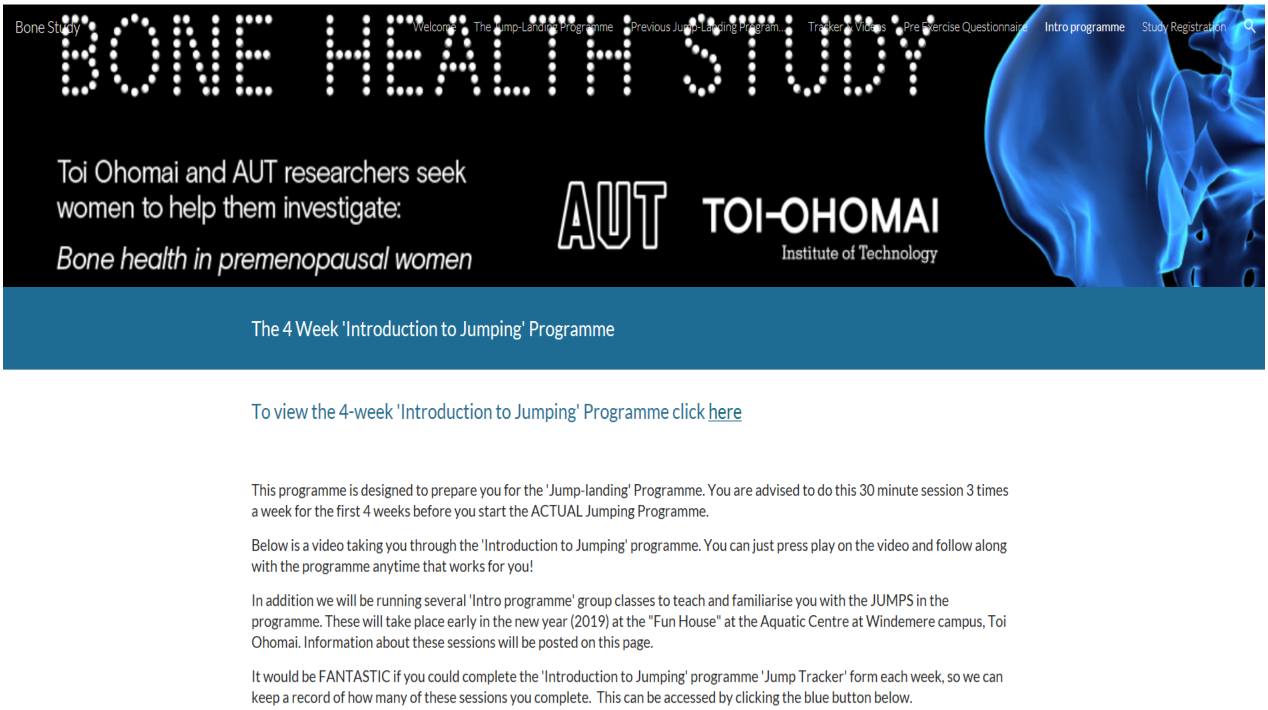
We didn't receive any jump data from you this week

No worries! It's easy to **add in your sessions** for previous weeks

Just head over to the jump tracker page **below**

https://sites.google.com/g.toiohomai.ac.nz/bonestudy/tracker-videos

Appendix 11. Online Introduction to the Jump-landing Programme (Videos)



BONE HEALTH STUDY

Toi Ohomai and AUT researchers seek women to help them investigate:

Bone health in premenopausal women

The 4 Week 'Introduction to Jumping' Programme

To view the 4-week 'Introduction to Jumping' Programme click here

This programme is designed to prepare you for the 'Jump-landing' Programme. You are advised to do this 30 minute session 3 times a week for the first 4 weeks before you start the ACTUAL Jumping Programme.

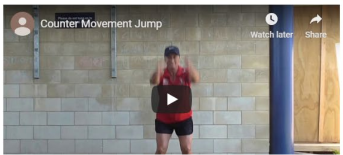
Below is a video taking you through the 'Introduction to Jumping' programme. You can just press play on the video and follow along with the programme anytime that works for you!

In addition we will be running several 'Intro programme' group classes to teach and familiarise you with the JUMPS in the programme. These will take place early in the new year (2019) at the "Fun House" at the Aquatic Centre at Windemere campus, Toi Ohomai. Information about these sessions will be posted on this page.

It would be FANTASTIC if you could complete the 'Introduction to Jumping' programme 'Jump Tracker' form each week, so we can keep a record of how many of these sessions you complete. This can be accessed by clicking the blue button below.

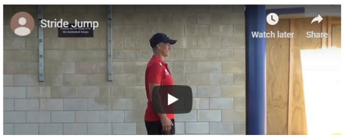
Appendix 12. Online Videos Jump-landing Exercises

Countermovement Jump



Star Jump

Stride Jump



Lateral Hop

Forward Hop

Appendix 13. Bone Study Facebook Page

Toi Ohomai and AUT researchers seek women to help them investigate:

Bone health in premenopausal women

Aneka Seerden
Founding Member · November 14, 2018

Hey ladies ⭐

I would like to say a massive THANKYOU for being a part of my project over this year! It has been wonderful working with you all and I hope you have all enjoyed your goodies and enjoyed what I was trying to do 🙂

Thankyou for all being a part of my last assessment of my degree 👩‍🎓 👩‍🎓 ... See More

9 · 5 Comments · Seen by 32

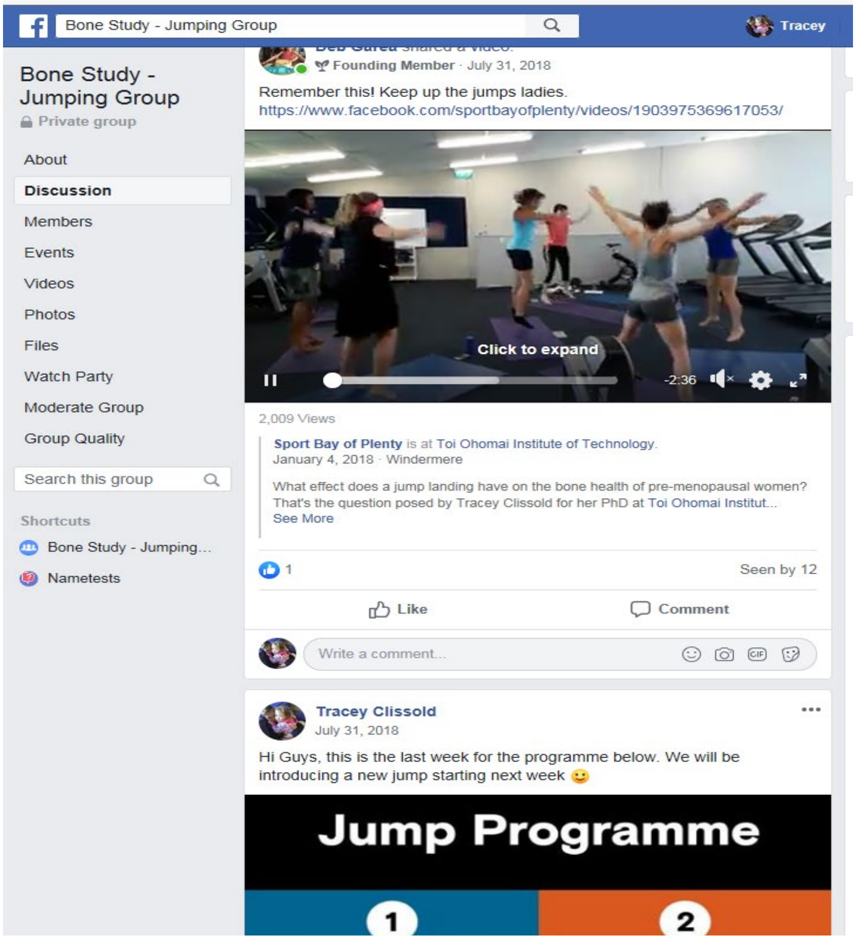
View 3 more comments

Add topics to posts to help group members find the information they're interested in.

Ruth Naidoo
Liz Apperley
Erin Kouwenhoven

This bone study group page has been created to keep you informed... See More

GROUP TYPE
General



Founding Member · July 31, 2018

Remember this! Keep up the jumps ladies.
https://www.facebook.com/sportbayofplenty/videos/1903975369617053/

2,009 Views

Sport Bay of Plenty is at Toi Ohomai Institute of Technology.
January 4, 2018 · Windermere

What effect does a jump landing have on the bone health of pre-menopausal women? That's the question posed by Tracey Clissold for her PhD at Toi Ohomai Institut... See More

1 · Seen by 12

Tracey Clissold
July 31, 2018

Hi Guys, this is the last week for the programme below. We will be introducing a new jump starting next week 🙂

Appendix 14. DEXA Testing Protocol

TOI-OHOMAI
Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Dual Energy X-Ray Absorptiometry (DEXA) Testing Protocol

What is DEXA (dual energy X-ray absorptiometry)?
The DEXA measurement technique is the most accurate and precise measurement of your bone mineral density and body composition. At present it is the gold standard technique throughout the world. DEXA bone density tests are non-invasive meaning that no needles or instruments are placed through the skin or body. You can remain fully dressed and the tests usually take no more than 20 minutes.

Protocol:

- The patient lies on the surface of the scanner table. An x-ray generator is located below the patient and an imaging device, or detector, is positioned above.
- To assess the spine, the patient's legs are supported on a padded box to flatten the pelvis and lower spine. To assess the hip, the patient's foot is placed in a brace that rotates the hip inward. In both cases, the detector is slowly passed over the area, generating images on a computer monitor.
- The DEXA bone density test combined with DEXA Body composition test is usually completed in 20 minutes.
- The measurements will be carried out by licensed technicians. Precision and calibration will be carried out in accordance with in-house procedure.

DEXA Bone and Body Composition scan: Important Information:

- Limit activity before your scan (no exercise please!).
- Please inform the technician if you are pregnant.
- Do NOT come in dehydrated.
- You do NOT need to fast for a DEXA scan.
- Please wear workout clothes without any metal.
- You will be asked to empty your pockets and remove any significant amounts of metal (watch, belt, glasses, jewellery, etc.).
- Small buttons or zippers that cannot be removed from clothing are fine
- Please wear socks!
- Do not have any gastrointestinal contrast, barium or other contrast medium, or radionuclides within 48 hours of your appointment.
- The amount of radiation used is extremely small—less than one-tenth the dose of a standard chest x-ray, and less than a day's exposure to natural radiation.

Appendix 15. Balance Testing Protocol

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AUT UNIVERSITY SPORT+ RECREATION

Balance Testing Protocol

Stork Balance Stand Test
The stork balance test requires the person to stand on one leg.

Purpose: To assess the ability to balance on one foot for 30-seconds.

Equipment required: This test will be performed standing on an AMTI Accusway Force Platform.

Procedure: Remove the shoes and place the hands on the hips, then position the non-supporting foot against the inside knee of the supporting leg. The subject is given one minute to practice the balance. The subject raises one leg to balance on one foot. The stopwatch is started once this position is initiated. The stopwatch is stopped if any of the follow occur:

- the hand(s) come off the hips
- the supporting foot swivels or moves (hops) in any direction
- the non-supporting foot loses contact with the knee.
- the heel of the supporting foot touches the floor.

- The test is repeated twice on each leg

Appendix 16. The Maximal Vertical Jump Testing Protocol

TOI-OHOMAI Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Maximal Vertical Jump Test Protocol

Vertical jump height measurement is a commonly used test of leg power. There are many techniques and various equipment used for measuring vertical jump height, with the Vertec one of them.

Equipment: The Vertec is one of the most common apparatus for measuring vertical jump ability. It is the vertical jump-testing device of choice for many college and professional teams. It is of steel frame construction with horizontal vanes which are rotated out of the way by the hand to indicate the height reached. Each vane is in 1cm increments, and the height of the vanes is adjustable to test elite athletes as well as beginners.

Figure 1. Performing a maximal vertical jump using the Vertec

Instructions:

1. Warm up: Participants will perform a ten-minute standardised warm up prior to testing that consists of easy cycling on a stationary cycle followed by dynamic stretching and bodyweight mobilisation exercises. Testing will commence five minutes after the warm up.

2. Take the standing height of the subject with one arm fully extended upward

3. Participants will be instructed to stand with feet shoulder-width apart with their arms raised above their head, then to bend their knees and hips with arms swinging downwards to perform a maximal jump for height, and touch the highest possible vane.

4. The jump height is the difference between standing height and jumping height.

5. Participants will be asked to perform 3 maximal vertical jumps with 30-seconds rest between each jump.

Appendix 17a. Height Testing Protocol

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Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Height Testing Protocol (Wall Mounted Stadiometer)

Height Definition: The perpendicular distance between the top of the head (the vertex) and the bottom of the feet.
Equipment: SECA 214 portable stadiometer.

Step 1.
Ask the subject to stand on the centre of the base with their back to the stadiometer. Ask them to put their feet together and move back until their heels touch the bottom of the stadiometer upright. Their buttocks and upper part of their back should also be touching the stadiometer upright. Their head does not have to touch the stadiometer.
The respondent's head should be in the Frankfort plane. This is achieved when the lower edge of the eye socket (the Orbitale) is horizontal with the Tragion [see Figure 1]. The vertex will be the highest point on their head. If their head is not aligned properly, (and for most respondents it probably won't be), ask them to raise or lower their chin until it is in the Frankfort Plane.

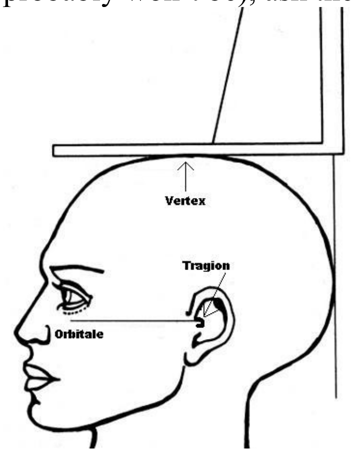

Figure 1: Head in the Frankfort Plane

Step 2.
When you are happy that the respondent is in the correct position, ask them to take a deep breath and hold it. Lower the blue headboard until it is in contact with the head. Compress the hair if needed. Make sure you don't bend the headboard from the horizontal, nor move the respondent's head. Hold the headboard firmly at its final position and take the reading to the nearest 0.1 cm.

Step 3.
When you have completed the reading, ask the respondent to step away from the stadiometer. Move straight to the computer and record your reading.

Appendix 17b. Weight and Body Composition Testing Protocol

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Institute of Technology

AUT UNIVERSITY SPORT+ RECREATION

Weight and Body Composition
(Inbody Bioelectrical Impedance Analyser, BIA)

Step 1.
Step on the InBody to measure your weight. Make sure to align your feet with the foot electrodes. Once the InBody confirms your weight, you will be asked to enter your personal profile. Using a user ID will allow you to monitor and track your progress. Confirm your personal profile. Then press enter to begin the InBody Test.

Step 2.
Grab the handles and place your thumbs on the oval electrodes. Keep your arms straight and away from your body.

Step 3.
Relax and keep your body still until the test is completed (30 seconds).
Test Completion.
Your InBody results will print automatically once the test is completed.

Pre-test Guidelines (for increased accuracy in body composition testing)
Prepare for your BIA test by adhering to the following instructions:

- Do not eat for 4 hours prior to testing
- Do not exercise 12 hours prior to testing
- Do not consume alcohol for 24 hours prior to testing
- Hydrate well the day before
- Do not drink caffeine on the day of your test
- Insure access to both feet with removable footwear (no socks or pantyhose)
- Do not wear jewellery- all jewellery will have to be removed prior to testing
- Do not put lotion on your hands and feet
- Do not exercise or take a shower before measurement
- Measure after standing for at least 5 minutes

Please note:
Bioelectrical Impedance Analysis (BIA) has been selected as is a non-invasive completely pain-free technique for determining body composition using low voltage electrical currents which are not detectable. The researchers will ensure safety during the use of this equipment and warn participants they cannot use this equipment if they have metal implants or a pacemaker.

Appendix 18. Effect Sizes: Calculation and Development of Criteria Relevant to Bone Mineral Density

Calculate Effect Sizes:

[Post-mean – Pre-mean (BMD in g/cm²) / 0.5 (SD1 + SD2)]

Proposed Effect Size Criteria
Trivial < 0.1
Small 0.1 - 0.2
Moderate 0.2 - 0.3
Large > 0.3

1. **Bassey et al (1998) 5-month study**

Site	**Pre-test Mean ± SD**	**Post-test Mean ± SD**	**ES**
Lumbar Spine (L2-4)	1.152 ± 0.117	1.142 ± 0.021	**0.15**
Femur neck	0.992 ± 0.132	0.972 ± 0.023	**0.26**
Trochanter	0.845 ± 0.113	0.821 ± 0.0665	**0.18**

Eg. Lumbar Spine (ES calculation)
1.152 - 1.142/ 0.5 (0.117 + 0.021)
ES = 0.15

2. **Vainionpaa et al (2005) 12-month study**

Site	**Pre-test Mean ± SD**	**Post-test Mean ± SD**	**ES**
Femur neck	0.789 ± 0.097	0.797 ± 0.093	**0.08**
Trochanter	0.992 ± 0.132	0.972 ± 0.023	**0.08**
Inter-trochanter	1.128 ± 0.129	1.136 ± 0.132	**0.06**

Eg. Femur neck (ES calculation)
0.797 – 0.789/ 0.5 (0.097 + 0.093)
= 0.08

3. **Winters-Stone & Snow (2006) 12-month study**

Site	**Pre-test Mean ± SD**	**Post-test Mean ± SD**	**ES**
Femur neck	0.835 ± 0.118	0.843 ± 0.118	**0.07**
Trochanter	0.690 ± 0.096	0.707 ± 0.095	**0.18**
Lumbar	1.088 ± 0.107	1.085 ± 0.108	**-0.3**

Eg Femur neck (ES calculation)
0.843 -0.835/ 0.5 (0.118 + 0.118)
= 0.07

Appendix 19. Smallest Worthwhile Change Calculations (for bone variables)

The smallest worthwhile change (%) for each dependant variable was calculated using Effect Sizes
(SWC = ES * Standard Deviation)

Using Effect Sizes:
[Post-mean – Pre-mean (BMD in g/cm^2) / 0.5 (SD1 + SD2)]

Proposed Effect Size Criteria
Trivial < 0.1
Small 0.1 - 0.2
Moderate 0.2 - 0.3
Large > 0.3

The smallest worthwhile change (%) for each dependant variable was also calculated using Coefficient of Varaiation (CV = Standard Deviation/ Mean) *100

The table below shows a comparison for two methods of determining the SWC (ES vs CV)

Site	Using ES	Using CV
Femoral neck (BMD)	0.19	1.63
Femoral neck (BMC)	0.36	0.21

Eg. Femoral neck BMD (ES calculation)

SWC = 0.10 * 1.89 = 0.19

Femoral neck BMD (CV calculation)

SWC = 1.89/1.16 = 1.63

Appendix 20: RELIABILITY OF BALANCE VARIABLES ASSOCIATED WITH THE AMTI ACCUSWAY BALANCE FORCE PLATE IN PREMENOPAUSAL WOMEN (TECHNICAL REPORT)

Prelude

Balance has been described as the ability to preserve the bodies centre of gravity over its base of support whilst maintaining steadiness and minimising sway. The capacity to maintain balance is complex, and it is estimated that 30 - 60% of older adults likely to fall at least once a year, resulting in 10 - 20% of these falls ending up in hospital with a fracture, it is important to gain a greater understanding about how to improve balance throughout life. Therefore, the ability to assess balance, as a factor which effects falls risk, is essential when evaluating the effectiveness of an exercise intervention programme to be used for osteoporosis prevention in premenopausal women.

Although force plates provide an ability to quantify balance variables such as centre of pressure, postural sway lengths and postural sway velocities, these variables have not been assessed on a sample of premenopausal women. Therefore, the purpose of this study was to quantify the variability associated with AMTI balance force plate measurements of interest for premenopausal women, by providing measures of absolute (CV) and relative consistency (ICC). It was deemed important to identify if any balance variables achieved the acceptable test-retest reliability required to be included as a dependant variable to monitor change during the 12-month experimental study (Chapter 9). Therefore, the purpose of this study was to determine if any balance measures had acceptable reliability and therefore could be used in the ensuing training intervention.

Introduction

Although studies have examined balance as a risk factor for sports injuries (Hahn, Foldspang, Vestergaard, & Ingemann-Hansen, 1999; Han, Anson, Waddington, Adams, & Liu, 2015), the focus of this research is on measuring balance in older adults, relating to falls risk and osteoporotic fractures. It is estimated that 30 - 60% of older adults are likely to fall at least once a year, resulting in 10 - 20% ending up in hospital with a fracture (Meshkati, Namazizadeh, Salavati, & Mazaheri, 2011; Moghadam et al., 2011). These statistics also state that women will fall more often than men and represent 75% of all hip fractures. Susceptibility to falls have been linked to a variety of factors including; impaired musculoskeletal, neuromuscular, reduced postural response and deconditioning linked to inactivity (Lusardi et al., 2017). Balance has been described as the ability to preserve the bodies centre of gravity over its base of support whilst maintaining steadiness and minimising sway (Hahn et al., 1999; Horak, 1987). Hence the capacity to maintain balance is complex and involves the interaction of the visual, vestibular, somatosensory systems with the coordination of movement via muscle activity (Emery, 2003). Therefore, the ability to assess balance is essential when evaluating the effectiveness of an exercise intervention programme to be used for osteoporosis prevention in premenopausal women.

Tests have been developed to assess static standing balance (e.g. the stork), using time to assess the ability to maintain a stable position, however force plates provide an ability to quantify balance variables such as centre of pressure, postural sway lengths and postural sway velocities. Previous researchers of osteoporosis prevention in premenopausal women have assessed different types of dynamic balance tasks (Bassey et al., 1998; Heinonen et al., 1996), however most studies have neglected to measure any balance variables (Bailey & Brooke-Wavell, 2010b; Kato et al., 2006; Niu et al., 2010; Tucker et al., 2014; Vainionpää et al., 2005; Winters-Stone & Snow, 2006). A further limitation is that no studies have utilised force plate technology or have presented any test-retest reliability associated with balance variables in premenopausal women.

The test-retest reliability of balance variables is crucial if balance is to be used as an outcome variable to assess change, and to determine the degree of reproducibility of the test result when performed under identical conditions. For a full understanding of the variability associated with measurements it is recommended that the measures of absolute (coefficients of variation - CV) and relative consistency (intra-class correlation coefficients - ICC) should be presented (Hopkins, 2000). Previous researchers have described the reliability of force plate balance measurements in elderly and athletic populations with ICC's > 0.75, and CV's < 15% as describing acceptable and excellent reliability (Enderlein, 1988; Meshkati et al., 2011; Moghadam et al., 2011; Shrout & Fleiss, 1979), however these values have not been established in premenopausal women. Given these limitations, the purpose of this study was to quantify both absolute and relative consistency for the variability associated with the AMTI balance force plate measurements in premenopausal women. It was hypothesised that some, but not all, of the balance variables measured would achieve the acceptable test-retest reliability required to be included as a dependant variable to monitor change for our 12-month experimental study.

Methods

Experimental Approach to the Problem

A test-retest reliability study design was utilised to assess the reliability of the balance variables of interest. Data was collected using Accusway force plate (AccuSway, AMTI, Watertown, MA, USA). Force platforms are used to measure the ground reaction forces produced by the participant to provide an indirect assessment for change in postural sway during the balance test. Variable of interest include; centre of pressure, sway amplitude, sway path and sway velocity. Data was collected for each participant during the baseline testing session, with each participant completing two trials on each leg. A 30-second one-leg static balance test was used to measure postural sway, as this test has been shown to be a significant and easy-to-administer predictor of injurious falls (Vellas et al., 1997). The methods and procedures used in this study were approved by the New Zealand Health and Disability Ethics Committees (17/NTB/155).

Participants

Thirty-eight healthy premenopausal women, volunteered to participate in this study (see Table 9.1). All participants were considered healthy as determined by a Physical Activity Readiness Questionnaire (PAR-Q) and inclusion criteria required participants to be younger than 51 years of age, in conjunction with the participants reporting a regular menstrual cycle to determine premenopausal status. All participants provided written informed consent after having being briefed on the potential risks associated with this research. The methods and procedures used in this study were approved by the New Zealand Health and Disability Ethics Committees (17/NTB/155).

Table 9.1 Baseline characteristics of the participants (mean ±SD)

Demographics	All Participants (n = 38)
Age (yr.)	32.3 ± 7.70
Height (cm)	166.5 ± 5.90
Body mass (kg)	69.1 ± 23.2

Testing Protocol

Participants performed a ten-minute standardised warm up prior to testing that consisted of easy cycling on a stationary Wattbike (Wattbike Trainer, Nottingham, United Kingdom) followed by dynamic stretching and bodyweight mobilisation exercises. Testing commenced five minutes after the warm up. All instructions were standardised for every participant. Participants were asked to stand on the force platform on both legs, then asked to stand on one leg, for a timed 30-sec period. Participants were asked to stand quietly while barefoot, with hands on their hips, looking straight ahead at an image on the wall (Figure 8.1). Although foot positioning was standardised using foot outlines drawn on the top of the force plate, participants were free to place their foot within these confines. Interestingly, some researchers have concluded that foot positioning was not important in eyes-open conditions for protocols assessing balance (single and double-leg stance), and had minimal effect on sway distance, area or velocity (Schneiders, Gregory, Karas, & Mündermann, 2016).

Each subject completed two trials on each leg (alternating legs), with 1-minute rest between each trial, and force plate output variables were represented as an average of the two trials. Both balance testing sessions were performed on the same day using the same force plate by the same technician, with a 10-minute rest period interspersed between testing sessions. All jump testing was performed indoors in a temperature-controlled Sports Science testing facility.

Figure 9.1 Pictorial representation of the balance test utilised in this study

Statistical Analyses

Descriptive statistics were used to describe the cohort characteristics. Reliability of balance measures was evaluated by intraclass correlation coefficients (ICC) using a two-way random effects model, absolute agreement and average measures ICC (Shrout & Fleiss, 1979). ICCs were classified as follows: 'poor' (≤ 0.40), 'moderate' (0.41 - 0.60), 'good' (0.61 - 0.80), or 'excellent' (≥ 0.81) (Enderlein, 1988; Shrout & Fleiss, 1979). 95% confidence intervals (95% CI) were calculated to assess relative consistency for all reliability measures. Coefficients of variation (CV) were also calculated (CV = SD/mean * 100) for each dependant variable to assess absolute consistency. Data analyses were conducted using SPSS 22.0 for Windows (SPSS Inc., Chicago, IL, USA). Significance was set at $p < 0.05$.

Results

Cohort Characteristics

There were 38 participants that completed the force plate balance testing twice on the same day. Participants were between 30 and 50 years of age, with 100% also recruited for the 12-month jump-landing study (Table 9.1).

Test Retest Reliability (Left leg)

The test-retest reliability data of left leg balance measures are reported in Table 9.2. Relative consistency (ICC) for all measures ranged between 0.60 to 0.98, the lowest ICC was associated with a velocity measure (Vy min). Absolute consistency ranged between 0.81 to 18.6%, the greatest CV was also associated with path length area. The variables that demonstrated excellent reliability were path length, unit path (ICC = 0.92; CV = 13.5 and 17.8%), and velocity measures (except Vy min) (ICC = 0.81 to 0.98; CV's 0.81 to 10.7%).

Test Retest Reliability (Right leg)

The test-retest reliability data of balance measures that were shown to have excellent reliability for the left leg were calculated for the right leg (see Table 9.3). Relative consistency was good to excellent for all of these balance measures (ICC's = 0.72 to 0.82), the lowest ICC was associated with path length. Absolute consistency ranged from 4.18 to 20.3%, the highest CV was also associated with path length.

Please note that the variables reported in this results section are the principle variables of interest to this thesis and those reported the most in the literature. A full analysis of all variables can be observed in the supplementary material in the appendices.

Table 9.2 Test-retest reliability of left leg balance measures

Test – retest Reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
Path Length Measures						
Path Length	124 ±36.0	120 ±33.4	0.92^s	0.85 to 0.96	13.5	Excellent
Unit Path	4.16 ±1.20	3.95 ±1.15	0.92^s	0.84 to 0.96	17.8	Excellent
Path Area	13.5 ±3.39	12.9 ±2.77	0.74^s	0.50 to 0.87	18.6	Good
Velocity Measures (V)						
Vx Max	37.1 ±20.5	37.0 ±19.5	0.98^s	0.95 to 0.99	0.81	Excellent
Vx Min	99.9 ±24.6	99.6 ±24.4	0.95^s	0.90 to 0.97	1.34	Excellent
Vy Max	16.5 ±8.25	16.6 ±8.64	0.81^s	0.64 to 0.90	1.20	Excellent
Vy Min	16.9 ±6.84	16.3 ±6.32	0.60^s	0.22 to 0.79	10.1	Good
V Average	4.13 ±1.23	4.00 ±1.11	0.92^s	0.84 to 0.96	10.7	Excellent

Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.05$; CV Coefficient of Variation

Table 9.3 Right leg test-retest reliability balance measures that were shown to have excellent reliability for the left leg

Test – retest Reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
Path Length Measures						
Path Length	111 ±38.9	119 ±40.1	0.72^s	0.46 to 0.85	20.3	Good
Unit Path	4.02 ±1.51	3.96 ±1.34	0.77^s	0.56 to 0.88	4.18	Good
Velocity Measures (V)						
V Average	3.89 ±1.33	3.96 ±1.34	0.82^s	0.66 to 0.91	5.18	Excellent

Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.05$; CV Coefficient of Variation

Discussion

The purpose of this study was to present a full understanding of the variability associated with AMTI force plate balance measurements of interest for premenopausal women, by providing measures of absolute (CV) and relative consistency (ICC), as previously these values have not been reported in this population. It was deemed important to identify whether any balance variables achieved the acceptable test-retest reliability required to be included as a dependant variable to monitor change during the 12-month experimental study. Although studies have shown that balance variables assessed for the single-legged stance do not usually differ between dominant and non-dominant leg, we were interested in assessing reliability for both limbs (Hoffman, Schrader, Applegate, & Koceja, 1998). Our results showed that sway path length, unit path and average sway velocity were the only balance measures to have acceptable reliability for analysing performance changes over time in both legs. Significant correlations were observed for these balance measures and reliability ranged from good to excellent (ICC = 0.72 to 0.82; CV's 4.18 to 20.3%) when measured in a cohort of premenopausal women.

According to Palmieri and colleagues (2002), the understanding of balance variables is crucial to understanding what we are measuring and what aspects of the postural-control system these represent, stating that the variables that provide the greatest reliability should be the central focus for the clinical quantification of balance (Palmieri, Ingersoll, Stone, & Krause, 2002). They propose that sway path length and velocity measures represent the strategies utilised by the body to maintain stability, and are therefore important variables to focus on in terms of fall prevention. It is therefore favourable that of the balance data measured in this study, sway path length (ICC = 0.72; CV = 20.3%), unit path (ICC = 0.77; CV = 4.18%) and average sway velocity (ICC = 0.82; CV = 5.18%) were the balance measures to have acceptable reliability for analysing performance changes over time in both legs. Although acceptable reliability ranges for these values are yet to be determined in premenopausal women, previous researchers have described ICC's > 0.75, and CV's < 15% as acceptable and excellent reliability for force plate balance measurements in elderly and athletic populations (Meshkati et al., 2011; Moghadam et al., 2011).

An increase in sway path length (the total distance covered by the centre of pressure during the test duration), and an increase in sway velocity (sway path divided by the test duration), represents a reduced ability to maintain balance by the postural-control system (Ekdahl, Jarnlo, & Andersson, 1989). Although some studies have reported these balance and stability measures using force plate technology in elderly and athletic populations, none have utilised this technology in osteoporosis prevention studies with premenopausal women. Furthermore, the measurement error and thus the reliability of using force plates to evaluate balance as a risk factor for falling is poorly understood in this population (Meshkati et al., 2011). It is therefore advised that future studies present both CV and ICC values to further advance understanding of the variability associated with these identified force plate balance measurements, and to enable acceptable error precision ranges to be established for this population.

Conclusion

We have provided a comprehensive description of the reliability (relative and absolute consistency) associated with AMTI balance force plate measurements not previously presented for premenopausal women. In addition, we have reported acceptable reliability results for sway path length, unit path and average sway velocity, in both legs, for the 30-second one-legged balance test. Thus, we have selected these three balance variables to be included as a dependant variable to monitor change during the 12-month experimental study in a cohort of premenopausal women.

Appendix 21. DEXA Reliability Tables

Table 9.4 Test-retest reliability of DEXA left hip measures (n = 17)

Test – retest reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
Neck Area (cm^2)	4.96 ±0.30	4.88 ±0.31	0.91^s	0.72 to 0.97	2.13	Excellent
Neck BMC (g)	4.74 ±0.63	4.70 ±0.76	0.98^s	0.94 to 0.99	2.01	Excellent
Neck BMD (g/cm^2)	0.95 ±0.11	0.96 ±0.11	0.99^s	0.97 to 1.00	1.12	Excellent
Neck Z score	1.13 ±1.04	1.24 ±1.04	0.99^s	0.96 to 1.00	3.75	Excellent
Trochanter Area (cm^2)	10.6 ±1.18	10.2 ±1.16	0.98^s	0.94 to 0.99	1.81	Excellent
Trochanter BMC (g)	9.10 ±1.60	8.97 ±1.55	0.99^s	0.97 to 1.00	2.07	Excellent
Trochanter BMD (g/cm^2)	0.86 ±0.18	0.85 ±0.12	0.99^s	0.96 to 1.00	1.27	Excellent
Trochanter Z score	1.59 ±1.18	1.50 ±1.15	1.00^s	0.98 to 1.00	3.83	Excellent
Inter Trochanter Area (cm^2)	18.9 ±2.39	19.1 ±2.32	0.99^s	0.97 to 1.00	1.50	Excellent
Inter Trochanter BMC (g)	23.3 ±4.47	23.5 ±4.52	0.99^s	0.99 to 1.00	1.53	Excellent
Inter Trochanter BMD (g/cm^2)	1.23 ±0.13	1.22 ±0.13	1.00^s	0.99 to 1.00	0.80	Excellent
Inter Trochanter Z score	0.96 ±0.86	0.86 ±0.85	0.99^s	0.96 to 1.00	5.23	Excellent
Total Area (cm^2)	34.5 ±3.08	34.6 ±2.96	0.99^s	0.98 to 1.00	0.95	Excellent
Total BMC (g)	37.2 ±6.25	37.2 ±6.27	1.00^s	0.99 to 1.00	1.12	Excellent
Total BMD (g/cm^2)	1.07 ±0.12	1.07 ±0.12	1.00^s	0.99 to 1.00	0.64	Excellent
Total Z score	1.21 ±1.06	1.16 ±1.05	1.00^s	0.99 to 1.00	2.22	Excellent

Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.001$; CV Coefficient of Variation; BMC; Bone mineral content; BMD Bone mineral density

Table 9.5 Test-retest reliability of DEXA lumbar measures (n = 17)

Test – retest Reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
L1 Area (cm^2)	14.3 ±1.57	14.4 ±1.60	0.99^s	0.97 to 1.00	1.14	Excellent
L1 BMC (g)	15.9 ±3.16	16.0 ±3.09	0.99^s	0.98 to 1.00	1.45	Excellent
L1 BMD (g/cm^2)	1.11 ±0.15	1.11 ±0.15	1.00^s	0.99 to 1.00	0.92	Excellent
L1 Z score	1.25 ±1.45	1.25 ±1.51	1.00^s	0.99 to 1.00	4.13	Excellent
L2 Area (cm^2)	15.0 ±1.34	15.1 ±1.34	0.99^s	0.98 to 1.00	0.83	Excellent
L2 BMC(g)	17.5 ±3.24	17.5 ±3.15	1.00^s	0.99 to 1.00	0.95	Excellent
L2 BMD (g/cm^2)	1.16 ±0.13	1.15 ±0.14	0.99^s	0.98 to 1.00	0.97	Excellent
L2 Z score	1.36 ±1.32	1.36 ±1.36	0.99^s	0.98 to 1.00	1.54	Excellent
L3 Area (cm^2)	16.6 ±1.20	16.6 ±1.17	0.99^s	0.97 to 1.00	0.77	Excellent
L3 BMC (g)	20.0 ±3.99	21.4 ±5.78	1.00^s	0.99 to 1.00	0.92	Excellent

L3 BMD (g/cm^2)	1.20 ±0.18	1.19 ±0.18	1.00^{s}	0.99 to 1.00	1.24	Excellent
L3 Z score	1.26 ±1.77	1.21 ±1.78	1.00^{s}	0.99 to 1.00	9.41	Excellent
L4 Area (cm^2)	18.6 ±2.06	19.0 ±2.60	0.98^{s}	0.94 to 0.99	1.27	Excellent
L4 BMC (g)	21.1 ±3.02	21.4 ±3.26	1.00^{s}	0.99 to 1.00	0.88	Excellent
L4 BMD (g/cm^2)	1.15 ±0.11	1.13 ±0.12	0.97^{s}	0.90 to0 .99	1.87	Excellent
L4 Z score	1.01 ±1.14	0.83 ±1.18	0.97^{s}	0.91 to 0.99	11.7	Excellent
Total Area (cm^2)	63.3 ±6.56	65.1 ±4.56	0.99^{s}	0.95 to 1.00	0.56	Excellent
Total BMC (g)	72.2 ±8.91	73.5 ±9.02	1.00^{s}	0.99 to 1.00	0.70	Excellent
Total BMD (g/cm^2)	1.16 ±0.15	1.15 ±0.15	0.99^{s}	0.98 to 1.00	1.08	Excellent
Total Z score	1.28 ±1.50	1.18 ±1.52	0.99^{s}	0.98 to 1.00	10.2	Excellent

Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.001$; BMC bone mineral content; CV Coefficient of Variation; BMC bone mineral content; BMD bone mineral density; L1 - L4 Lumbar spine (1 - 4)

Table 9.6 Test-retest reliability of DEXA left hip structural analysis measures (n = 17)

Test – retest Reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
Narrow Neck CSA (cm^2)	3.50 ±0.51	3.52 ±0.58	0.91^{s}	0.98 to 1.0	1.56	Excellent
Narrow Neck Z (cm^3)	1.64 ±0.32	1.64 ±0.31	0.99^{s}	0.97 to 1.0	1.88	Excellent
Narrow Neck Cort. Thick. (cm)	0.23 ±0.03	0.23 ±0.03	0.99^{s}	0.95 to 1.0	1.45	Excellent
Inter Trochanter CSA (cm^2)	6.15 ±0.95	6.07 ±0.94	1.00^{s}	0.97 to 1.0	1.08	Excellent
Inter Trochanter Z (cm^3)	5.46 ±1.13	5.74 ±1.69	0.98^{s}	0.91 to 1.0	2.13	Excellent
Inter Trochanter Cort. Thick. (cm)	0.50 ±0.08	0.48 ±0.06	0.99^{s}	0.97 to 1.0	1.09	Excellent
Femoral Shaft CSA (cm^2)	4.72 ±0.69	4.69 ±0.67	1.00^{s}	0.99 to 1.0	0.76	Excellent
Femoral Shaft Z (cm^3)	2.46 ±0.53	2.48 ±0.47	0.94^{s}	0.82 to 0.98	1.47	Excellent
Femoral Shaft Cort. Thick. (cm)	0.63 ±0.01	0.62 ±0.01	0.97^{s}	0.93 to 0.99	1.35	Excellent
Neck shaft Angle (°)	130 ±5.58	129 ±4.63	0.91^{s}	0.75 to 0.97	1.29	Excellent

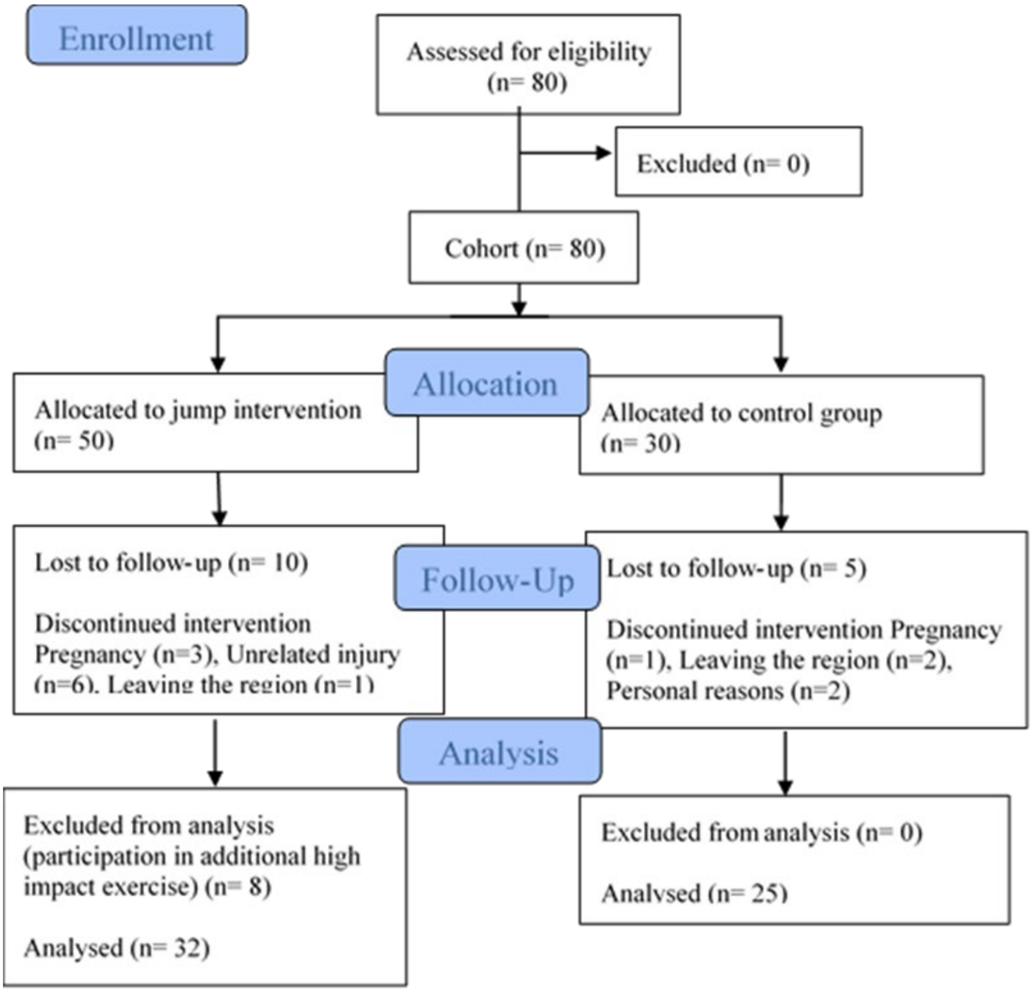
Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.001$; CV Coefficient of Variation; Cort Cortical; Thick Thickness

Table 9.7 Test-retest reliability of DEXA body composition measures (n = 17)

Test – retest Reliability	Mean ±SD		ICC AvgMea	95% CI	CV %	Qualitative Inference
	Trial 1	Trial 2				
Total Body Bone Area (cm^2)	2132 ±180	2134 ±186	1.00^s	0.98 to 1.0	0.62	Excellent
Total Body BMC (g)	2546 ±358	2549 ±360	1.00^s	0.99 to 1.0	0.36	Excellent
Total Body BMD (g/cm^2)	1.19 ±0.10	1.20 ±0.11	0.96^s	0.89 to 0.99	0.87	Excellent
Total Body Fat Mass (g)	20630 ±9019	20409 ±9107	1.00^s	0.99 to 1.0	1.23	Excellent
Total Body Lean + BMC (g)	52021 ±7793	52179 ±7837	1.00^s	0.99 to 1.0	0.69	Excellent
Total Body Mass (g)	72586 ±15343	72588 ±15441	1.00^s	1.0 to 1.0	0.32	Excellent
Total Body Fat (%)	27.5 ±6.70	27.2 ±6.77	1.00^s	0.99 to 1.0	1.23	Excellent

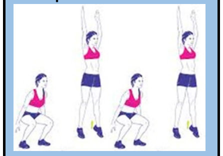
Key: ICC Intraclass correlation coefficient; AvgMea Average measures; ^{s} $p < 0.001$; CV Coefficient of Variation; BMC bone mineral content; BMD bone mineral density

Appendix 22: A flow Diagram Depicting the Recruitment and Retention of Participants During the 12-Month Training Study (Chapter 8.)

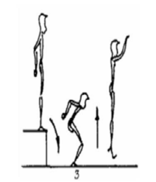


Appendix 23. Sample Jump-landing Programme Templates Provided for the Chapter 8 Training Study Manuscript.

Weeks 1-4:

Weeks	Jump Type	Frequency (times per week)	Sets x Reps	Volume (landings per day)	Volume (landings per week)	Rest (between jumps)	Rest (between sets)
1 - 4	Countermovement Jump* 	2x	4 x 4	32	64	5 sec	30 sec
		3x	4 x 4	32	96		
		4x	4 x 4	32	128		
		3x	4 x 4	32	96		

Weeks 17-20:

Weeks	Jump Type	Frequency (times per week)	Sets x Reps	Volume (landings per day)	Volume (landings per week)	Rest (between jumps)	Rest (between sets)
17-20	Drop Jump* 	4-5x	2 x 4	32	128 -160	2-5 sec	30 sec
	Stride Jump** 	4-5x	2 x 4 *start each set with different leg forward)				

The jump-landing program was designed to progressively increase in magnitude and rate of strain, number of ground contacts (32 - 42 per day), frequency (2 - 5 sessions per week), and technical difficulty (i.e. bilateral to unilateral) over the 12-month period (see Tables above).