GROUND REACTION FORCE ANALYSIS OF A VARIETY OF JUMPING ACTIVITIES IN GROWING CHILDREN

by

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Abstract

In recent years, the role of physical activity for the development and maintenance of a healthy skeleton and for the prevention of osteoporosis has garnered significant research interest. These studies have revealed that high impact loads with an unusual strain distribution are generally thought to be more effective in eliciting an osteogenic response than low impact repetitive activities. Also, immature bones appear to have a greater capacity to adapt to mechanical loads than mature bone.

Childhood intervention programs that utilized different weight bearing activities and games including jumping have demonstrated a positive bone response to mechanical loading (McKay et al., 2000, Bradney et al., 1998, Morris et al., 1997, Heinonen et al., in press). However, the biomechanical characteristics of effective interventions have never been described.

We addressed the question "what ground reaction forces (GRFs) are associated with pediatric mechanical loading intervention programs?" To accomplish this we measured the maximum GRF, rates of force, impulses and time to maximum force for twelve different jumping activities on a Kistler 9251A force platform (Winterthur, Switzerland). Jumps measured included drop jumps from 10, 30 and 50 cm, followed by a plyometric jump, submaximal and maximal jumping jacks, alternating feet, counter movement jumps and side to side jumps over 10 and 20 cm foam barriers. We also examined the relationship between bone mineral density (BMD) at the proximal femur, physical activity (PA) and dynamic power.

The subjects were 70 children (36 boys and 34 girls), 8.3 – 11.7 years old. Height (cm) and mass (kg) were measured using standard techniques. BMD (g/cm^2) at the hip and lean and fat mass (g) from the total body scan were assessed by dual energy X-ray absorptiometry (DXA, Hologic Inc). PA was assessed by questionnaire and a composite loading activity score was derived for each subject. Dynamic power was assessed with a vertical and standing long jump using standard procedures.

Subjects ranged in height from 128.4 – 172.6 cm and with mass of 25.0 – 57.0 kg, on average. Mean (SD) for vertical jump was 24.2 (5.5) cm and 135.2 (16.6) cm for standing long jump. The children engaged in loaded PA an average of 5.7 (5.2) hours per week. BMD (g/cm^2) for total proximal femur, femoral neck and trochanter was 0.70 (0.09), 0.67 (0.08) and 0.58 (0.08), respectively

The highest mean maximum GRFs, normalized for body weight (BW), were generated from the plyometric portion of the drop jumps and the counter movement jump (on average 5 BW) compared to 3.5 BW for jumping jacks. Similarly, highest rates of force were 514 BW/sec for the plyometric jump from 10 cm and 493 BW/sec for the counter movement jump. In hierarchical regression, lean mass ($\beta = 0.56$) and long jump distance ($\beta = 0.33$) were significant predictors of femoral neck BMD accounting for 42% of the total variance. Our findings demonstrated that relatively high and diverse GRFs and rates of force are generated by jumps included in a pediatric exercise intervention trial. As forces at the hip are known to be approximately 3 times the measured GRF (Bassey et al., 1997), the GRFs measured in the present study would be associated with forces 15 BW at the proximal femur. These findings could be used to modify ongoing interventions or to develop new targeted interventions for bone health in children.

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Glossary of Terms/Abbreviations

BMC: Bone mineral content (grams); the absolute amount of mineral present in a bone or regions of a bone

BMD: Bone mineral density in g/cm^2 when measured by DXA; the relative amount of bone mineral per measured area of bone; or, BMC divided by the area of the region scanned

BW: Body weight

CI: Confidence interval

CSMI: Cross-sectional moment of inertia.

DXA: Dual energy x-ray absorptiometry

FN: Femoral neck

GRF: Ground reaction force measured by a force platform.

MES: Minimum effective strain.

MF: Maximum force

MRF: Maximum rate of force

PA: Physical activity

PE: Potential energy

PF: total proximal femur

SD: Standard deviation

troch: Trochanter

UBC: University of British Columbia

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1. INTRODUCTION

Osteoporosis is defined as "bone mineral density at least 2.5 SD below adult peak mean " by the World Health Organization. Degeneration of bone predisposes individuals to osteoporotic fractures. With the demographic shift towards an older population and increased life expectancy, we will see an increase in the incidences of osteoporotic fractures. In the past, research on osteoporosis has focused primarily on women after menopause and on the treatment rather than the prevention of osteoporosis. However, it must be realized that the precursors to osteoporosis start early in childhood. With more than 90% of adult bone mineral present by the end of adolescence (Bailey et al., 1996), the attainment of optimal peak bone mass during childhood may be a preventative measure for osteoporosis.

Immature bone appears to have a greater capacity to adapt to mechanical loading than mature bone. During adulthood, bone remodeling involves the coupling of formation and resorption of bone. However, during childhood and adolescence, the majority of bone surfaces are modeling, rapidly forming and mineralizing bone matrix on non-adjacent surfaces. Therefore, lifestyle factors influencing bone mineral accretion may have the greatest effect during growth.

There are multiple factors that affect the accrual of bone mineral during growth including: age, gender, heredity, hormonal status, nutrition, and physical activity (skeletal loading), with heredity being the primary factor (Kelly et al., 1991). However, there are two factors that can be easily modified that affect bone mass: nutrition and skeletal loading. It has been shown that nutrition, especially calcium, and physical activity have significant bearing on the skeleton at all ages (Rice et al., 1993 and Young et al., 1995). The type of loading during physical activity is also an important factor. High impact skeletal loading, as compared to low impact activity, is generally thought to be more effective in eliciting a positive osteogenic response (Grimston et al., 1993). It is also known that bone strength is a function of high-impact loading in uncustomary strain environments, such as during jumping (Grimston et al., 1993, Bassey and Ramsdale, 1994, Heinonen et al., 1996).

High impact loading prior to skeletal maturity may represent an appropriate strategy for maximizing bone mass. Recently, there have been studies that utilized a bone loading protocol with prepubertal and adolescent children. These studies have shown that skeletal loading is an effective osteogenic stimulus if introduced before puberty (McKay et al., 2000, Bradney et al., 1998 and Morris et al., 1997, Heinonen et al., in press). However, the type, duration, intensity, and frequency of the impact loading that provide the maximum response in bone is not completely known.

Experimental studies with animals have shown that strain magnitude, rate, and pattern of distribution of strain are more important osteogenic features of dynamic loading than the number of strain cycles. However, the biomechanical features of these parameters have not been thoroughly examined. Since the transmission of ground reaction forces (GRF) through the skeleton is a primary mechanism for bone development, there is a relationship between the nature of these forces and bone strength. The primary focus of this thesis was to examine the GRFs and other characteristics of weight bearing jumps, performed at different levels of intensity and the relationship between these forces and bone mineral. Ultimately, by studying the loads and loading of different jumps we will increase our understanding of the relationship of weight-bearing PA, mechanical bone properties, and bone mineral.

This study assessed the GRFs and rates of force generated from a variety of jumps performed by prepubescent boys and girls. It also investigated the relationship between these forces and PA and between PA and bone mineral density at the proximal femur. The subjects performed twelve different jumps adapted from a bone loading intervention program in elementary schools. These jumps represent a range of GRFs to maximum that a child may experience during daily activities. The following sections will provide an overview of the most relevant literature including: structure and properties of bone, biomechanics, and mechanical adaptations of bone to impact loading.

2. LITERATURE REVIEW

In growing children, information about the impact of exercise and PA on skeletal integrity is relatively new and incomplete. The first part of the review will evaluate the principles of skeletal development and adaptation, with an emphasis on the role of mechanical loading. Although the basic form and development of bone is genetically predetermined, bone's final mass and architecture is governed by adaptive mechanisms sensitive to mechanical stimuli. Bone loading and relative bone strength is, in turn, closely linked with the characteristics of bone. These bone characteristics include both material and geometric properties that adapt to bone mechanical stimuli and to the overall loading environment.

2.1. *Structural and Material Properties of Bone*

Bone's rigidity and hardness are properties that make it a unique tissue. Bone consists mainly of stiff inorganic crystals, hydroxyapatite (calcium and phosphate), and an organic matrix of collagen fibres. This mixture of hydroxyapatite and collagen form a fibre-reinforced composite that provides both the stiffness and "toughness" of bone. The hydroxyapatite crystals provide strength and rigidity and the high resistance of bone to compression, accounting for 80-90% of the variance in bone compression strength (Sledge and Rubin, 1989). Along with these properties, bone also serves to provide support for the body, act as a rigid lever for muscles, and as a reserve for ions, specifically calcium. The skeleton also provides protection for soft tissue and body organs.

2.2. *Anatomy*

Macrostructure: Bone tissue consists of two main types: cortical (compact) and trabecular (cancellous) bone. Cortical bone is a dense solid mass that comprises a large portion of the appendicular skeleton (long bones) and covers the external surfaces of all bones. Collagen fibres in cortical bone are densely packed with small spaces, creating a strong structure for mechanical support. The orientation of the fibres in cortical bone creates a structure that is stronger in compression than in tension and is weakest with a shear load (Reilly et al., 1975).

Trabecular bone consists of a lattice of rods, plates, and arches. Trabeculae are organized in a porous manner, with a rich network of blood supply that serves mainly metabolic functions. Its structure is weaker and not as stiff as cortical bone (Currey, 1984). Trabecular bone is found mainly at the epiphyses of long bones and vertebral bodies and has a higher turnover rate than cortical bone. Approximately 75-80% of the total skeletal mass is cortical bone, while 20-25% is trabecular bone.

Microstructure: Both cortical and trabecular bone have a lamellar structure with collagen fibres orientated in multiple layers. Primary lamellar bone consists of thin, sequential layers of bone micro-composite and cement, arranged in a plywood-like fashion. These layers contribute to bone's mechanical properties. Secondary lamellar bone consists of small cylindrical units, osteons, formed from a concentric assembly of a small number of primary lamellae. These larger, cylindrical units are also cemented together and form additional interfaces.

During times of fracture or microfracture, woven bone may form as a temporary repair structure. Woven bone is less organized than lamellar bone, but is formed and mineralized more rapidly (Martin and Burr, 1989). Bone's initial response to mechanical loading is to form woven bone, followed by replacement with lamellar bone. Unlike the regularly oriented collagen fibres of lamellar bone, collagen fibres in woven bone are randomly oriented, this result in less dense bone. Woven bone provides a quickly developed source of mechanical strength and the framework for the slower development of lamellar bone.

2.3. Bone Physiology

Throughout life, bone is continually forming and resorbing due to changes in hormones and mechanical stimuli. These changes alter bone mass and architecture. Three processes are primarily involved in bone turnover: growth, modeling, and remodeling. In the immature skeleton, all three processes are active simultaneously.

Growth: Growth of bone is a genetically preprogrammed enlargement of the skeleton, which is driven primarily by hormones until epiphyseal closure. During growth, the activation of muscles and weight-bearing exercise form a mechanical environment that induces cellular activity that achieves and maintains normal architecture. During this period, the skeleton is sensitive to mechanical stimuli (Forwood and Burr, 1989, Kannus et al., 1995, and Morris et al., 1997). By around age 20, peak bone mass and density is achieved (Matkovic et al., 1993; Haapasalo et al., 1998).

Endochondral ossification is the growth process that is responsible for increases in bone length. During endochondral ossification, the cells in the zone of calcification hypertrophy, lose their transverse walls, and their longitudinal walls calcify, while capillaries carrying osteogenic cells (osteoblasts and osteoclasts) invade the dying cells. The osteoblasts then lay down osteiod on the calcified spicules of cartilage, which becomes fully calcified, while further erosion is caused by the osteoclasts. Proliferating and maturing cells at the upper end of the growth plate replace the dying hypertrophic cartilage cells. This process is repeated until the growth of bone is complete. Growth in diameter is achieved by the apposition of new bone on existing bone surfaces. Bone matrix is laid down by osteoblasts on existing bone and then becomes mineralized.

Modeling: Modeling is the process that alters the shape and mass of bones in response to mechanical loading factors. Modeling occurs primarily during the growing years. Modeling of bone is the simultaneous removal and formation of bone at different sites. For example, modeling increases bone strength by adding mass and changing the architecture specifically at high load locations. The ability of bone to adapt to loading factors is much greater during growth than after maturity.

The surfaces of bone may be quiescent, actively forming, or resorbing mineral. Bone turnover is controlled by the activity of bone cells: osteoblasts, osteoclasts, osteocytes, and bone-lining cells. Osteoblasts, in formation drifts, add new bone and osteoclasts, in resorption drifts, remove bone during modeling. Osteoblasts are bone-forming cells that secrete collagen and ground substance. Osteoclasts synthesize and secrete lysomal enzymes that digest the proteins linking hydroxyapatite crystals and collagen. This results in resorption cavities. Osteocytes are mature osteoblasts, embedded in the bony matrix, that form a communication network with other osteoblasts and bone-lining cells. This network is used by the cells to perceive and respond to mechanical stimuli is known as "mechanotransduction" (Duncan and Turner, 1995).

Mechanotransduction: It appears that osteocytes and bone lining cells are responsible for mechanically adaptive (re) modeling to ensure that bone mass, architecture, and material properties, are related to the applied load. Frost (1991, 1997) and others (Kimmel, 1993) have proposed that this network of cells detects strain and sends signals to the cells. Bone is then removed or added at relevant sites. These cells perform with the benefit of feedback, which informs them about the prevailing suitability of this relationship. Mechanical adaptive bone (re) modeling can therefore be regarded as a homeostatic mechanism. The objective is to regulate functional bone strain, defined as the change in length of bone due to external stresses. Biewener et al. (1986) and Keller and Spengler (1989) concluded that strain levels and strain distributions remained constant during growth, although the location of the tissue being strained varied (Biewener et al., 1986; Keller and Spengler, 1989).

Remodeling: Remodeling, although present in the young, is the dominant process modifying shape and mass in adults. Remodeling is the coupling between removal of old bone and the formation of new bone on one surface for an extended period of time. The principal functions of remodeling are maintenance and repair of fatigued-damaged bone. Basic multicellular units, organized osteoblasts or osteoclasts, are active on one surface and act in a specific sequence of events. First quiescent surfaces are activated, secondly bone is resorbed followed by the formation of new bone, and finally bone is mineralized (Parfitt, 1994). The entire remodeling process takes approximately 4 to 6 months to complete. The resorption phase takes about 3-4 weeks, while the mineralization phase takes 4-5 months (Eriksen et al., 1984). In young and growing animals, most bone surfaces are active and modeling is the primary activity, while in adult animals 80-90% of the bone surfaces are quiescent (Parfitt, 1983). In modeling, osteoblasts are at work at one site for a number of years, adding and shaping bone. This mechanism is responsible for the net gain of bone during growth. In the remodeling phase, however, they operate at one site for a relatively short period (Parfitt, 1994). Over time in adults, remodeling becomes the dominant process. Where new bone being laid down does not completely replace the resorbed bone this result in the net loss of bone mineral that accompanies aging.

2.4. Mechanical Properties of Bone

One of the functions of the skeleton is to provide support and to maintain an upright posture. While providing upright support, the skeleton accommodates large external forces such as those involved in jumping. The nature of the load imposed by body weight is characterized by the increase in bone size cephalo-caudally. That is, the bones of the lower extremities and the lower vertebrae are larger than those of the upper extremities and upper vertebrae.

Stress and Strain

During movement, muscles and GRFs place stress and strain on bone. Stress can be classified as tensile, compressive, or shear. These stresses and strains determine the mass, shape and strength of the bone (Turner, 1991). Stress is defined as force applied per area (units of stress Pascal = Pa), while strain is defined as the relative change in unit length of a structure under load (Frost, 1983). It is equivalent to the change in length divided by the original length of the bone. Strain is dimensionless and is reported as a fraction or percentage. The structural behavior of bone depends on the forces applied to it and the resulting deformations. This deformation can be measured and plotted as a load-deformation curve, also called a stress-strain curve (Figure 2.1).

From such a curve, the load and deformation are linearly related until the yield point. The area beneath the linear portion of the curve is the elastic strain region. The elastic region is where applied forces cause temporary bone deformation. Once the load is removed the bone returns to its original shape. Beyond the yield point, the slope of the curve plateaus and is the area beneath this part of the curve is called the plastic region. It marks the point where local fractures, other damage, and permanent deformation occur. If the load increases beyond the plastic strain region, the failure point of the structure is reached.

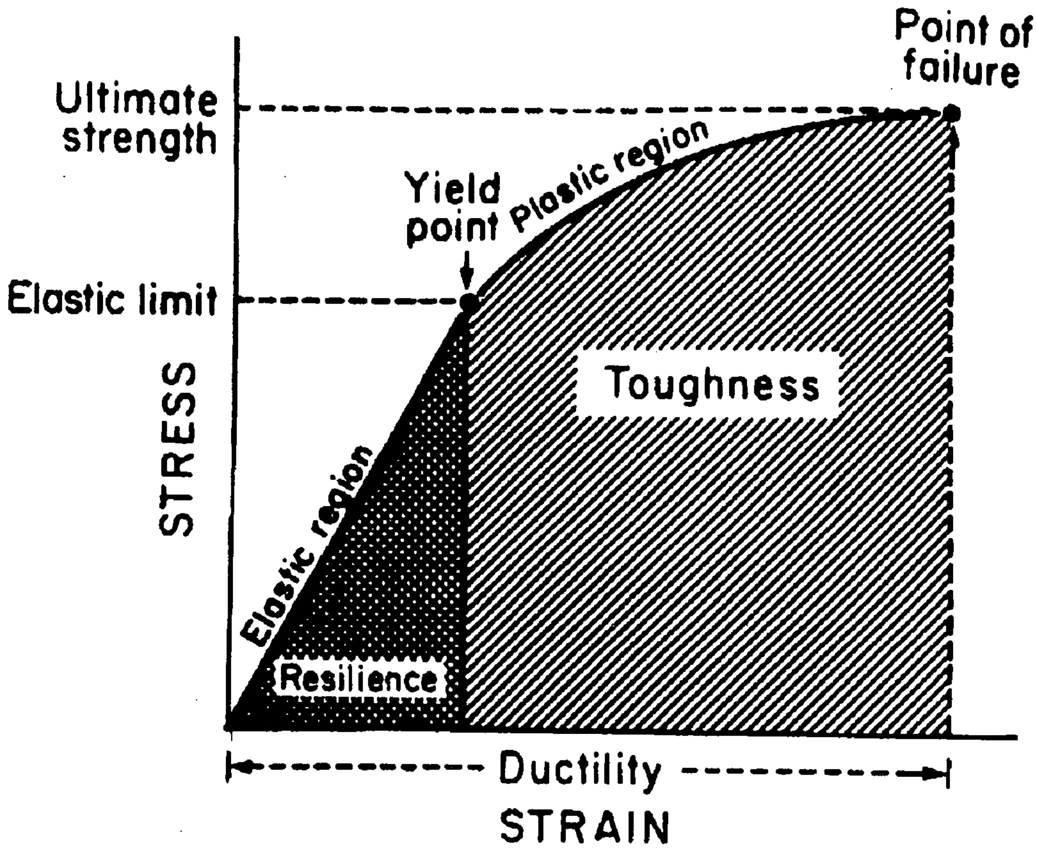


Figure 2.1. Stress-strain curve.

The magnitude of the stresses and strains generated are properties related to the quality of the material (bone) experiencing the load. Stress is not easily measured directly so it is often estimated from the cross-sectional moment of inertia (CSMI), the ratio of column diameter to wall thickness:

$$\boxed{S = (F/A) + Mc/CSMI}$$

where S = *stress,* F = *axial load,* A = *cross section of the bone,* M = *bending moment,* and c= *the distance from the cross-sectional centre of mass.*

Strain can be measured *in vivo* with strain gauges attached to bone. Strain describes the deformation of a material without regard to its geometry. Axial strain can be calculated using Hooke's Law:

$$\boxed{\varepsilon = S/E}$$

where ε = *strain,* S = *stress,* and E = *Young's Modulus.*

Strength and Stiffness

Strength is defined as the load at the yield or failure point, where local fractures begin. The strength of bone in tension is typically about 2.21 MPa, as compared to 2.54 MPa when loaded in compression (Neil et al., 1983). Stiffness is a function of bone composition and its hollow cylindrical shape. The stiffness of a structure indicates the amount of force that is required to deform the structure a given amount. Stiffness and strength can be determined from a stress-strain curve. The initial linear portion of the stress-strain curve, or slope, indicates the stiffness of the material. Under normal loading conditions, the stiffness is known as the modulus of elasticity, or Young's modulus. Young's modulus is about 13.0 GPa in human trabecular bone (Ashman and Rho, 1988).

2.5. Geometric Properties

Alternating the distribution of bone or its shape can modify the stiffness of bone. Bone must resist tension, compression, and shear forces, yet it must be lightweight for efficient locomotion. The skeleton has evolved and is designed with a minimal amount of material, to reduce weight. Stresses must then be reduced and applied over a cross-sectional surface. The distribution of bone mass and the geometry of bone is closely related to bone strength and stiffness. A hollow cylinder provides the least mass and the greatest strength during bending and torsional loading. To minimize weight and maximize the ratio of column diameter to wall thickness, for any CSMI, the whole cross-sectional area should be as far away from the neutral axis as possible (Figure 2.2). A larger CSMI would require less area, which in turn means less mass is needed to maintain a set strength. During exercise-induced bone loading, bone formation accelerates at the periosteal surface on the bone shaft (Forwood and Turner, 1995). The bone is strengthened due to an increase in mass, but more importantly the formation of new bone increases the CSMI (Hillam and Skerry, 1995).

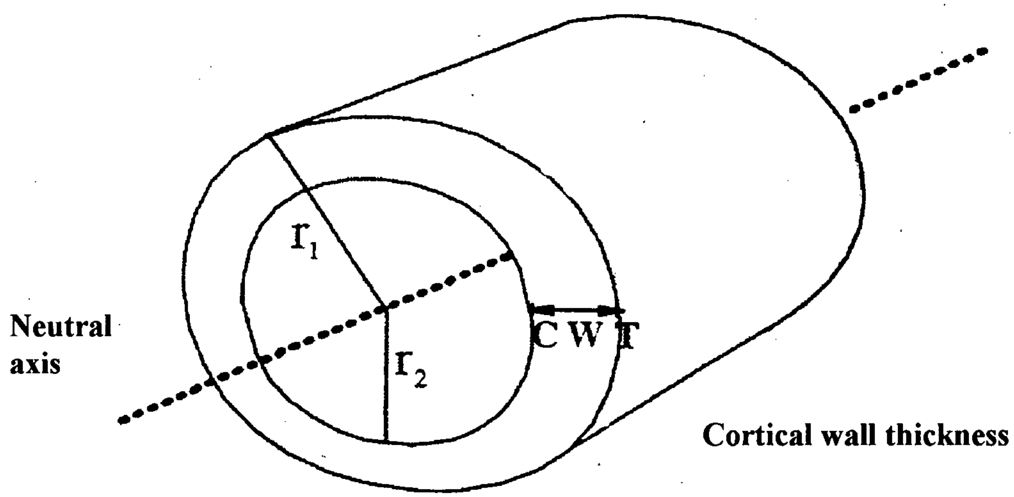


Figure 2.2. Definition of cross-sectional moment of inertia (CSMI) for a circular hollow tube, where r_1 is the outer radius and r_2 is the inner radius and CWT is the cortical wall thickness. From Heinonen, 1997.

The mechanical competence of bone is a function of all of the geometric properties previously discussed. These include its macroscopic geometric characteristics (size, shape, density, cortical thickness, cross-sectional area, trabecular architecture), intrinsic material properties (stiffness and strength) and the loading conditions (mode, direction, and rate) at any skeletal site (Carter and Hayes, 1976). A close relationship between mechanical loading and increased bone mineral content (BMC) and BMD has been clearly established in animal studies. And, although DXA has accepted limitations (discussed on p.17) it is a safe and precise clinical tool and its primary outcome (BMD) is closely associated with fracture risk in humans. However, bone mass is only one component of overall bone strength (Mosekilde, 1993). In a DXA study where CSMI was not calculated, BMD accounted for 80-90% of the variance in the strength at the proximal femur (Lotz and Hayes, 1990 and Johnston and Slemenda, 1993). Despite the proliferation of DXA studies it is important to note that the mechanical competence of bone may improve by improving the geometry of the bone without changes to bone mineral (BMC or BMD) (Kimmel, 1993). Therefore, it is important to include or estimate other geometric properties, such as CSMI, whenever possible when determining bone strength. During exercise induced bone loading, bone formation accelerates mainly at the periosteal surface on the bone shaft (Raab-Cullen et al., 1994). Therefore the skeleton is strengthened not only by an increase in bone mass, but more importantly the placement of new bone in a place that has a maximum positive effect on the CSMI (Kimmel, 1993). By was of explanation, in bending situations, the CSMI is more important in resisting loads than bone mass or density (Kimmel, 1993). However, this parameter was assessed in relatively few studies.

2.6. Properties of Osteogenic Stimuli

One of the principal responsibilities of the skeleton is to support the mechanical loads related to physical activity. These loads result in a mechanical strain on the bone tissue to which the skeleton responds and adapts. Bone's ability to adapt to these demands was recognized over a hundred years ago by a German anatomist, Julius Wolff, and is referred to as Wolff's Law (Wolff, 1892). Wolff's law states that bone attempts to optimize structure so that it can withstand functional loading and to make locomotion as metabolically efficient as possible. More specifically, the function of cells responsible for mechanically adaptive modeling and remodeling are to ensure that the mass, geometry, and material properties are appropriate to the applied load.

Load bearing most likely exerts its influence through the dynamic and high strains encountered at the bone tissue. Mechanically adaptive bone modeling and remodeling can be regarded as a homeostatic mechanism regulating functional strains at each location throughout the skeleton. The longitudinal curvature and cross-sectional shape of a number of bones encounter strain during functional loading. These strains vary across the bone's cross-section. The adaptive response of bones to load bearing therefore results in functional strains, which are neither uniform in distribution nor minimal in magnitude. Most of what we know about the influence of these properties on bone comes from animal models. The main mechanical variables associated with bone modeling and remodeling are strain magnitude, strain rate, strain distribution, and strain cycles (Lanyon, 1996).

Strain Magnitude

In an avian model, it was shown that bone formation increases with larger strain magnitudes (Rubin and Lanyon, 1984). Researchers have also suggested that bone adaptation is error driven, in that bone responds to mechanical loads to which it has not previously adapted (i.e. higher strains) (Frost, 1987). It has also been proposed that bone will only respond and adapt within a defined range of loading (Frost, 1987). Frost introduced the term "mechanostat" to describe the mechanisms that control cellular activity of bone to increase or decrease mass in response to mechanical loading; in order to maintain strain within an optimal level (Frost, 1987).

Frost's "mechanostat" theory conceptualizes Wolff's law and describes a control system in which a minimum effective strain (MES) is necessary for bone maintenance (Frost, 1987). The theory has four zones of mechanical loading, with each zone defined by MES thresholds (Figure 2.3). The trivial loading zone ranges from 50 to 200 $\mu\varepsilon$. In this zone, the predominant process is remodeling, resulting in a net bone loss. Immobilization stimulates bone resorption and depresses formation, which results in a decreased volume-related bone mass and deteriorated material and architectural structures. In an animal study, sheep protected from strain by a rigid bar, but allowed to walk for 20 minutes demonstrated inadequate bone retention (Skerry and Lanyon, 1995). This suggested that low strains during controlled locomotion might be inadequate to maintain bone structure.

The physiological loading zone ranges from 200-2000 με and is from the theoretical remodeling MES to the modeling MES. In this zone, mechanical loading stimulus causes formation and resorption, which maintains bone structure (Lanyon, 1987, Turner, 1991). The overload zone is from 2000-4000 με and strains in this range elicit a modeling response and the deposition of lamellar bone (Turner, 1991, Frost, 1990, and Frost, 1990b). The result is a net increase in bone as it is added in response to the new level of mechanical stimuli. Strains above 4000 με are in the pathological overload zone. In this zone, bone responds to high demands by quickly adding disorganized woven bone.

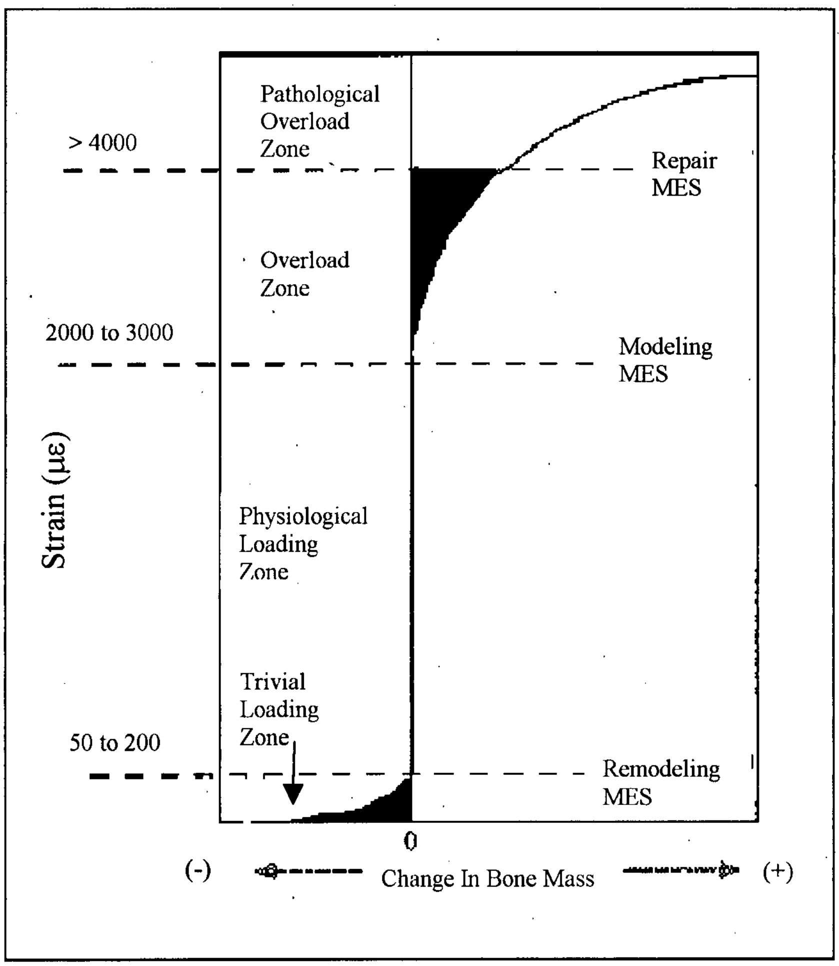


Figure 2.3. Frost's mechanostat theory. Adapted from Burr, 1992.

The fracture strain of cortical bone is about 25,000 $\mu\varepsilon$ in tension or compression. However, individuals cannot produce peak longitudinal compression and tension in cortical bone that exceeds 1500-3000 $\mu\varepsilon$ even with the most vigorous voluntary activity (Reilly and Burstein, 1974). This limiting strain range persists with little relative change between birth and skeletal maturity, suggesting that bone functions at an optimal level of strain.

Activities that elicit high peak forces (or high strain magnitudes) may have a greater effect on bone mass than activities associated with a large number of loading cycles (Whalen and Carter, 1988). It seems that high-impact exercise is effective in improving and maintaining bone mineral mass and preventing age-related bone loss. Umemura et al. (1995) compared jump training versus running training in rats and found that jumping was more effective than running for bone hypertrophy. They also reported that jumping had a higher strain rate and magnitude (Umemura et al., 1995). Lanyon suggested that high impact exercises, such as jumping, are a good way to elicit an osteogenic response (Lanyon, 1996).

A given load might elicit a greater strain on immature bone than the same load applied to mature bone. This may explain the positive response to loading in less mineralized and therefore weaker immature bone. Also during growth, there is a rapid increase in muscle mass, which would create more stress on under-mineralized bone. Additional stress from exercise creates higher strains and stimulates remodeling activity (Frost, 1987).

Strain Rate

There is a strong correlation between remodeling, strain rate and strain magnitude (O'Connor et al., 1982). In an animal study, O'Connor et al. (1982) suggested that strain rate had the most important influence on the amount of new bone deposited. Turner et al., (1995) proposed that mechanical loads are coupled to bone cells by stress generated fluid flows within bone tissue, which in turn, depend on the rate of change of bone strain. A high magnitude load, unusual distribution and static load (continuous strain rate), was no more effective than disuse in protecting bone from atrophy (Rubin and Lanyon, 1984).

This suggested that the rate at which strain is developed is important factor in the adaptive response (Martin and Burr, 1989). The rate of force and unusual strain distribution (in sports such as squash and gymnastics), rather than strain magnitude, may be the most important osteogenic stimuli for humans (Fehling et al., 1995).

Strain distribution

Rubin and Lanyon (1985) found that loading in an unusual direction could stimulate new bone formation. Even high strains would not produce an adaptive response if the strains were normally distributed (Rubin and Lanyon, 1985). These researchers suggested that bone responds to what they termed "error" strain. The "error strain distribution hypothesis" suggests that the bone cell population maintains the skeleton's structural competence by making architectural adjustments to eliminate or to reduce perceived deviations from normal dynamic strain distributions (Rubin and Lanyon, 1985). To test this hypothesis, Mosley and Lanyon applied mechanical loads to rat ulna. They noted an osteogenic effect only at very high strains (4000 $\mu\varepsilon$) where 1300 $\mu\varepsilon$ is the normal strain experienced (Mosley and Lanyon, 1995). These normally distributed strains stimulated osteogenesis only if they were above the peak strain level physiologically achievable at that location. Conversely, Rubin and Lanyon (1984, 1985) found that in avian ulnae loaded at 1000 $\mu\varepsilon$, but in an unusual distribution, new bone formation was stimulated. They concluded that the strain required to elicit an adaptive response may be lower if the manner of loading differs from the usual pattern of loading (Rubin and Lanyon, 1983).

Strain Cycles

Although the number of strain cycles may influence the skeletal response to loading, they appear to be less important than strain magnitude (Lanyon, 1987). However, we know that a minimum number of loading cycles are required for a positive response. Rubin and Lanyon (1984) showed with an avian model that loading at 2000 $\mu\varepsilon$, saturated after only 36 consecutive loading cycles (a total of 72 seconds per day). Further loading cycles did not produced an additional osteogenic response. Therefore, there appears to be a threshold above which the number of loading cycles is no longer effective in eliciting bone formation. However, at a lower strain magnitude the importance of the number of strain cycles increases (Whalen and Carter, 1988). The most effective strain frequency is in the range 15 to 30 Hz (Rubin and McLeod, 1994). These experimental studies with animals showed that magnitude, rate, and pattern of distribution are more important osteogenic features of dynamic loading than the number of cycles.

Repetitive Loading in Humans

The functional adaptation of bone likely also depends on loading history (Carter et al., 1987). The loading history, in turn, reflects the repetitive loading or strain cycles developed in bone associated with use (Lanyon, 1984). A number of human studies have assessed the relationship between strain cycles and the bone mineral accrual response. Interventions in human studies that utilized exercise associated with a low strain magnitude and a high number of strain cycles, like walking, have had conflicting results. Cavanaugh and Cann showed that in postmenopausal women, a brisk walking program did not prevent bone loss (Cavanaugh and Cann, 1988). Others have reported that walking can prevent bone loss and even increase bone mineral mass in postmenopausal women (Chow et al., 1987).

Strain magnitude, strain rate, strain distribution, and strain cycles are all contributing factors in skeletal remodeling. Subsequently all strain related variables, including strain cycles, are integrated into loading conditions. These factors create an ideal environment for mechanical adaptation of bone. However, the relative contribution of each to remodeling under diverse loading conditions is not clearly understood. That is, the exact characteristics of the mechanical strains that induce bone formation are not known. It is believed that exercise programs for humans should include activities generating high strains or high strain rates, and unusual distributions for effective adaptation by the bone. Several exercise programs have included exercises with jumping as it can create a high mechanical force or high rate of force in a diverse movement (Morris, 1997, Bradney, 1998, and McKay et al., 2000).

Assessing Bone In Vivo (Bone Densitometry)

Bone densitometry is a safe, painless, extremely low dose radiation procedure, which is routinely used in the practice of modern medicine. Dual-energy x-ray abosorptiometry (DXA) estimates BMC and areal density at clinically relevant sites. The total exposure per session is less than 8 millirem, which is similar to the background radiation one would receive making a one-way flight from Vancouver to Halifax on a commercial airline. Bone densitometry provides a means of estimating BMC as a surrogate for bone mass. BMC is the amount of mineral in an anatomic region and will vary due to differences in size between individuals and it is proportional to the cross-sectional area of the bone (Sievanen et al, 1999). To partially account for size, BMC is expressed per unit area, areal BMD (aBMD). However, there are problems with aBMD as it is a two dimensional representation of the three dimensional properties of bone. DXA is widely used for clinical and research purposes and aBMD is highly correlated with bone strength ($r = 0.85 - 0.90$) (Ashman, 1989). DXA measurement of BMC and aBMD is precise, with a coefficient of variation in the range of 1% for aBMD at all sites (unpublished data, University of British Columbia Bone Densitometry Lab).

2.7. Forces Acting On Bone

The magnitude of force and the rate of force application affecting the human skeleton are mainly determined by the movement conditions (velocity of the segments, number of repetitions, muscular activities) and the boundary conditions (anthropometric factors, fitness levels, surface, weather, and type of shoes (Less, 1981, Nigg, 1985, and Ricard and Veatch, 1994). The rate of force application may be more important in certain sports like gymnastics and dance, where the forces and friction on the surface can produce high torques on the bones. Sports with high acceleration and deceleration may produce high forces and subsequently high strain on bone. It appears then that any changes in the movement condition affects the kinematics and kinetics of the movement and likely the mechanical stress affecting bone.

Bone tissue is an anisotropic material and, therefore, the behaviour of bone will vary depending on the direction of the applied load. The skeleton is subjected to a variety of different types of forces so that bone is loaded in various directions. There are loads produced by weight bearing, gravity, muscular forces, and external forces. The forces produced include: tension, compression, shear, bending, and torsion. In general, bone tissue can handle the greatest loads in a longitudinal direction, the direction of habitual loading, and the least amount of load when applied across the surface of the bone.

Ground Reaction Forces

Force has traditionally been described as a push or a pull exerted by one body on another. Anytime a body exerts a force on a second body, the body exerting the force experiences a force called "reaction force". Force is measured in Newton's (N). Newton's third 'law of motion' states that forces result from the mutual interaction of bodies and therefore occurs in pairs. Furthermore, Newton's law states that these forces are always equal to each other in magnitude and opposite in direction. These forces do not cancel as they act on two different bodies. For example, as we walk forward, our foot exerts a force on the ground and the ground exerts a force on the foot that is equal and opposite in direction this is termed a GRF.

GRFs can be measured on a force platform. The "Kistler" type force platform has four sets of piezoelectric transducers located at its corners that create a charge when force is applied to it. The charge is amplified and converted from an analog signal to a digital signal. This digital signal is then interfaced to a computer, where the voltage is displayed and scaled to known units of force. The forces from a force platform are measured in three directions: vertical, medio-lateral, and anterio-posterior, depending on the orientation of the coordinates.

GRF data can be displayed as a force time curve, which illustrates the change in force over time. A typical GRF plot for a frog-like jump is shown (Figure 2.4). The curve begins with a value of the vertical component equal to body weight. The forces rise until the jumper leaves the ground and then GRFs fall to zero (A-B). The force platform then reads zero as the jumper is in the air (B-C). There is a large reaction force at the point of landing (C-D). The integral of this curve (area under the curve) is impulse (Ns) or a change in momentum. The larger the impulse generated against the floor from a vertical jump, the greater the change in the performer's momentum, and the higher the resulting jump. The impulse generated by a person who lands rigidly will result in a relatively large GRF sustained over a relatively short time interval. On the other hand, by flexing the hip, knee and ankle during landing, the time interval over which the landing force is absorbed increases, thereby reducing the magnitude of the force sustained.

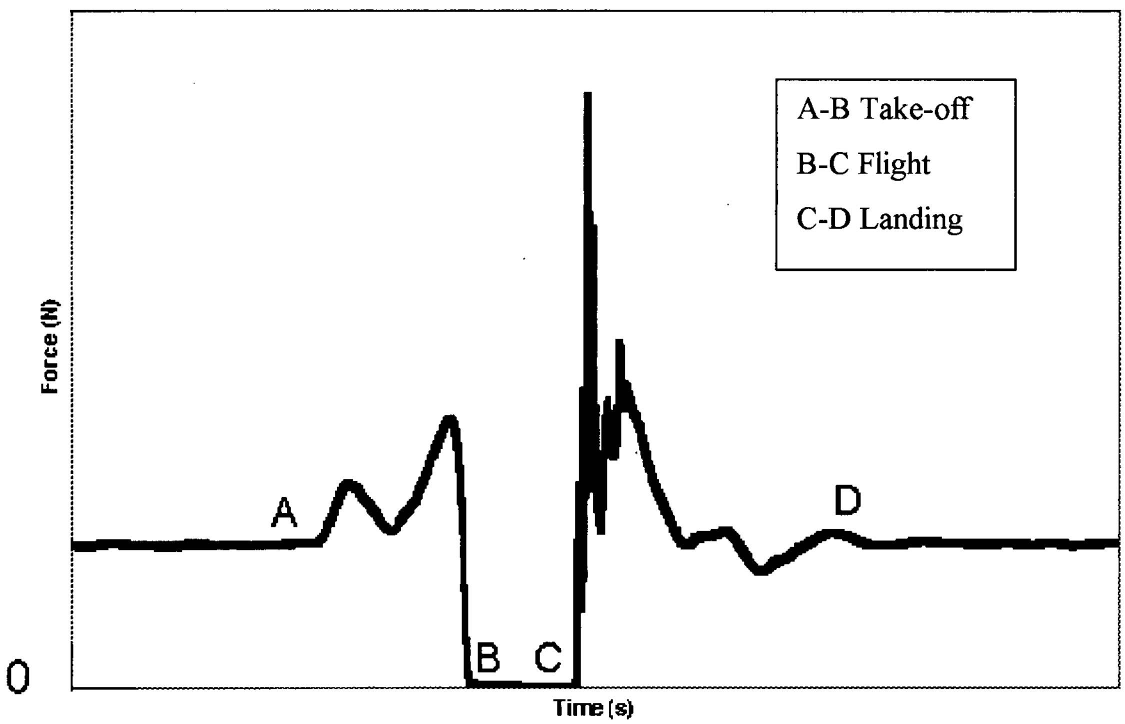


Figure 2.4. A typical ground reaction force plot for a frog-like jump.

GRFs from typical activities are one of the primary (re)modeling factors for developing bones (Frost, 1987). There have been a few studies where strain gauges have been attached to human bone to measure strain *in vivo* (Burr et al., 1996; Milgrom et al., 1998). Tibial strains were higher during vigorous activities like sprinting and hill running, compared to walking (Burr et al., 1996; Milgrom et al., 1998).

In vivo strain magnitudes of various activities in humans have also been documented with strain gauges implanted on artificial limbs. One study reported implant loads and GRFs in the same individual during slow jumping, fast continuous jumping, and jogging (Bassey et al., 1997). The implant forces were greatest during take-off from jumping resulting in femoral and hip forces 2.5 to 3.0 times the GRFs. During landing from the jump, the implant forces exceeded the GRFs by only ~50% (Bassey et al., 1997). Therefore, it is important to study take off forces as well as landing forces. Fast jumping produced the highest implant forces at the femur, while jogging and slow jumping stimulated high, but slightly lower forces. They found that the relationship between GRFs and the implant forces were linear under a variety of exercise conditions (Bassey et al., 1997). In other studies, jumping and running induced GRFs 3-5 times body weight, which may equal up to 10 – 15 times body weight at the tissue level (Burdett, 1992). Therefore, activities that produce greater GRFs should have a larger osteogenic effect especially if they are unusual in distribution (Bassey et al., 1997).

2.8. Tensile, Compressive, and Shear Forces of the Lower Body

Tension is produced on bone when two forces are directed away from each other along the same straight line. It is unusual for bone to experience purely tensile forces. *Compression* is produced when two forces are directed towards each other along the same straight line. *Shear* forces are produced when two forces are directed parallel to each other but not along the same line. These three forces can be combined to produce complex loading patterns. Bending results from tensile and compressive forces; tension is placed on the convex side while compression is placed on the concave side.

Compression forces bring the ends of bones together and are produced by muscles, weight bearing, gravity, or external loading. The compressive stress and strain causes bone to shorten and widen, and to absorb maximal stress on a plane perpendicular to the compressive load. Compressive forces are necessary for the growth and development of bone. The stress and strain produced by compressive or other types of forces are responsible for facilitating the deposit of osseus material. The hip joint must absorb compressive forces of approximately 3 to 7 times body weight during walking (Riegger, 1985; Nordin and Frankel, 1989).

GRFs are transmitted from the foot and up along the lower body. The transmission of the forces along the leg can be modelled as a system of three rigid links (Figure 2.5), where each rigid link represents a separate part of the leg.

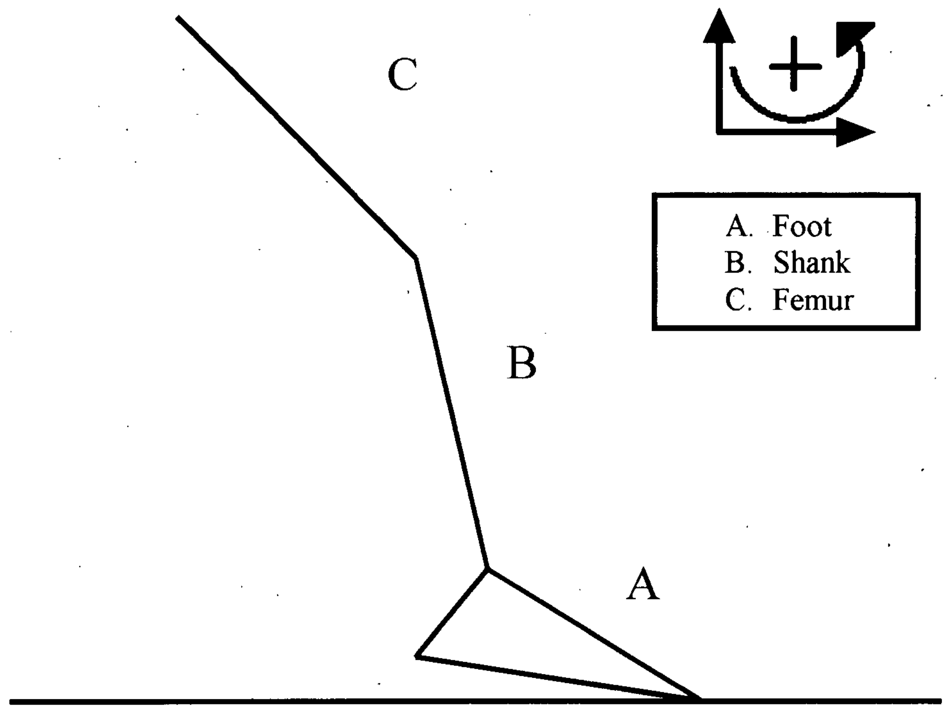


Figure 2.5. A rigid-link model representation of the lower body.

Each link can be treated as a free body so that the forces on each body can be determined through a Newtonian formulation. GRFs act along the base of the foot (A), which can be summed into one resultant force. This resultant force can be resolved into horizontal (F_x) and vertical (F_y) components (Figure 2.6).

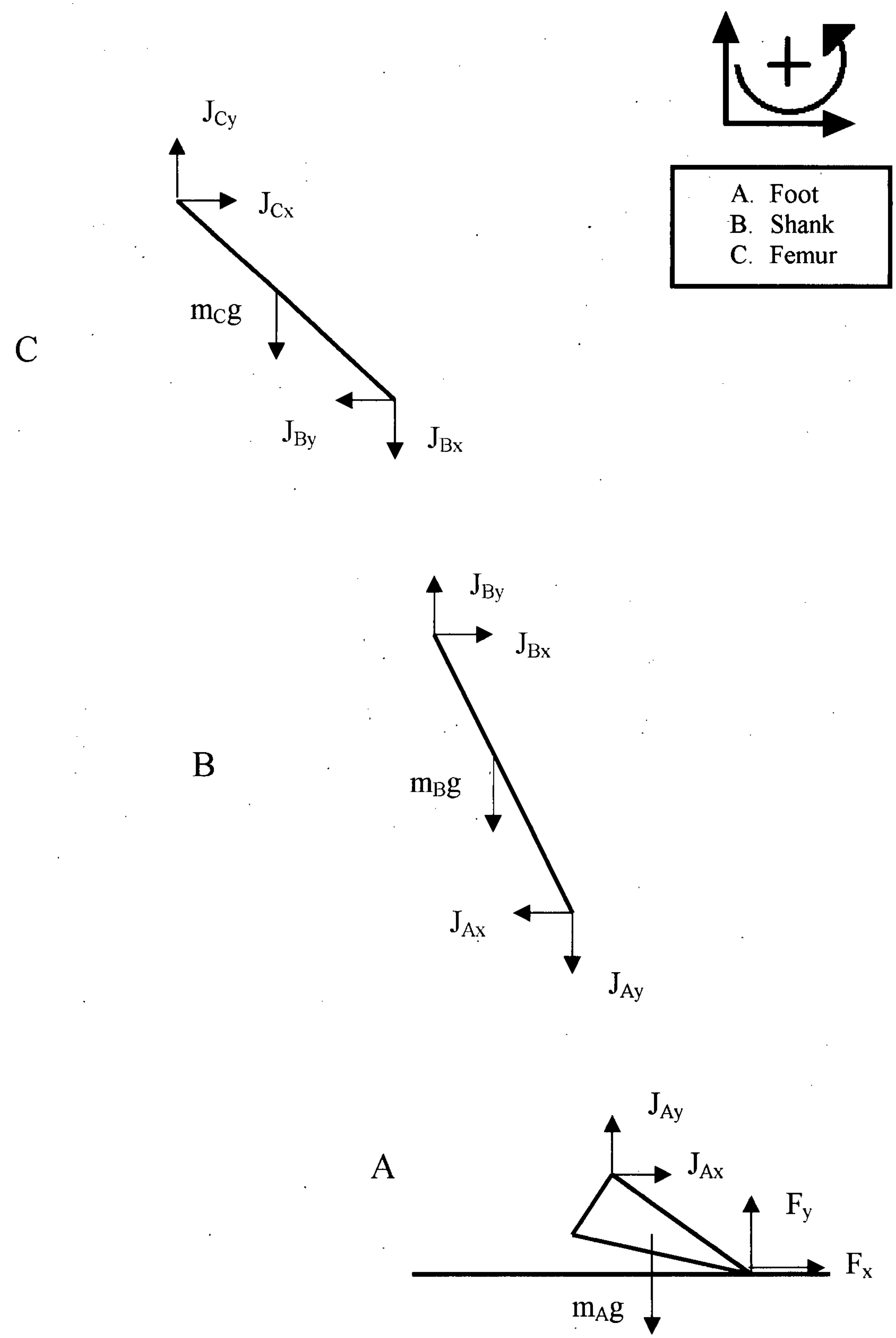


Figure 2.6. A free-body diagram of the leg showing the GRFs at the foot and the joint reaction forces at the ankle, knee, and hip.

The forces at the foot can be resolved as follows:

$$\Sigma F_x = F_x + J_{Ax}$$
$$\Sigma F_y = F_y + F_{Ay} - m_A g$$

where F is the force in the horizontal and vertical directions and m is the mass of each part of the lower limb.

These forces at the foot are transmitted to the tibia and fibula (shank) and are equal and opposite in direction. Figure 2.6 (B) represents the free body diagram of the shank and would have the following equations:

$$\Sigma F_x = -J_{Ax} + J_{Bx}$$
$$\Sigma F_y = -J_{Ay} + J_{By} - m_B g$$

The forces at the shank are transmitted to the femur (C) in a similar manner (Figure 2.6, C) and the upper leg forces can be expressed as:

$$\Sigma F_x = -J_{Bx} + F_{Cx}$$
$$\Sigma F_y = -J_{By} + J_{Cy} - m_C g$$

Forces at the Hip: During normal standing, the pelvis resting on the femora is like a supported beam. The proximal end of each femur acts as an eccentrically loaded cantilever, with body weight distributed equally over both hip joints. Each joint takes approximately 33 1/3 percent of superincumbent body weight (Romaines, 1972; Nordin and Frankel, 1989). The forces from the ground are transmitted up the tibia and fibula, to the femur. The forces act in a compressive manner along the shaft of the femur. These forces causes shear forces at the femoral neck. The shear stress acts almost equally along the length of the head and neck of the femur as shown in the stress diagram (Figure 2.7). The load at the hip joint produces a bending moment in the neck of the femur around the anatomical axis of the femoral shaft and a shearing stress along the head and neck of the femur.

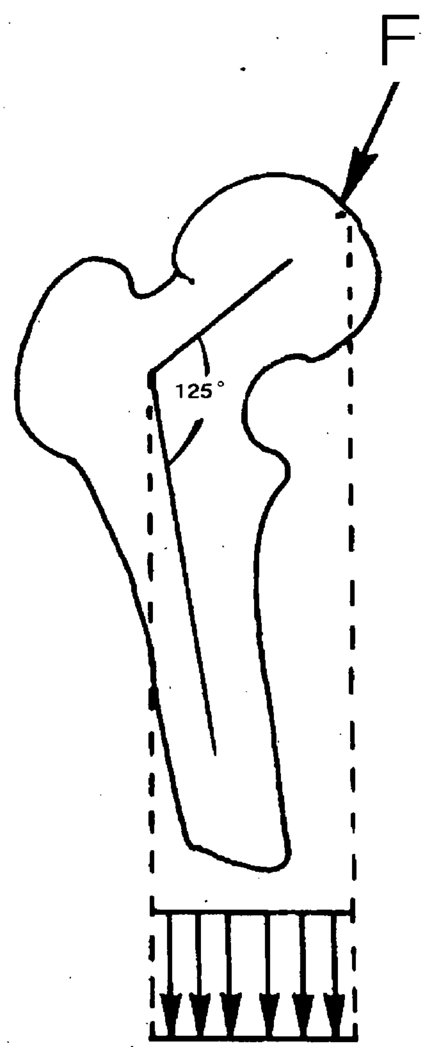


Figure 2.7. Diagram of shear stress along the head and neck of the femur during weight bearing in an adult hip. F is the force at the head of the femur. (Adapted from Singleton and LeVeau, 1975).

Therefore during normal standing posture, there are large compressive forces on the inferior portion of the femoral neck and large tensile forces on the superior portion of the neck (Figure 2.8). In a standing position, the bending moment produced by the force acting on the femoral head increases. A resisting moment within the neck counteracts the bending moment by setting up tension and compression stresses. Tension stress is located in the superior aspect of the femoral neck and compression at the inferior portion. Since the load on the hip during normal standing is relatively small, the higher stresses incurred during ambulation are far more important.

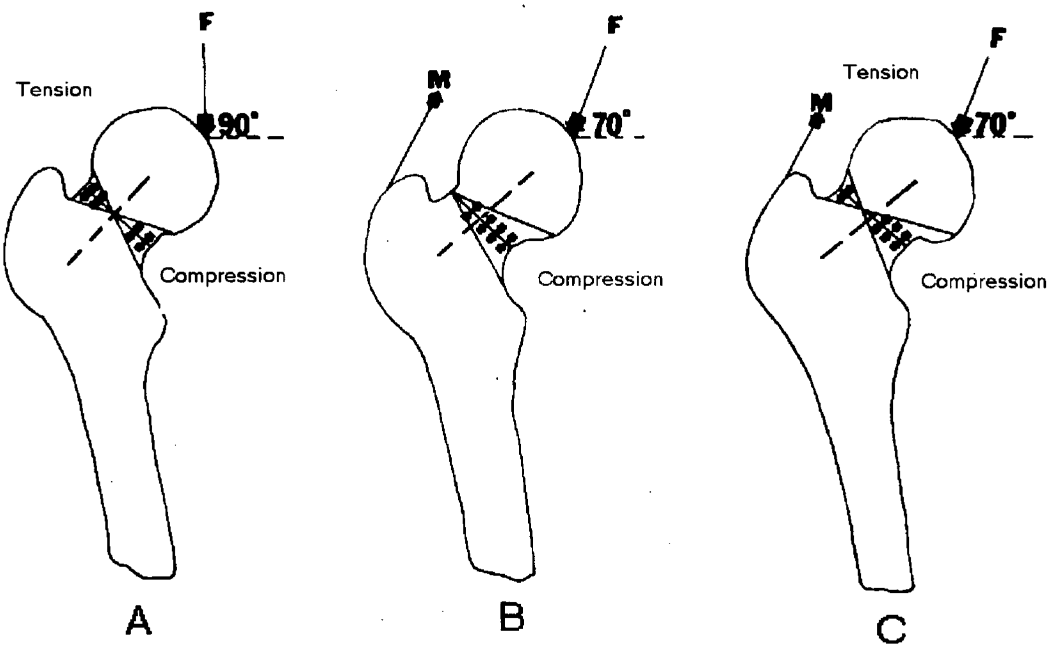


Figure 2.8. Tension and compression at the femoral neck. A. Standing on both limbs, tension and compression are equally distributed around the neutral axis. B. Standing on one limb. Tension component is eliminated by muscular force (M). C. Standing on one limb. Relative tension and compression when muscular force is less than B. (Adapted from Singleton and LeVeau, 1975).

The hip abductors (gluteus medius) insert into the greater trochanter of the proximal femur and contract to counteract body weight during normal stance. These muscles also produce a compressive load on the superior aspect of the femoral neck that reduces the tensile forces. Since bone will usually fracture sooner with a tensile force, the potential for injury in the femoral neck is reduced.

During normal stance, there is also bending at both the femur and the tibia. The femur bends both anteriorly and laterally due to its shape and the manner of the force transmission. The position of the acetabulum and of the femoral head and neck determine the forces. The force of gravity acting on the hip is mitigated via an oblique downward opening in the frontal plane across the opening of the acetabulum at an angle approximately 60 degrees with the transverse or horizontal plane. This angle helps to determine the direction of force exerted by the superincumbent weight acting at the hip joint. The angle of inclination is formed by the axis of the femoral neck and the axis of the shaft of the femur, which is about 150 degrees in newborn infants and 125 degrees in adults (Figure 2.9).

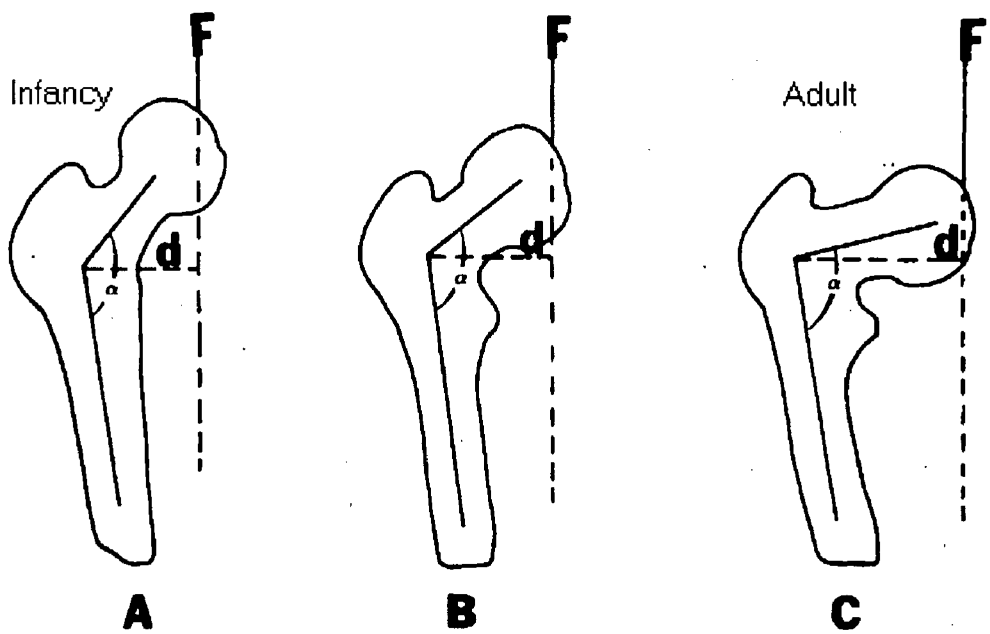


Figure 2.9. Angle of inclination (α) of the femoral neck. The distance (d) between the apex of the angle of inclination and the vertical component of force (F) on the head of the femur increases as the angle (α) decreases. A. $\alpha = 150°$, B. $\alpha = 125°$, C. $\alpha < 125°$. (Adapted from Singleton and LeVeau, 1975).

This change is the result of gravitational and muscular forces, imposed as the infant develops an upright posture. The angle helps determine the direction of joint force and lever arm length of the hip joint. A second angle formed by the neck and shaft of the femur lies in the transverse plane and reveals inward rotation of the shaft on the neck and head of the femur, called antetorsion and anteversion. There is considerable individual variation in these angles.

2.9. Bone Mineral Response to Mechanical Loading in Children

Although the body of literature that evaluates the effect of mechanical loading on the growing skeleton is sparse compared to adult groups, there have been some important studies published in recent years. This section reviews unilateral control studies, cross-sectional studies, and prospective observational studies in children and young adults. Most importantly exercise intervention trials in pediatric groups are reviewed.

Unilateral-control Studies

Unilateral control studies have compared dominant versus non-dominant arms of athletes participating in sports that load one side of the body. These studies provide convincing evidence that exercise during childhood acts as an osteogenic stimulus (Kannus et al., 1995). The strength of this study design is that both limbs share the same genetic, nutritional, and endocrine factors, and these factors are therefore controlled. Any difference observed may then be attributed to differences in loading. An early study of 27 year olds males and 24-year-old females compared the cortical dimensions of the lower humerus in tennis players (Jones et al., 1977). The cortical cross-sectional area of the dominant side was on average 41% greater than the non-dominant side ($p < 0.05$). Significantly higher ($p < 0.05$) BMC and BMD were also noted in the dominant arms of non-athletic children aged 8-16 years (Faulkner et al., 1993).

Cross-sectional Observational Studies in Young Athletic Groups

There have been a number of cross-sectional studies that compared bone parameters across sporting groups in children or adolescents (Fehling et al., 1995; Heinonen et al., 1993). These studies have also shown that training that produces strains at a high rate and high peak forces in diverse movements such as gymnasts is most effective for enhancing bone formation in young women (Fehling et al., 1995; Slemenda and Johnston, 1993). In one such study of 7 – 9 year old participants, gymnasts had the highest total body BMD compared to swimmers ($p < 0.001$) who had similar BMD to controls (Cassell et al., 1996). By nature, swimming unloads bone so the outcome is likely related in part to the buoyant nature of the sport and the number of buoyancy hours these athletes experience while training. In a study of cyclists and cross-country skiers athletes (n = 29, mean age of 24 y), had similar BMD to controls despite large tensile force difference between sports (Heinonen et al., 1993).

Adolescents and young adults participating in physical activities with relatively high impact loads have reportedly higher BMD. For example, college-aged gymnasts had high BMD at the femoral neck ($p = 0.0001$) and lumbar spine ($p = 0.0001$) than runners and controls (Robinson et al., 1995). In a study of junior Olympic male weight lifters, aged 17 years, athletes had significantly greater BMD at the femoral neck ($p < 0.05$) and lumbar spine ($p < 0.05$) compared to age-matched controls (Conroy et al., 1993).

Prospective Observational Studies

There are very few prospective human studies in pediatric groups as longitudinal studies that span the entire pubertal period are time consuming and costly. One study has shown a significant effect of physical activity over a three-year period on BMD accrual at the lumbar spine, proximal femur, and distal radius in prepubertal children (Slemenda et al., 1994). A six-year longitudinal study that looked at the relationship between PA and bone mineral accrual in growing children found that active boys and girls had a greater total body BMC that their inactive peers (Bailey et al.,.1999). This study also showed a greater peak bone mineral accrual rate and greater bone mineral accumulation for the 2 years around peak for children that are highly active over those that are not as active. The total body BMC was 9% and 17% greater for active boys and girls, over same age inactive children.

Intervention Studies

There have been different types of bone loading intervention protocols that have attempted to increase bone mineral in young children (McKay et al., 2000, Morris et al., 1997, and Bradney et al., 1998). The results of these studies are different from adult studies and from each other for a number of reasons.

In adult human exercise studies, the changes to bone mass take place slowly and the changes are generally small and localized (Lanyon, 1996). Results are also generally difficult to compare as different exercises and training programs impose different loads on the skeleton at different sites. The ages and maturity of the subjects and the length of the intervention may vary, as might the instrument system used to assess bone mineral. There are only three published reports on the effects of a loading intervention in children (McKay et al., 2000, Morris et al., 1997, and Bradney et al., 1998) of these only one was randomized (McKay et al., 2000).

A bone loading intervention study with prepubertal girls (aged 9 – 10 years) monitored change in bone density over an 8-month intervention period (Morris et al., 1997). The girls in the intervention program participated in "high impact" aerobics, soccer, Australian football, step aerobics, skipping, ball games, bush dance, modern dance, and weight lifting for 30 minutes three times per week. The girls in the intervention group had a significantly greater whole body (1.0%, $p = 0.001$), lumbar spine body (2.6%, $p = 0.04$), and femoral neck areal BMD (aBMD) body (10.0%, $p = 0.01$). The increase in BMD seen in studies with prepubertal girls is greater than for intervention studies with premenopausal women (Snow Harter et al., 1992). In a similar bone loading intervention study in boys, there were twenty subjects (mean age of 10 years) in an exercise group and twenty age-matched controls (Bradney et al., 1998). They found an increase in aBMD that was double the increase in controls at weight-bearing sites (Bradney et al., 1998).

In a randomized school based exercise intervention study in pre and early pubescent children (grades 3 and 4), the exercise group ($n = 63$) did 10 tuck jumps 3 times weekly and incorporated jumping, hopping, and skipping into twice weekly physical education classes. The control group (n = 81) did regular physical education classes. The exercise group showed significantly greater changes in femoral trochanteric aBMD (4.4% vs. 3.2%, $p < 0.05$) (McKay et al., 2000). These studies provide further evidence that "childhood" is a critical period of bone mineral accrual. However, these intervention studies do not clearly define the exact load required to elicit an osteogenic response in young children.

Summary

Pediatric exercise intervention studies are sparse but suggest that childhood is an opportune time for increasing bone mass. The literature suggests that bone mineral in children can be enhanced by loading factors associated with physical activity. However, the specific nature of the activity that induces an osteogenic response has not been characterized. From animal studies, we know that strain magnitude, strain rate, and strain distribution are important factors in the adaptation of bone to mechanical loading. Jumping is believed to be a good osteogenic stimulus as it provides a high strain magnitude and rate in a diverse distribution.

The literature has shown that GRFs correlate positively with strains at the femoral neck, and that these strains help model and shape bone throughout life. It is known that higher GRFs elicit a greater bone response (Whalen and Carter, 1988). However, to our knowledge GRFs across activities at different levels of intensity have not been clearly outlined in pediatric groups.

3. PILOT STUDY

3.1. *Pilot Study Research Questions and Objectives*

A pilot study was performed with the following objectives:

1) to delineate if all selected activities were feasible for children to perform
2) to observe the different skill levels between children performing selected activities
3) to determine the time required for the ground reaction measurements and analysis
4) to determine the relevant outcome variables

The methodology and results of the pilot study are included in Appendix A.

From the pilot study results, we noted several factors that may have affected the study outcome. These include: the variability in jumping ability of subjects (aged 8 to 10 years), the number of jumps performed for each activity, the interpretation of the instruction from the measurer, which could potentially compromise the jumps being performed in a standardized way. The following is a brief discussion of our observations regarding each of these.

Skill Level: We observed a wide range of ability between children performing the same jump, demonstrated by the high inter-subject variability in our results. The highly skilled subjects were able to jump in a controlled fashion. We know that skill and motor control will vary with level of maturity, and that maturity varies considerably in children of this age.

For our pilot study, the subjects were shown how to perform the jumps and allowed several practice jumps. Some of the subjects had trouble staying on the relatively small force platform during, especially rapid, repeated jumps.

Instruction: We did not standardize the instructions for the subjects for the pilot study. The subjects were simply told how to perform the jump. This is likely to have increased the variability and decreased the reproducibility of the results.

3.2. Conclusion

The pilot data was useful for highlighting several important factors that must be considered within the design of the major project. The specific findings that will be utilized in the large study design are:

1) Subjects will perform five repeated jumps in succession, and trials with three or more acceptable jumps will be recorded and analyzed.
2) A standardized instruction set, including demonstrations and number of practice jumps will be used for every subject. (Appendix B).
3) The pilot data also allowed us to determine the optimal number of jumps to be recorded. As there are no published reports of GRF from the activities that comprise our protocol, we used the pilot data to calculate the sample size for the larger project. The standard error of the mean (SEM) was used to determine the accuracy of our data.

SEM = Standard deviation / SQRT (N)

Standard deviation of the jumps ≈ 1.7

SEM = 1.7 / SQRT 50 = 0.240	
	8.8 % difference
SEM = 1.7 / SQRT 60 = 0.219	
	7.3 % difference
SEM = 1.7 / SQRT 70 = 0.203	
	6.4 % difference
SEM = 1.7 / SQRT 80 = 0.190	

With a SEM of 0.240, we would be 68% certain that the population mean ground reaction force would be ± 0.240, or 95% certain that it would be ± 0.480. A smaller SEM would give us a smaller range at a given percentage of certainty. As the percent difference in

SEM was similar between 60-70 subjects as between 70- 80, we selected a sample size of 70 for the larger study, 35 males and 35 females.

4. SUBJECTS AND METHODS

4.1. Research Questions and Hypotheses

The primary purpose of this study was to measure and describe the GRFs from a variety of jumps and the GRFs from the same jump at different levels of intensity in a group of normally children aged 9 - 11.

Primary Hypotheses:

1) For the same jump, maximum GRFs will be greater for jumps from a higher height (50cm) or performed maximally, than from a lower height (10cm) or performed submaximally.
2) For different jumps, the maximum GRFs will be different between the jumps.
3) For different jumps, the time to peak landing force will be different between the jumps.
4) For different jumps, the landing impulses will be different between the jumps.
5) There will be no difference between boys and girls for any anthromorphic, performance or GRF variables.

Our secondary purpose was to relate physical activity patterns of the children with BMD at the hip and with dynamic measures of muscular power.

Secondary Hypotheses:

6) The loaded physical activity time will correlate positively with BMD at loaded bone sites (proximal femur, femoral neck, and trochanter)
7) The amount of loaded physical activity time will correlate positively with dynamic measures of muscular power: vertical jump and long jump.

4.2. Subject Recruitment

Subjects in grades 4,5 and 6 attending elementary schools in the Richmond School District and currently participating in a high impact loading intervention study were randomly selected for GRF measurement. We first approached the principals at the Richmond School Board meeting. Principals who were interested in having their school participate then forwarded the names of classroom teachers willing to participate. Meetings were set up and details of the project were distributed. Presentations were made at the schools for the children, their parents, and teachers; information and consent forms were distributed.

4.3. Subjects and Study Design

This study was randomized and cross-sectional, designed to assess in GRFs for selected jumps and between levels (heights) of the same jump. We selected a variety of activities utilized in the aforementioned exercise intervention study as well as activities performed at different levels of intensity. Seventy children (36 boys, 34 girls) aged 9-11 years who volunteered to participate in "The Healthy Bones Study" (total N = 389) in the School of Human Kinetics at the University of British Columbia, Canada were randomly selected for the biomechanics study. Subjects were screened for musculoskeletal problems, metabolic disorders or the use of medications that might affect balance or strength. The subjects were all healthy and had a range of activity levels. The descriptive data for the subjects are listed in Table 4.1. All subjects and their parents gave their written informed consent prior to data collection. The study was performed with the approval of the University of British Columbia Behavioural Research Ethics Board.

Table 4.1. Descriptive data for age, height, mass, dynamic power, and physical activity. Bone mineral density (aBMD) at the femoral neck (FN), the trochanteric region (troch) of the proximal femur (PF) and for the total PF is provided.

	Mean (SD)	Boys (SD)	Girls (SD)	95% CI*
Age (years)	10.2 (0.7)	10.2 (0.7)	10.2 (0.8)	(10.0 to 10.4)
Height (cm)	143.6 (8.3)	142.6 (8.1)	144.7 (8.4)	(141.7 to 145.5)
Mass (kg)	36.4 (7.5)	36.2 (7.5)	36.7 (7.7)	(34.6 to38.2)
Vertical Jump (cm)	24.3 (5.5)	25.8 (5.3)	22.6 (5.3)	(22.9 to 25.6)
Long Jump (cm)	135.2 (16.6)	139.9 (16.6)	130.3 (15.3)	(131.0 to 139.4)
PA Total (score/5)	2.96 (0.62)	2.96 (0.62)	2.96 (0.64)	(2.82 to 3.11)
PA Loaded Time (hrs)	5.74 (5.16)	5.59 (5.70)	5.91 (4.60)	(4.53 to 6.95)
aBMD FN (g/cm^2)	0.67 (0.08)	0.68 (0.08)	0.65 (0.08)	(0.65 to 0.69)
aBMD Troch (g/cm^2)	0.58 (0.08)	0.58 (0.07)	0.58 (0.09)	(0.56 to 0.60)
aBMD PF (g/cm^2)	0.70 (0.09)	0.70 (0.07)	0.70 (0.10)	(0.68 to 0.72)

* 95% confidence interval for group means

4.4. Instruments and Procedures

A. Maturational Assessment: (Pubertal development was evaluated by self-assessment of breast (girls) and pubic hair (girls and boys), according to the method of Tanner (1955). The purpose of the rating procedure was explained to each child individually and children were allowed to privately select the line drawing that most accurately reflected their maturity level. The child returned their questionnaire in a sealed envelope.

B. Anthropometry: Stretch statures (without shoes) and sitting height were measured to the nearest 0.1 cm using a wall mounted stadiometer and standard protocol. The head was positioned in the Frankfort plane and gentle traction was applied with cupped hands beneath the mastoid process. Measurements were taken twice and mean values were used for analysis. Body mass (nearest 0.1 kg) was obtained with the subject standing motionless on the force platform. Body composition variables including fat mass and bone mineral free lean mass (lean mass) were estimated from DXA total body scans.

C. Physical Activity: A PA questionnaire was used to assess the activity level of the subjects (Appendix c). The PA questionnaire for children (PAC-Q) consists of nine items designed to provide a measure of a child's general PA level during the school year. PA was described as "sports, games, gym, dance, or other activities that make you breathe harder, make your legs feel tired, and make you sweat." Although this questionnaire was designed to be self administered, research assistants facilitated its completion and clarified any unclear responses with participants. An overall activity score was calculated by coding answers on a Likert scale from 1 – 5 (1 = not active; 5 = always active). A "load" score was derived from question 1 that asked the amount of weight bearing PA the children engaged in during the past week (hr/week). Questionnaires were analyzed to derive average activity scores, loaded activity time (hours per week in loading activities), and descriptive information regarding extracurricular activities.

D. Dynamic Power: Vertical jump and standing long were used as indicators of dynamic power. The vertical jump test was administered using standard protocol (Sargent, 1921, Appendix D). A measurement of full reach was taken prior to jumping; a two-foot take off was performed from a standing position. Jump height was measured as the distance between the full reach point and the highest point touched during the jump. Two practice jumps were allowed. Two measured jumps were performed unless the jumps differed by more than 1 cm, then a third jump was performed.

Standing long jump was also measured to evaluate lower limb power (Appendix D). The subjects positioned their feet behind a starting line prior to the long jump. The subjects were allowed to swing their arms in preparation for the jump. Jump distance was measured from the starting line to the heel position at landing.

E. Bone Measurement: Areal bone mineral density (aBMD, grams/cm^2) were measured at the femoral neck (FN), the trochanteric region of the proximal femur (troch), and the total proximal femur (PF) using a Hologic QDR 4500 bone densitometer (Hologic Inc., Waltham, MA). Participants wore plain loose fitting clothes, usually a T-shirt, shorts, and shoes and all metal objects were removed (glasses, watches, jewelry, etc.) Measurements were made by one of two trained and qualified measurers (Dr. Moira Petit or Kerry MacKelvie) under the supervision of Dr. Heather McKay. A typical DXA print out for a PF bone densitometry scan is provided (Appendix E).

Data Collection Procedures

The child's participation in this project involved one 40-minute testing session in the Biomechanics Laboratory, School of Human Kinetics, at the University of British Columbia (UBC). Children were transported to UBC by minivan in small groups (5 or 6) and supervised en route by a study staff person. Each child wore their regular physical education clothing (T-shirt, shorts, or sweat pants, and running shoes).

Upon arrival at the biomechanics lab, the children were introduced to the investigators and to the lab equipment. A data sheet was marked with a unique identification number for each subject. This number was used as an ongoing reference and ensured confidentiality during data analysis and reporting. Birth date and anthropometric data were also recorded on the data sheet. The GRF data were collected by Kelly Moore.

Jumps: GRF was assessed for each of the 12 jumps that have been utilized in a randomized controlled intervention trial in a pediatric group. A standardized set of instructions was used to convey the proper techniques for the different jumps (Appendix B). First, the correct jump technique was described verbally, next each jump was demonstrated for the child, and finally the child was allowed to practice each jump three times. The subjects were instructed to perform each jump five times. Each subject performed the following jumps with abbreviation in Table 4.2:

1) Counter movement
2) Drop from 10 cm
3) Drop from 20 cm
4) Drop from 50 cm

5) Plyometric jump 10 cm
6) Plyometric jump 30 cm
7) Plyometric jump 50 cm
8) Maximal jumping jacks
9) Submaximal jumping jacks
10) Alternating feet
11) Side to side over a 10 cm foam barrier
12) Side to side over a 20 cm foam barrier

Ground Reaction Force Measurement and Data Processing

GRFs for the selected jumps were measured on a Kistler 9251A multi-component force platform (Winterthur, Switzerland) by the same investigator. The jumps performed in random order were recorded for 8 seconds at 300 Hz. Prior to the collection of jumping forces, the mass of the subject was recorded from the force platform (mass = force/gravitational acceleration). The GRFs were converted by an analog/digital board (DT2821 Data Translation, Marlboro, MA) and interfaced to the program Peak Motus – Motion Measurement System (Peak Performance Technology, Englewood, Colorado).

The raw GRF data were exported from the Peak Motus (Peak Performance Technology, Englewood, Colorado) motion measurement program as text files to a Pentium II 350 personal computer for analysis. Each subject had nine files corresponding to the twelve jumps. The jump and body mass (kg) data were transferred to the Pentium II 350 personal computer and the text files were converted to Excel 2000 (Microsoft Office) files. The primary variables were *maximum vertical force*, *maximum rate of rise in force*, and *impulse*. The secondary variables were *time to peak force* and *flight time*.

GRF data for each individual were normalized and converted from Newton's (N) to body weight (BW). Each type of jump was performed three to five times. The exceptions were the counter movement jump (CMJ) and the drop jumps (DJ)/ plyometric jumps (PJ), which were performed only once. Mean and standard deviation (SD) were calculated for each jump series for each subject, which were, in turn, used to calculate means (SD) for the 70 subjects. For each type of jump, the points of initial contact on landing (L_T), global maximum observed (F_T), and take-off (TO) were manually noted from the force production curve. These points were used to calculate the primary outcome variables. Figure 4.1 is a representation, in arbitrary units, of how the parameters analysed in the study were determined.

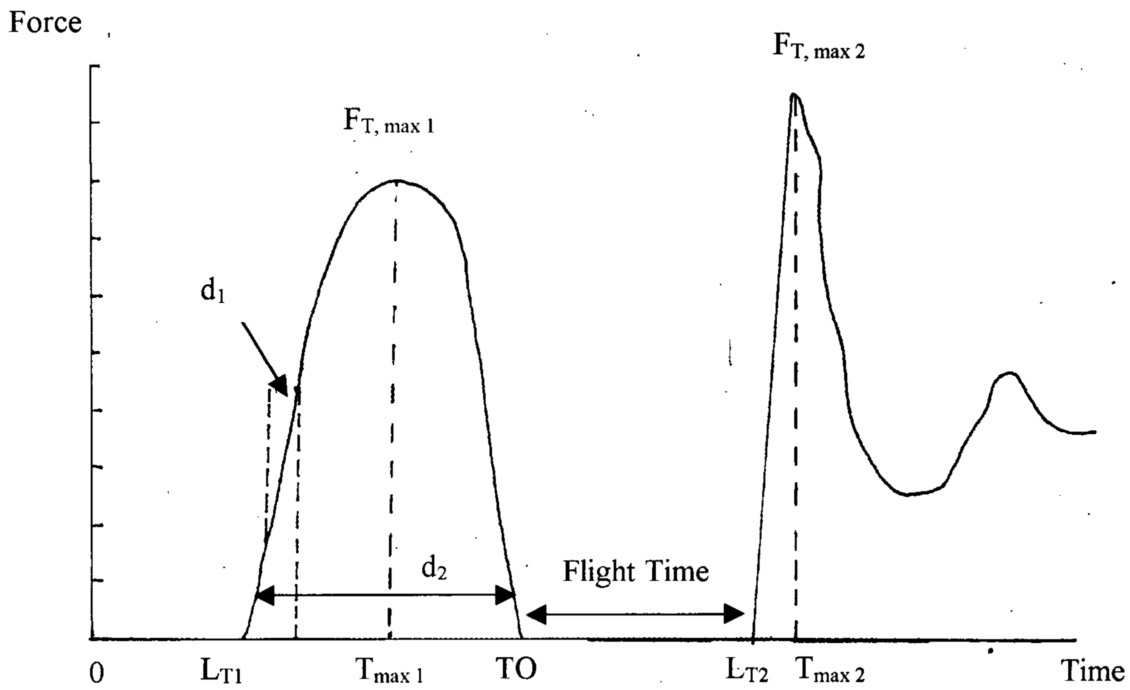


Figure 4.1. Diagram of the determination of the parameters analysed. Where L_{T1} and L_{T2} are the landings of the jump, $F_{T, max 1}$ and $F_{T, max 2}$ are the maximum forces, $T_{max 1}$ and T_{max2} are the times points of the $F_{T, max1}$ and $F_{T, max 2}$, d_1 is the time interval for the differentiation calculation, d_2 is the time interval in the impulse analyses and TO is the take off. Impulse is the area under the force-time curve from L_{T1} to TO. Time to maximum forces is from L_T to $F_{T, max 1}$ and flight time is from TO to L_{T2}. The vertical axis represents the amplitude in arbitrary units.

Maximum Forces: For each type of jump, maximum forces (MF) were determined by manually identifying the point of maxima ($F_{T, max1}$), the value at that point was determined as the MF. For the DJs, there were two MF values ($F_{T, max 1}$ and $F_{T,max 2}$), one for landing from the drop and one for landing from the PJ (Figure 4.1).

Maximum Rate of Force: The maximum rate of rise in force (MRF) was defined as the point of highest positive change in GRF. This was calculated by differentiating the GRF profile and determining the greatest positive change for the first part of the landing. The data were differentiated by estimating the slope of the curve according to the following formula:

$$\boxed{MRF = (F_{T+d1} - F_{T-d1})/\ d_1}$$

F_T = force at time T
d_1 = time interval

Where F_T is the force at time $_T$ and d_1 is the time interval between the subsequent value and previous value of the force time curve.

Impulse: Impulses (I) were calculated for each jump by using the trapezoid rule equation to integrate the force time curve. The trapezoid rule equation is:

$$\boxed{I = [(0.5 \text{ x } L_{T1}) + (0.5 \text{ x } TO) + (\sum_{LT1+1}^{TO-1} All)] \text{ x } d_2}$$

L_{T1} = landing 1
TO = take off
d_2 = time interval

The impulses were calculated the time period while the subject was in contact with the force platform. However, for the CMJ, impulse was calculated only the take-off portion of the jump and not the landing. For the DJs, the impulses were calculated only for the drop portion of the DJ/ PJ sequence.

Time to maximum force: Time to maximum force ($T_{max\ 1}$) was calculated according to the following formula:

$$T_{max\ 1} = T_{max\ 1} - L_{T1}$$
$$T_{Fmax\ 2} = T_{max\ 2} - L_{T2}$$

T_{max} = time at maximum force
L_T = time at landing

For jumps with one landing, the first equation was used. For the DJ jump where there were two landings, one from the drop and one from the plyometric jump, therefore, both equations are used to determine each time to maximum force.

Flight Time: Flight time was defined as the time between take off (TO) and landing (L_{T2}) for the CMJ and DJs (Figure 4.1). For the other jumps, there were no flight times, as the subject would land off of the force platform and then jump back on the force platform. Flight time is calculated as follows:

$$\boxed{\text{Flight time} = L_{T2} - \text{TO}}$$

The jumps are described below, listed (Table 4.2), and schematically illustrated Appendix C.

Jumping Jacks: Subjects first stood stationary on the force platform with their hands on their hips, feet together. They then jumped up and moved their feet apart so that they straddled the force platform; followed by a return to the force platform landing with feet together. This sequence was repeated five times, although the last jump is not used in the analysis. For the maximal jump the subjects were instructed to jump as high as they could each time. For the submaximal jump, the subjects jumped at a moderate height and rate. A sample force-time curve for a typical jumping jack is shown in Figure 4.2.

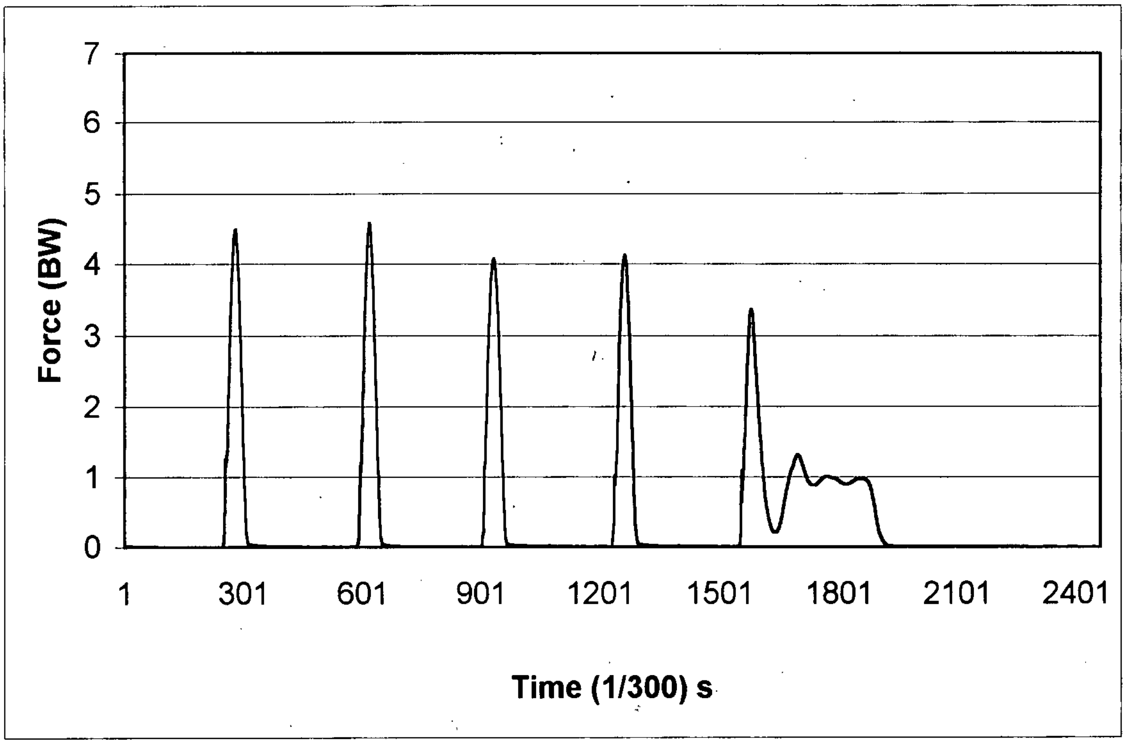


Figure 4.2. Typical GRF profile of five repeated jumping jacks.

Alternating Feet: Subjects began with both feet on the force platform and hands on their hips. They then jumped to one side of the force platform, landing on one foot, and then back on the platform landing on the other foot. This jump was repeated so that there were five single foot landings on the force platform. This is the only jump where the subject landed on one foot. Figure 4.3 shows a typical force-time curve of an alternating feet jump.

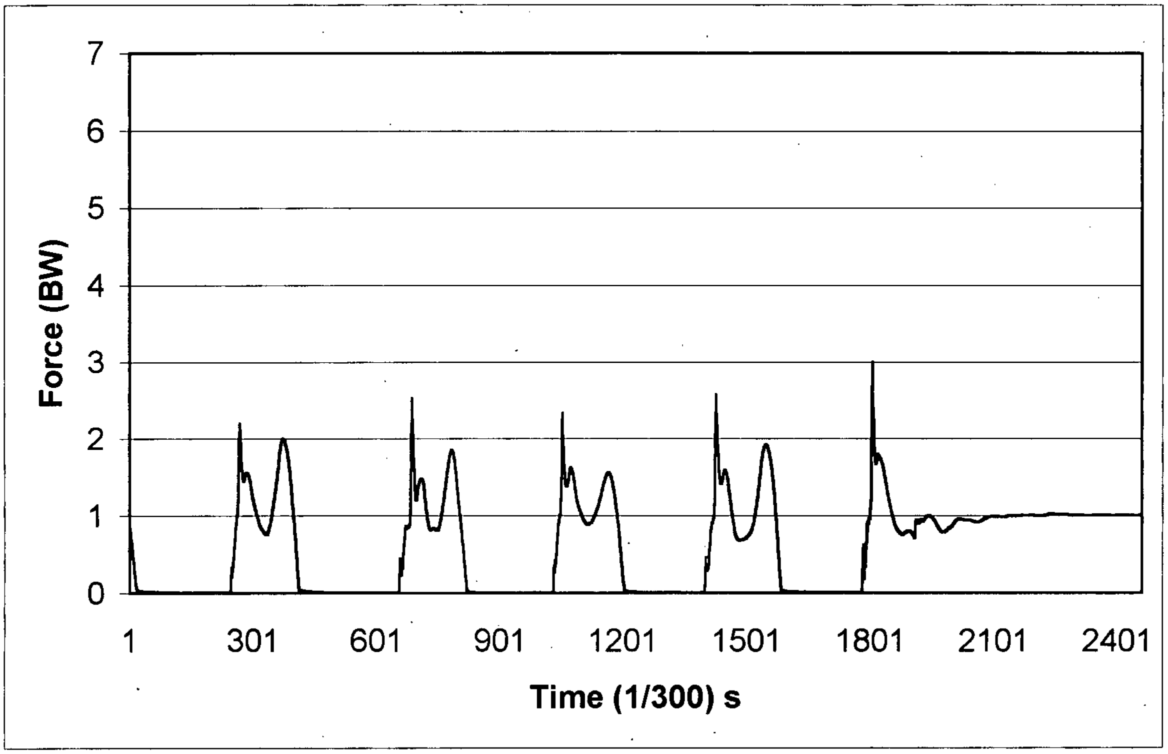


Figure 4.3. Typical GRF profile of five repeated alternating feet jumps.

Side-to-side Jump: The side-to-side jumps involved a two-foot lateral jump off of the force platform, over a foam barrier, onto the side of the force platform and then back on. With hands on hips, subjects jumped with feet together so that both feet were in contact with the force platform on landing. Five landings on the force platform were recorded. This jump had two levels; the lower level required the subject clear a 10 cm foam barrier, while at the higher level the barrier was 20 cm. The GRF profile for a typical side-to-side jump is represented (Figure 4.4).

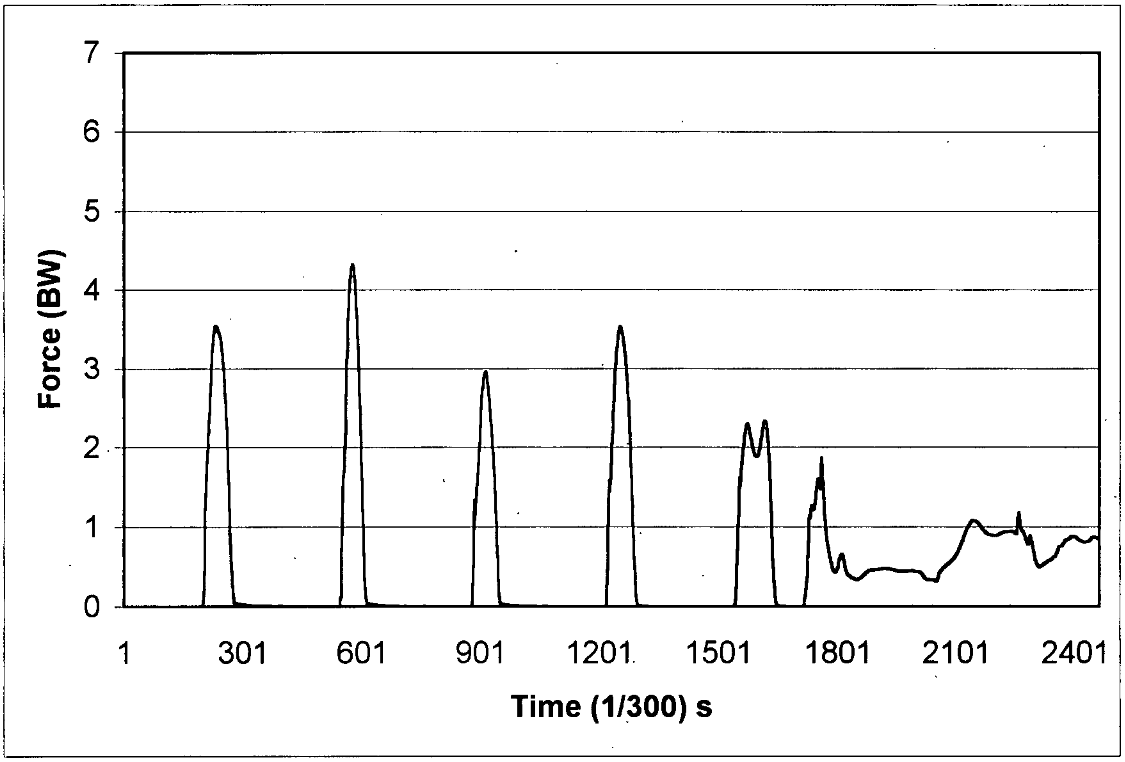


Figure 4.4. Typical GRF profile of five repeated side-to-side jumps.

Counter Movement Jump: The counter movement jump consisted of one tuck-like jump on the force platform. Subjects began by standing stationary, hands on hips. They then bent their knees rapidly (counter movement) and extended them as they jumped. The subjects were instructed to jump as high as they could and to land with both feet on the force platform. Figure 4.5 shows the GRF profile from a typical counter movement jump.

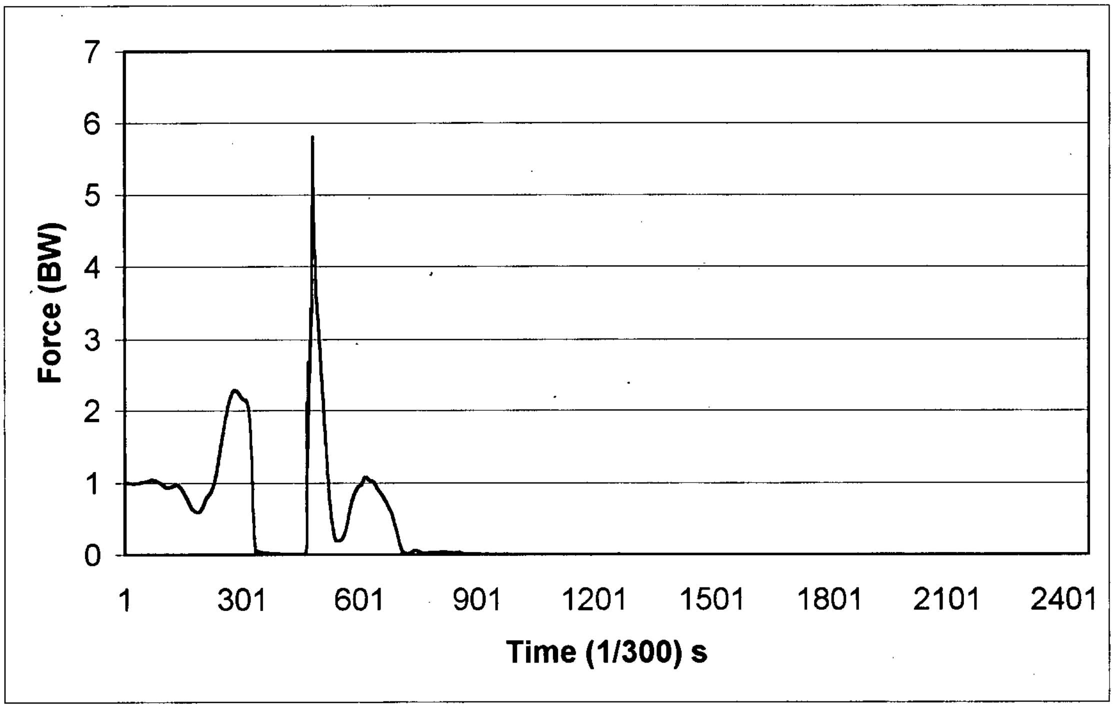


Figure 4.5. Typical GRF profile of counter movement jump.

Drop Jump/ Plyometric Jumps: Subjects stood, hands on hips, on an elevated step positioned adjacent to the force platform, dropped onto the force platform, and then quickly performed a PJ. Consequently, for each jump, there were two landings, the drop landing and the PJ landing. This jump was performed from: 10, 30 and 50 cm. A representation of a typical GRF profile for a DJ is provided (Figure 4.6).

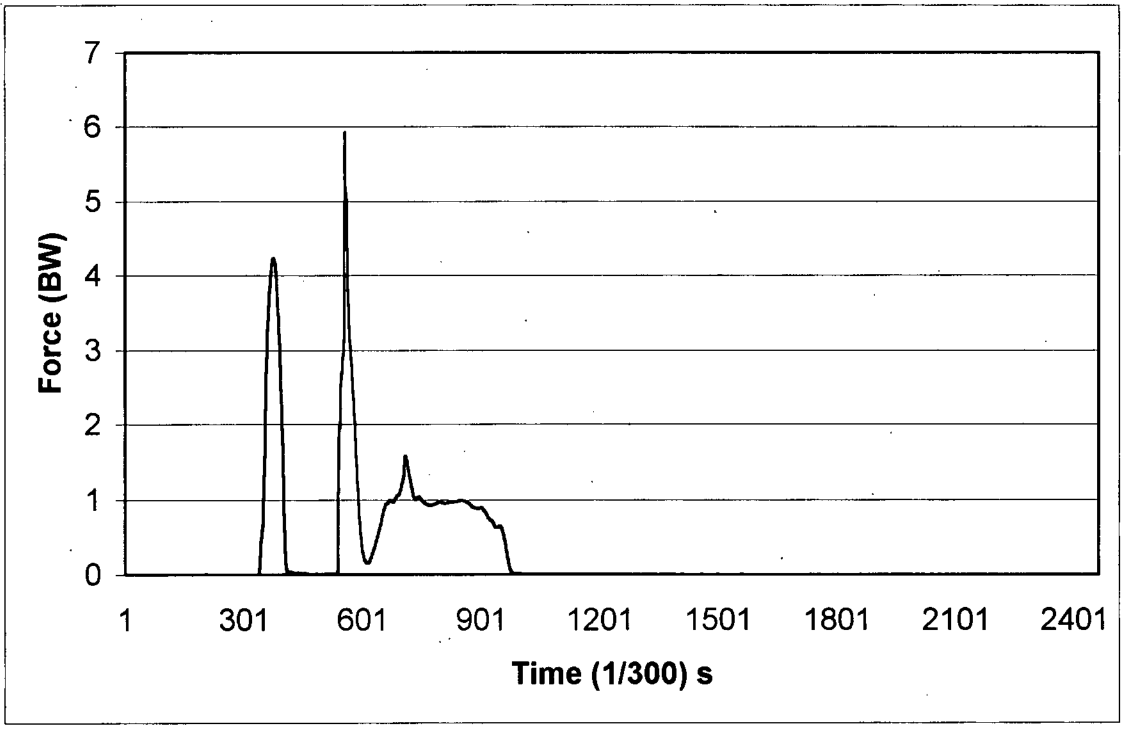


Figure 4.6. Typical GRF profile of a drop jump.

Table 4.2. Jump abbreviations for the twelve selected jumps.

Jump Type	Abbreviations
Single Jumps	
Counter movement jump	CMJ
Drop jump 10 cm	DJ_{10}
Drop jump 30 cm	DJ_{30}
Drop jump 50 cm	DJ_{50}
Plyometric jump 10 cm	PJ_{10}
Plyometric jump 30 cm	PJ_{30}
Plyometric jump 50 cm	PJ_{50}
Repeated Jumps	
Submaximal jumping jacks	JJ_{submax}
Maximal jumping jacks	JJ_{max}
Alternating feet	Alternating
Side to side over 10 cm barrier	$S\text{-}S_{10}$
Side to side over 20 cm barrier	$S\text{-}S_{20}$

4.5. Statistical Methods

Descriptives: Means and standard deviations for vertical jump, standing long jump, loaded physical activity, and aBMD were calculated. From the GRF data, we examined maximum force, maximum rate of force, vertical impulse, time to maximum, and flight time

Confidence Intervals: For the loading variables, we utilized confidence intervals (CI) to present outcome data. The central limit theorem states that when the sample size is large, about 95% of the sample mean will fall within 1.96 standard errors of the population mean. Therefore, we can be 95% confident that the population mean is contained within that interval when the values of the variable are normally distributed in the population. The selected confidence level is the percentage equivalent to the decimal value of $1 - \alpha$. When a 95% CI is used, $\alpha = 0.05$ (Bluman, 1997). For example, if we know the 95% CI for a certain variable under condition x and the mean value under condition y lies outside of this confidence interval, the means are different at $p < 0.05$. This is similar to performing a t-test. CIs can be used to conduct hypothesis testing and results will determine whether there are significant differences. Therefore, we calculated 95% CI to determine the differences between the jumps.

Statistical Analysis:

T-tests were utilized to analyze the differences in maximum GRF and rate of force between boys and girls. Pearson product moment correlations were used to determine the association between aBMD (proximal femur, femoral neck, and trochanter), physical performance variables (physical activity, loaded physical activity, vertical jump, and long jump), and maximum GRF. We utilized hierarchical regression to determine the contribution of the predictor variables (lean mass, long jump, loaded physical activity, and fat mass) to the outcome (aBMD) variables. Data were analysed using SPSS for Windows, Version 8.0 (SPSS Inc, Chicago). Results were considered significant if $p < 0.05$.

5. RESULTS

Subjects

Results are presented as means (SD) unless otherwise noted. Age for boys was 10.19 (0.69) years and for girls was 10.23 (0.78) years. Height for boys was 142.63 (8.12) cm and 144.72 (8.43) cm for girls. Total body mass for boys was 36.00 (7.44) kg and 36.76 (7.62) kg for girls. Of the 70 subjects, there were 16 girls at breast Tanner stage I, 14 at Tanner II and 4 at Tanner III, for the boys there were 31 at pubic hair Tanner I, 4 at Tanner II, and 1 at Tanner stage Tanner III. Descriptive results for the outcome variables of interest, means (SD) and 95% CI are presented in Table 5.1.

Gender Differences

There were no differences in age, height, or body mass between boys and girls. There were, however, gender differences in the dynamic power performance measures, vertical jump and standing long jump. The boys jumped 14.5% higher and 7.4% further than the girls (both, $p = 0.014$). There were no differences in time engaged in PA or loaded PA time between boys and girls.

T-tests also revealed differences in maximum forces for CMJ ($p = 0.007$), PJ_{30} ($p = 0.041$), and PJ_{50} ($p = 0.005$). Maximum rate of force also varied significantly for JJ_{submax} ($p = 0.011$), JJ_{max} ($p = 0.005$), CMJ ($p = 0.04$), PJ_{30} ($p = 0.001$), PJ_{50} ($p = 0.002$), and DJ_{50} (= 0.048) between genders. There were no significant differences between boys and girls for aBMD at the total proximal femur or its regions.

Table 5.1. Means (SD) for the group for maximum force, maximum rate of force, impulses, and time to peak force for the 9 jumps. N= 70.

Type of Jump[Ψ]	Maximum Force (BW)[Z]		Maximum Rate of Force (BW/s)		Impulse (BW s)		Time to Maximum Force (s)	
	Mean (SD)	95% CI*	Mean (SD)	95% CI*	Mean (SD)	95% CI*	Mean (SD)	95% CI*
CMJ	5.3 (1.6)	(4.9 to 5.8)	493 (306)	(422 to 565)	NA	NA	0.054 (0.020)	(0.049 to 0.059)
DJ_{10}	3.2 (1.1)	(3.0 to 3.5)	241 (198)	(194 to 287)	0.314 (0.046)	(0.303 to 0.325)	0.152 (0.157)	(0.116 to 0.189)
DJ_{30}	3.9 (1.2)	(3.6 to 4.1)	299 (203)	(251 to 347)	0.364 (0.041)	(0.354 to 0.373)	0.095 (0.108)	(0.069 to 0.120)
DJ_{50}	4.7 (1.7)	(4.3 to 5.1)	388 (281)	(323 to 454)	0.399 (0.039)	(0.390 to 0.408)	0.055 (0.021)	(0.050 to 0.060)
PJ_{10}	5.5 (2.0)	(5.1 to 6.0)	514 (347)	(433 to 595)	NA	NA	0.055 (0.022)	(0.050 to 0.060)
PJ_{30}	5.2 (1.5)	(4.8 to 5.5)	440 (263)	(378 to 502)	NA	NA	0.058 (0.020)	(0.053 to 0.062)
PJ_{50}	5.4 (1.6)	(5.1 to 5.8)	457 (257)	(397 to 517)	NA	NA	0.057 (0.016)	(0.053 to 0.061)
JJ_{submax}	3.5 (0.5)	(3.45 to 3.63)	160 (74)	(143 to 177)	0.214 (0.017)	(0.210 to 0.218)	0.117 (0.035)	(0.109 to 0.125)
JJ_{max}	3.4 (0.4)	(3.3 to 3.6)	211 (959)	(188 to 233)	0.284 (0.024)	(0.278 to 0.289)	0.125 (0.048)	(0.114 to 0.137)
Alternating	2.1 (0.3)	(2.07 to 2.22)	126 (59)	(112 to 140)	0.078 (0.021)	(0.073 to 0.083)	0.161 (0.103)	(0.137 to 0.185)
$S\text{-}S_{10}$	3.7 (0.6)	(3.6 to 3.9)	229 (75)	(211 to 246)	0.300 (0.018)	(0.296 to 0.304)	0.094 (0.042)	(0.085 to 0.104)
$S\text{-}S_{20}$	3.8 (0.6)	(3.7 to 4.0)	251 (99)	(228 to 274)	0.310 (0.026)	(0.304 to 0.316)	0.092 (0.043)	(0.082 to 0.102)

[Ψ] See Table 4.2
[Z] body weight
* 95% confidence interval

5.1. Ground Reaction Force

Maximum Force Between Different Jumps

The PJ from 10,30, and 50 cm and CMJ jumps had similar MFs (Table 5.1). These jumps produced GRFs greater than 5 times body weight. These jumps also had the largest variability in GRF as represented by standard deviations between 1.5 to 2.0 times BW. The mean GRF of PJ $_{30}$ was approximately 11% greater than DJ $_{50}$ and PJ $_{10}$ was 75% greater than DJ $_{10}$. Alternating feet jumps demonstrated the lowest variability and lowest GRFs (range: 1.5 - 3.3 BW). Both S-S and JJ jumps produced GRF between 3.4 - 3.8 BW on average.

Means and 95% CI demonstrated similarities and differences between maximum GRFs for jumps and groups of jumps (Table 5.1). The mean GRFs for the jumps fell into 3 groups. Those with GRF approximately 5 times BW, **Group 1 (Group 1** ~ 5 BW): PJ $_{10,30,50}$, DJ 50, and CMJ. Those with GRFs less than 4 BW, but greater than 3 BW, **Group 2** ($3.2 \leq$ **Group 2** ≤ 3.9): DJ $_{10,30\ \mathrm{landing}\ 1}$, S-S$_{10}$, S-S$_{20}$, JJ $_{\mathrm{submax}}$, and JJ $_{\mathrm{max}}$. Alternating feet was approximately 2 BW, **Group 3 (Group 3** = 2.14 BW). The jumps have been grouped as defined above and they are depicted in decreasing order of magnitude of GRF (Figure 5.1).

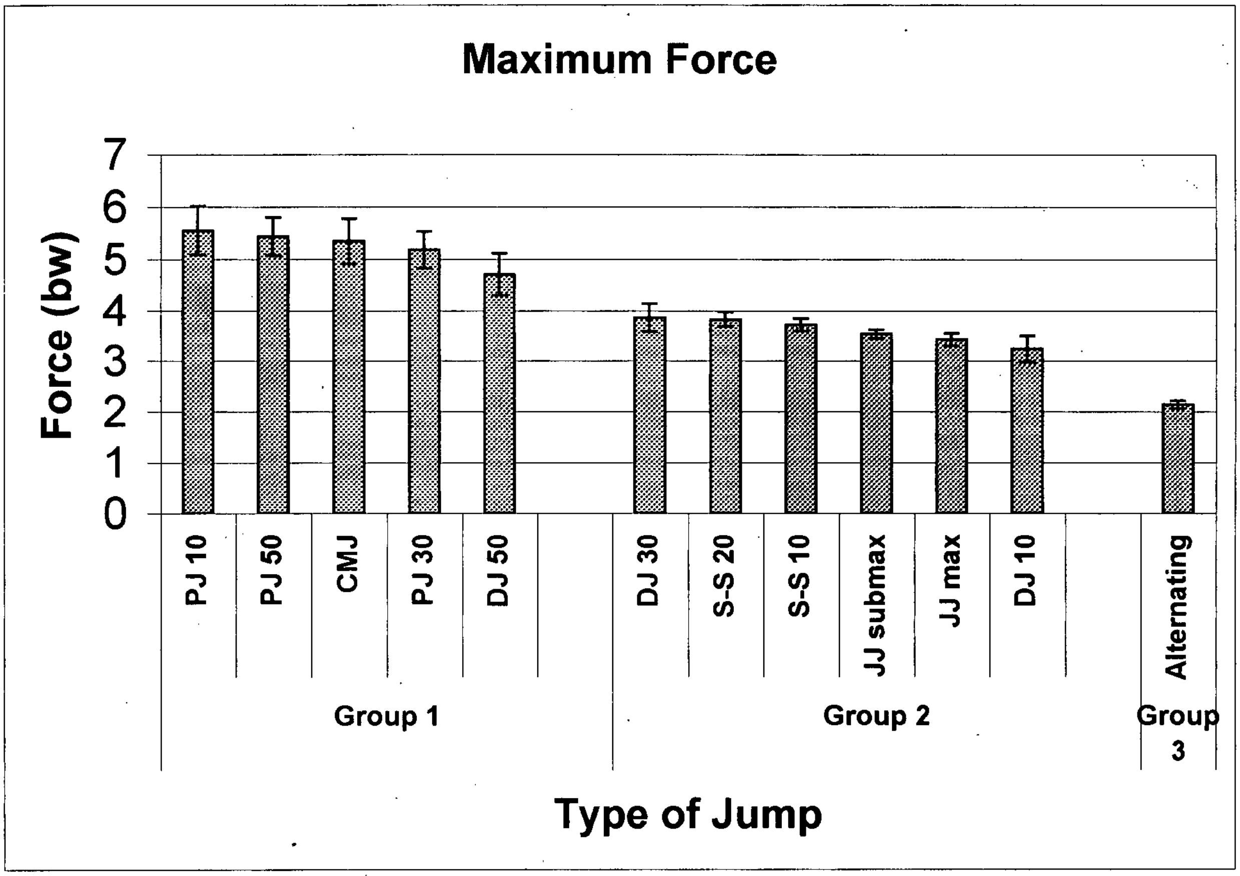


Figure 5.1. Comparison of mean maximum force for all jumps. The error bars indicate the 95% CI.

There was 18% difference in GRFs between the means for the highest (PJ $_{10}$) and lowest (DJ $_{50}$) in **Group 1**. Within **Group 1,** all jumps were significantly greater than DJ $_{50}$. The **Group 1** maximum GRFs were all significantly higher than **Group 2**, approximately 46%. There was a 20% difference between the means for the highest (DJ $_{30}$) and lowest (DJ $_{10}$) in **Group 2**. In **Group 2** jumps, the GRF at the DJ $_{30}$ level was significantly greater than all but S-S $_{20}$ and S-S $_{10}$ jumps. The GRFs of S-S $_{10}$ jumps were significantly greater than JJ $_{submax}$ jumps. Alternating feet jumps (**Group 3)** produced maximum GRFs that were significantly lower than all other jumps. The percent difference between **Group 2** and **3** was 69%, on average.

Maximum Force Between Levels of the Same Jump

Jumping Jacks: There was no significant difference in maximum GRF force between levels of JJs. A range of 1.9 – 6.6 BW versus 2.4 –6.0 BW was noted for JJ_{max} and JJ_{submax}, respectively.

Side-to-side: Different levels of side-to-side jumps were also not significantly different from each other. S-S $_{10}$ MFs ranged from 2.4 –6.5 BW and S-S $_{20}$ jumps from 2.5 – 5.9 BW.

Drop Jumps/ Plyometric Jumps: The three levels of DJs were significantly different from each other. DJ_{50} was 22% greater than DJ_{30}, which was greater 20% than DJ_{10}. The three PJs were not significantly different from each other. The range of MFs for the PJ are as follows: PJ_{10} (range: 1.9 – 11.2 BW), PJ_{30} (2.3 – 10.6 BW), and PJ_{50} (2.8 – 10.9 BW).

Maximum Rate of Force (MRF) Between Different Jumps

The pattern for MRFs was similar to that noted for maximum GRF (Table 5.1). PJ and CMJ had the highest MRF. The variability was also the greatest with these jumps. Absolute values for rates of force ranged from 8.1 kN/s (22.71 BW/s) in DJ_{10} to 500.8 kN/s (1463.16 BW/s) in a CMJ landing. The jump with the lowest rate of force and variability was again, the alternating feet jump.

As for maximum GRFs, the groupings for MRF are depicted (Figure 5.2). **Group 1** jumps (**Group 1** ≥ 440 BW/s) were: $PJ_{10,30,50}$, and CMJ. **Group 2** (299 ≤ **Group 2** < 388 BW/s) included the $DJ_{30,50}$. **Group 3** (210 ≤ **Group 3** < 251 BW/s) included: $DJ_{10, 30}$, S-S $_{10}$, S-S $_{20}$, and JJ_{max}. Alternating feet (range: 24.7 – 299.7 BW/s) and JJ_{submax} were in **Group 4** (**Group 4** < 160 BW/s).

The percent difference between the highest and lowest jump in **Group 1** was 16.8%. Between groups, DJ_{50} MRF was significantly different from **Group 2** and **3** jumps except for PJ_{30}. Mean values for DJ_{30} jump were significantly greater than all other jumps in **Groups 3** and **4**. Values ranged as much as 19% between highest and lowest MRF in **Group 3.** Significant differences were noted among **Group 3** jumps. S-S $_{20}$ jumps were significantly higher (19%) than JJ $_{max}$. For **Group 4**, JJ $_{submax}$ MRF was significantly higher than alternating feet and both of these **Groups 4** jumps had significantly lower MRF than all other jumps.

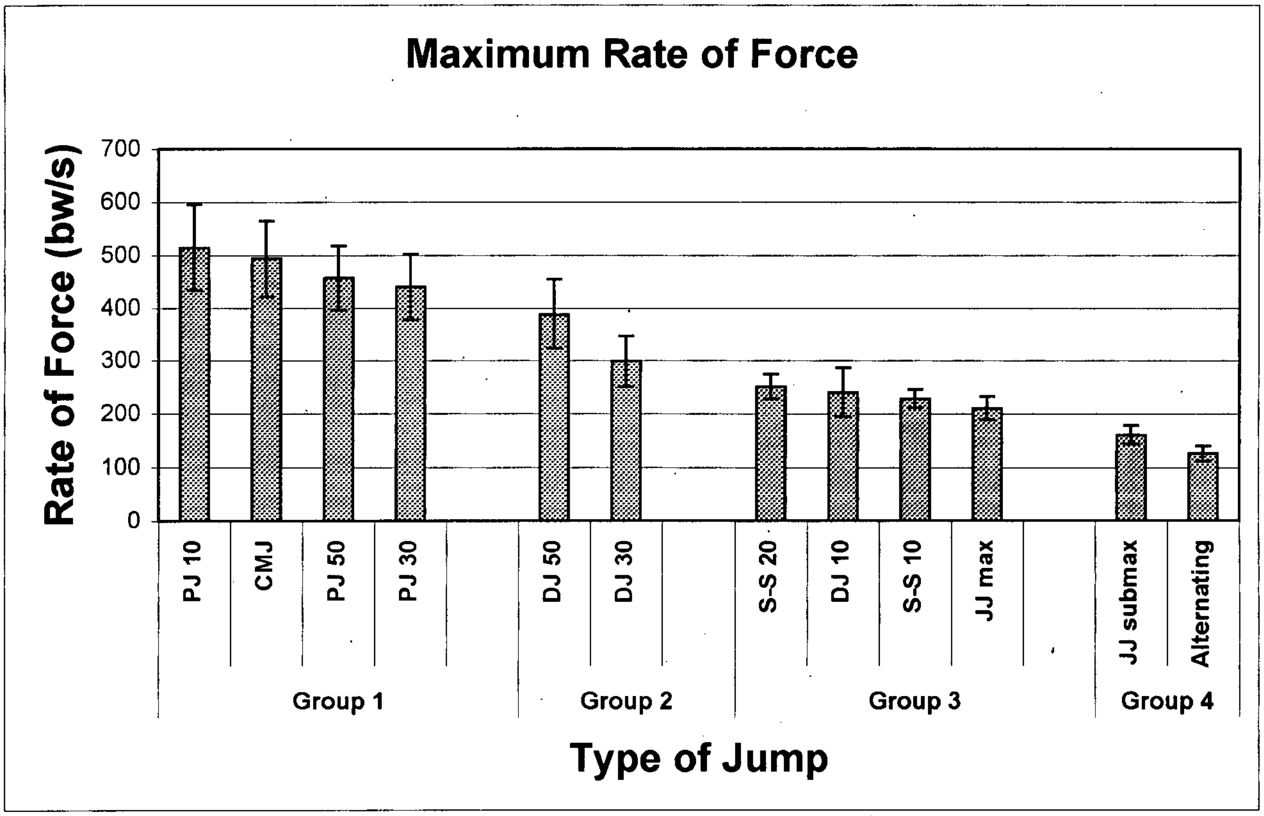


Figure 5.2. Comparison of mean maximum rate of force for all jumps. The error bars indicate 95% CI.

Maximum Rate of Force Between Levels of the Same Jump

Jumping Jacks: The maximum rate of force for the JJ $_{submax}$ was significantly lower (32%) than the JJ $_{max}$. The range in absolute values for maximum rate for JJ $_{max}$ was 45.5 – 637.7 BW/s and 43.5 – 565.2 BW/s for JJ $_{submax}$.

Side-to-side: S-S $_{20}$ jumps (range: 107.4 – 527.7 BW/s) were not different from S-S $_{10}$ jumps (range: 71.1 – 670.1 BW/s).

Drop Jumps/ Plyometric Jumps: For DJs, the rate of force generated by DJ $_{50}$ was significantly greater (29.8%) than DJ $_{30}$, which was significantly greater (24%) than DJ $_{10}$ jump. The absolute values for DJ ranged from 22.7 – 946.4 BW/s for DJ $_{10}$, from 62.2 – 853.9 BW/s for DJ $_{30}$, and from 91.0 – 1436.1 BW/s for DJ $_{50}$.

The PJs were not significantly different from each other. Absolute values ranged from 94.2 – 1488.3 BW/s for PJ $_{10}$, from 137.6 – 1246.6 BW/s for PJ $_{30}$, and from 96.3 – 1273.8 for PJ $_{50}$.

Impulses Between Different Jumps

As for maximum GRF and MRF, DJ's produced the highest impulse values (range: 0.314 - 0.399 BW s). The impulses for each jump are presented in Table 5.1. The impulse for alternating feet was significantly lower (147% – 412%) compared to all other jumps. Impulses ranged from 0.078 BW s for the alternating feet jump to 0.399 BW s for DJ $_{50}$. DJ $_{30}$ and DJ $_{50}$ produced impulses greater (25% on average) than S-S jumps and (53% on average) greater than JJs. The S-S jumps produced significantly greater impulses than both of the JJs (22% on average).

Comparison of Impulses Between Levels of the Same Jump

Jumping Jacks: The impulse for JJ $_{max}$ was significantly greater (33%) than JJ $_{submax}$.
Side to Side: The S-S jump impulses are also different from each other. S-S $_{20}$ had a greater (3%) impulse than S-S $_{10}$.
Drop Jumps/ Plyometric Jumps: The DJs had impulses diminished significantly between levels. For all three jumps (JJ, SS, DJ) the highest impulse was noted for the jumps performed with highest levels of intensity. There was a 10% difference between DJ $_{50}$ and DJ $_{30}$ and a 16% difference between DJ $_{30}$ and DJ $_{10}$.

Comparison of Time to Maximum Force Between Different Jumps

The time to maximum force is also depicted as four groups (Figure 5.3). Mean values for time to maximum force for **Group 1** range from 0.054 to 0.058 s. These values for **Group 2** ranged 0.092 to 0.095 s. **Group 3** jumps ranged from 0.012 to 0.013 s. Finally, **Group 4** jumps time to maximum force ranged from 0.152 to 0.161 s. Time to maximum force for all the jumps are presented in Table 5.1. Generally, the time to maximum force increased as the maximum force decreased. Comparing groups, the longest mean time to maximum forces were observed for JJ $_{submax}$, JJ $_{max}$, DJ $_{10}$ and alternating feet jumps (0.117s). There were no differences within any of the groups. The differences between **Group 1** and **Group 2** were 59 % for PJ $_{30}$ and S-S $_{20}$ and 7% for CMJ and PJ $_{30}$, between **Group 2** and **3** the differences were 23% for JJ $_{submax}$ and DJ $_{30}$, and 36% for JJ $_{max}$ and S-S $_{20}$, and between **Groups 3** and **4** the differences were 21% for DJ $_{10}$ and JJ $_{max}$ and 38% for alternating and JJ $_{submax}$.

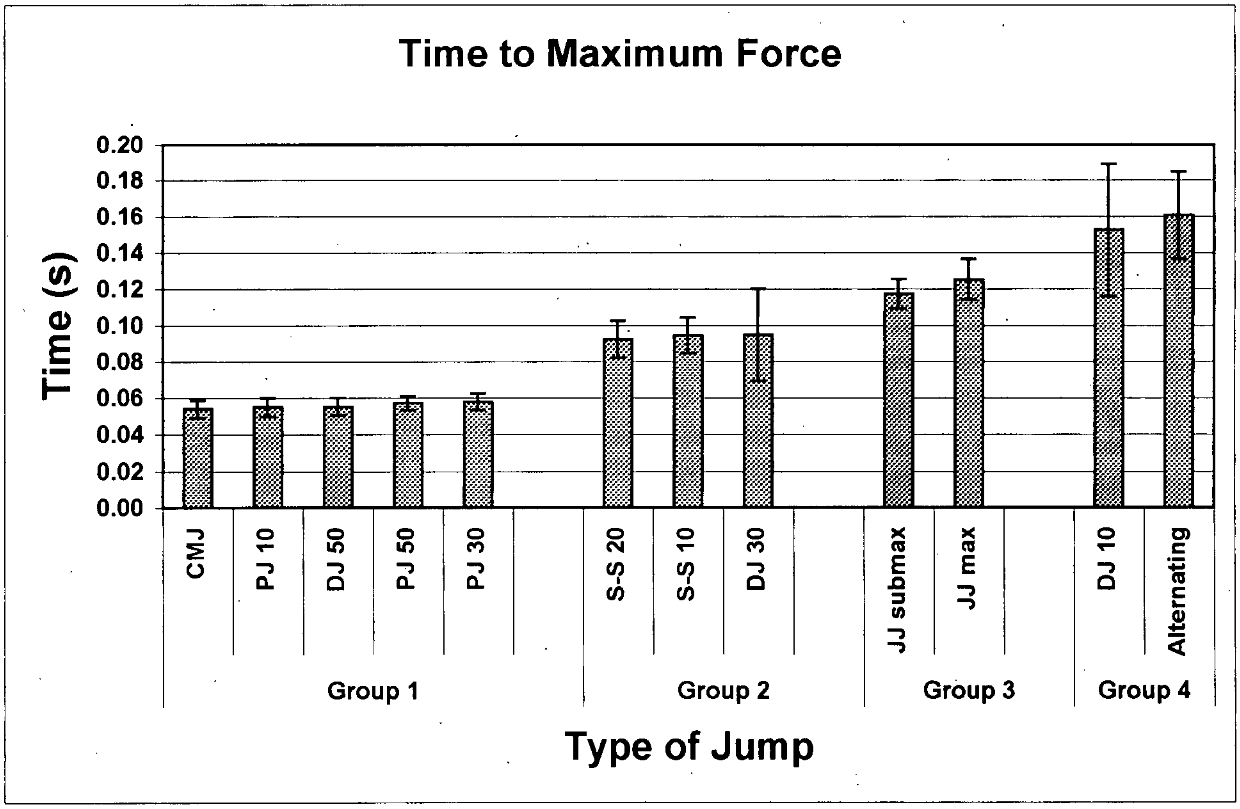


Figure 5.3. Comparison of mean time to maximum force across all jumps. The error bars indicate 95% CI.

Significant differences between jumps were noted for DJ $_{30}$ jumps and JJ $_{max}$. The time to maximum force for S-S jumps was significantly lower than JJ $_{submax}$, JJ $_{max}$, DJ $_{10}$ compared to alternating feet. Alternating feet jumps, had significantly higher time to maximum force as compared to all other jumps with the exception of DJ $_{10}$.

Comparison of Time to Maximum Force Between Levels of the Same Jump

Jumping Jacks: The time to maximum force for jumping jacks was not significantly different across the two levels. JJ $_{max}$ had a range of 0.02 – 0.65 s and JJ $_{submax}$ had a range of 0.03 – 0.41 s.

Side to Side: S-S jumps were also not significantly different across levels. The range for time to maximum force for S-S $_{10}$ was 0.04 – 0.31 s and 0.4 – 0.5 s for S-S $_{20}$.

Drop Jumps/ Plyometric Jumps: The DJs were all significantly different from each other. For the DJs, DJ $_{10}$ (range: 0.01 – 0.64 s) was significantly greater (50%) than DJ $_{30}$ (range: 0.01 s - 0.59 s), which in turn was greater (66%) than DJ $_{50}$ (range: 0.02 – 0.14 s). However, PJs were not significantly different from each other. The ranges for the PJs are as follows: PJ $_{10}$ range: 0.01 – 0.11 s, PJ $_{30}$ range: 0.01 – 0.10 s, and PJ $_{50}$ range 0.01 – 0.10s.

Flight time

The four jumps for which flight time was recorded were: CMJ and DJ $_{10,\ 30\ \text{and}\ 50}$. The flight time for the CMJ was 0.41 s (0.04), DJ_{10} = 0.40 s (0.07), DJ $_{30}$ = 0.39 s (0.06), and DJ $_{50}$ = 0.38 s (0.06). The CMJ flight time was significantly greater (5.4 – 6.5 %) than DJ $_{30}$ and DJ $_{50}$. There was no differences in the flight time across levels of the DJs.

5.2. *Relationship Between Bone Mineral Mass and Loading Characteristics*

Correlations: Pearson product moment correlations between areal BMD and maximum GRF and maximum rate of force were not significant. Partial correlations between physical activity and bone parameters controlling for height and weight are presented (Table 5.2). Loaded PA was significantly correlated to long jump (r = 0.299, p = 0.012) however, vertical jump was not.

Table 5.2. Partial correlations between physical activity and bone parameters.

Correlations	Total PA	Loaded PA	Long Jump	Vertical Jump
aBMD FN	0.12	**0.31***	**0.47***	**0.25***
aBMD Troch	0.16	**0.28***	**0.45***	**0.27***
aBMD PF	0.09	**0.28***	**0.46***	**0.28***

(significance $p < 0.05$)*

Regression: From available data, multiple regression equations were determined for the three bone parameters (Table 5.3). Lean mass was the most significant predictor of aBMD at every site and explained 32% (FN) to 39% (total PF) of the variance. Long jump (LJ) entered next as a significant predictor of aBMD and accounted for an additional 10%, 10%, PF 8% of the total variance at the troch, FN, and total PF respectively.

Table 5.3 Areal bone mineral density (aBMD) regression model summaries including standardized and unstandardized Beta coefficients and adjusted R^2 for trochanter, femoral neck, and proximal femur sites. Variables not in model: loaded physical activity time and fat mass

Variable	Predictor	Standardized Beta	Unstandardized Beta*	Adjusted R^2
Trochanter	Lean Mass	0.558	9.651 E-06	0.326
	Long Jump	0.327	1.563 E-03	0.425
Femoral Neck	Lean Mass	0.555	9.887 E-06	0.321
	Long Jump	0.325	1.600 E-03	0.420
Proximal Femur	Lean Mass	0.615	1.192 E-05	0.393
	Long Jump	0.295	1.579 E-03	0.473

*All predictors significant at $p < 0.001$

6. DISCUSSION

This project quantified GRFs experienced by children while performing different types of jumps selected from the "Healthy Bones Study" bone loading intervention. The implications of the study are discussed under headings related to biomechanical parameters, gender differences, and association with aBMD.

6.1. GRF: Maximum Force, Rate of Force, and Impulse

One of the key findings of this study was that maximum forces experienced by children (aged 9.5 ± 0.6) during jumping ranged from 2 to 5 times BW with all but the alternating foot jumps being greater than 3.4 times BW. To our knowledge, these are the first data for jumping in this age group. Previous studies found that children experience GRF approximately 1.1 BW while walking (Beck et al., 1981) and three times BW during running (Engsberg et al., 1991).

The maximum GRFs associated with jumping in children are similar in magnitude to those reported in older individuals. Adults produce GRFs three times body weight during running (Cavanagh and LaFortune, 1980). Low impact aerobics (where one foot is in contact with the ground at all times) produce GRFs of 1.5 BW, whereas high impact aerobics generates GRFs from 2 to 3.5 BW (Michaud et al., 1993). The upper range of landing GRFs arise when gymnasts land from the horizontal bars at 8.2 to 11.6 times BW (Ozguven and Berme, 1988) and from elite triple jumpers, who have GRFs over 15 times BW, during the 'step' phase of that event (Perttunen et al., 2000).

In the present pediatric study, the PJ landings and CMJ produced the highest MF and MRF as well as the highest impulses. The similarity of these variables between the two jumps is to be expected, as both jumps were maximal in nature. Furthermore, MRF and MF are interrelated, jumps with high MF tend to also have a high MRF and vice versa. In addition, the jumps that produced the highest impulses were the DJs. The impulse for the CMJ was not calculated. However, we would expect that the CMJ would be similar in value to the DJs as well, given the similarities in MF and MRF. The higher impulses in the DJs are likely due to the higher maximum forces during the jumps over a similar period of time. Also the time to maximum force tends to increase as the MFs decreases. Even though all these biomechanical variables are linked together, they provide us with valuable information about the jumps. For example, a short time to maximum force would indicate a landing with not much force attenuation, whereas a longer time to MF would indicate a possible attenuation of landing GRFs while holding MF constant.

There were large ranges for the biomechanical parameters. Possible sources of variability might include: varying interpretation of the instructions by the subject, arousal levels of the subject, previous jump experience, and feedback to the subject. During data collection, it should be noted that the subjects were in a new environment. Upon arrival to the laboratory, the subjects were familiarized with the operation of the force platform and its output on the computer display prior to data collection. This may partially explain the wide ranges for the biomechanical variables.

Potential energy is defined as [PE = (mg) * h], where mg is gravitational force and h is height of the centre of mass from a reference line. For a given object, PE is proportional to height as gravitational attraction is constant. This potential energy is transformed to kinetic energy during a drop. Upon landing, the velocity must return to zero before push off can occur. Thus it was not a surprise that higher DJs result in a greater maximum force than jumps with less elevation. However, the relationship between MF and PE was not linear, the results of the present study imply that children may use different landing strategies for the different maximal jumps. Landings from higher levels contained more potential energy, yet the landing forces were similar with several jumps. This may be one of the landing strategies used by the subjects to reduce landing forces.

Landing strategies

While landing from a jump, there are many variations between subjects in the magnitude of the peak force over the first 150-200 ms after impact (Lees, 1981). Extreme cases can be classified as hard or soft landings, which describe the magnitude of peak forces during landing. During hard landing after impact, where the upper body and legs are kept fairly rigid, the time for negative acceleration of the total body is small thus creating high GRFs.

During soft landing, on the other hand, where the body is in a more flexible state and the musculature is correctly pre-tensioned, this reduces the high peak force seen in the hard landing as the reaction to impact occurs over a longer period of time. The important features of impact landing occur in a time period shorter than reaction time (Lees, 1981). Therefore, to reduce force levels during the impact absorption phase, subjects must alter their 'motor programme' (Lees, 1981). In a survey of two groups of schoolboys mean age of 8.9 and 11.4 (n=20), there were no subjects who could produce what was described as a soft landing. The typical peak negative acceleration demonstrated by the subjects was between 40-60 m/s/s; while for adults it is only 20-30 m/s/s (Lees, 1981). Landing type was not examined in the present study but the data suggested that hard landings were mainly prevalent.

McNitt-Gray noted that with skilled athletes, during landings from jumps of increasing height, knee flexion increased significantly (McKitt-Gray, 1993). Another study showed that subjects modified their DJ landing technique according to the height of the jump (Dufek and Bates, 1990). Hoffman et al. have shown that experienced parachutists may use a different landing strategy than novice jumpers (Hoffman et al., 1997). This difference was reflected in the GRF generated during impact and a more efficient utilization of muscle power during the impact phase of the landing between advanced and novice jumpers (Hoffman et al., 1997). A study with elite gymnasts and recreational athletes looked at drop landings and showed that recreational athletes, compared to gymnasts, flexed the hip joint to a lesser degree during landings from the low height and to a greater degree during landings from the high height (McNitt-Gray, 1991). As there were no elite athletes in our group; we would expect the landings of our subjects to be similar to a recreational athletic group. Kinematic studies with children would reveal whether or not landing strategies explained differences in GRFs.

Possible mechanisms influencing forces generated by various levels of the same jump

Pre-stretching the muscles eccentrically before subsequent rapid concentric contraction causes increased muscular force during the concentric phase of the movement. This in effect increases the power exerted by the muscle. Fast stretching of a muscle stores energy in the elastic components of the muscle. This stored energy is available to the muscle only during a rapid/fast subsequent contraction (Hunter-Griffin, 1991). It is important to realize that this stored energy is lost as heat if the eccentric contraction is not followed immediately by a concentric effort. This whole process is frequently called the stretch shortening cycle and is the underlying mechanism of plyometric training.

Some jumps in our study were not different in maximum GRF, even though there were different levels of intensity (JJ and S-S). This suggests that the energy was being stored and utilized in some fashion. The present study found that GRFs were similar between different maximal jumps and between levels of the same jump. This can be explained by the different jumping techniques involved in each jump. During fast and repeated jumping, the landing and take-off are fused together because the action is fast enough to exploit the absorption of elastic energy that occurs during landing and is reutilized during take-off (McNitt-Gray, 1993). The repeated submaximal jumps (e.g. JJ_{submax} and $S\text{-}S_{10}$) of the present study were of this nature. The force time curves (Figure 4.2 and 4.4) show that subjects landed and pushed off in a short period of time. The short time period available to begin the next jump prevented subjects from 'catching' themselves and softening the landing before jumping again. The plyometric nature of the DJs may also explain the high landing forces.

In our study, for the maximal jumping jack, the subjects land and flex their knees and catch themselves as they prepare to jump as high as they can. The JJ_{max} jumps produces GRFs with an initial landing peak followed by a reduction in force before the next peak, where the muscles are likely active and pushing off. This pause before the muscles are pushing off may eliminate the stretch shortening cycle benefit. The JJ_{submax} force time curve reveals a much different curve. The landings for JJ $_{submax}$ do not have a distinct landing and take-off phase, there is only one peak force for each jump. This suggests that the stretch shortening cycle may be active during this time, as the landing and take off are combined. Furthermore, the time to maximum force is shorter for the JJ $_{submax}$, indicating less attenuation of landing forces. The storage and utilization of elastic energy may be typical for this type of jump. The range of muscle lengthening or shortening is very small in hopping and the plantar flexors are the major, if not sole, contributors to the bouncing-type action (Fukashiro and Komi, 1987).

Fukashiro and Komi (1987) analyzed joint moments during three different jumps (squat jump, hopping and CMJ, of interest here are the latter two). They found that hopping produced the greatest peak moment at the ankle followed by the knee and then the hip. For the CMJ jump, the greatest moments were at the hip followed by the knee and then at the ankle. They concluded that CMJ movements depended mainly on hip extensors, whereas the movement in hopping depends primarily on the ankle plantar flexors. In hopping, they also found that the mechanical energy was lower than CMJ, however, the GRF was greater. Fukashiro and Komi noted that the differing maximum GRFs and energy expenditure indicate that the stretch shortening cycle plays an important role in the storage and utilization of elastic energy in hopping but not for the CMJ. This saved energy, as the energy from the landing was partially stored and released. We might expect similar results with the JJ $_{submax}$ and JJ $_{max}$ jumps. For our jumps, the JJ_{max} jump required the subjects to bend their knees and jumped as high as they can, while the JJ $_{submax}$ jump required the subject to perform JJs in a hopping fashion at the own height and rate. We conclude that the JJ $_{max}$ jump is like a CMJ and the JJ $_{submax}$ jump is like hopping. It seems possible that JJ $_{submax}$ would be a more osteogenic jump than JJ $_{max}$ as the utilization of the stretch shortening cycle would place high forces on the bones.

Bobbert et al. reported that moments and power output about the knee and ankle joints reached larger values during the DJs than CMJ (Bobbert et al., 1987). They determined that during the CMJ, the distance over which the body's centre of mass moved downward and upward was greater than the DJs. This was attributed to greater flexion angles at the hip and knee joints during the downward motion. DJs moved through a smaller vertical range than CMJ that resulted in a shorter push off phase (Bobbert et al, 1987) and they did not jump as high. In our study, we noticed that the flight time for the CMJ was significantly greater than DJ $_{50}$, we would expect that our DJs also moved through a smaller vertical range and would have a shorter push of phase compared to the CMJ.

6.2. Gender Differences

In the present study, boys generated significantly higher rate of force and maximum force (JJ_{max}, JJ_{submax}, CMJ, PJs, and DJs) than girls. Boys also jumped further (long jump) and higher (vertical jump) than girls. These findings are consistent with sex-related differences in development of motor performance at this age group. Malina and Bouchard (1991) have shown that at the onset of the adolescent growth spurt (ages 10 to 12 on average) differences in motor performance become evident, generally in favor of the male. Before puberty, males tend to outperform females on selected tasks of running, throwing, and jumping. Females, on the other hand, excel in tasks that require fine motor control such as hopping and skipping (Malina and Bouchard, 1991).

Generally at this age (10 yrs) boys have marginally greater muscle mass and less body fat than girls. This may partially explains the greater jump performance in boys (Malina and Bouchard, 1991). However, there were no significant differences in fat mass, lean mass, height or weight between genders in the present study that may explain the gender differenencs. Limb lengths and breadths were not measured, so we do not know if there were any differences in limb lengths that may explain the differences in dynamic power, therefore, the explanation for the gender difference in dynamic power, maximum GRF, and maximum rate of force is not known.

However, as tasks that require a higher degree of skill can be improved with practice one could speculate that boys spend more time in physical activities that involve running and jumping. Such a difference in activity, if proven, could partly explain the gender differences found in our study.

6.3. *Jumps and Bone Mineral*

In the present cross-sectional study, GRFs and rates of force were not correlated with bone mineral density at the total proximal femur or its subregions. Although the GRFs experienced upon landing may reflect the loading patterns of individual children, a strong link between GRF and proximal femur bone mineral density has not previously been established. Although, in theory, if habitual loading forces are 3 - 5 times BW, an osteogenic response might be initiated, we have no clear indication of the daily loads imposed on the skeletons of this cohort. What we do know is that maximal forces from the plyometric jumps were higher than forces experienced during walking (1.1 BW) and running (3 BW) (Cavanagh and Lafortune, 1980). It has been shown that higher forces at the feet are transmitted up along the lower limb to the hip, where forces may be up to 10 times BW (Burdett, 1992). In a recent study of adolescent girls (aged 14.6 years) who engaged in a nine-month plyometric program (Witze and Snow, 2000), the authors reported a significant increase (compared to zero) at the greater trochanter for the exercise group compared to controls. Also there was a trend toward greater bone mass for the whole body, femoral neck, lumbar spine, and femoral shaft in the exercise group. They concluded that plyometric jumping may a good method for osteogenic stimulus.

The positive associations we observed between hours of loaded physical activity and bone mineral, support similar relationships that have been previously reported in cross-sectional studies of young elite gymnasts (Robinson et al., 1995, Bass et al., 2000) and between high and low active groups of children in a normally active range (Bailey et al., 1999). Weight bearing activities have generally been considered to have a positive effect on bone health in both young and adult populations. Our correlations of loaded PA and the parameters (r=0.30 on average) were slightly lower, but in the same range as those reported by others (0.39-0.47) (Bailey et. al, 1999). Differences between studies may reflect the relatively similar physical activity patterns of our participants. The correlations may seem low, but are actually quite good considering other factors like hereditary and nutrition also plays a role in bone mineral. All of the children reported some level of physical activity in their day-to-day lives (4.53-6.95 hours per week, 95% CI).

In the present study, the measures of lower limb dynamic power (long jump and vertical jump) correlated significantly with FN, PF BMD, and trochanteric BMD, respectively. Several large muscle groups, including the gluteal muscles, utilized in these tests of dynamic power attach at the proximal femur and resultant stresses would be imposed at that site during mechanical loading.

In hierarchical regression lean mass and long jump were significant predictors of aBMD at the proximal femur. Others have developed similar predictive equations and muscle mass accounted for 10 - 58% of the variance on average (Morris et al., 1997). In growing children, lean mass was a stronger predictor than fat mass of absolute BMC/aBMD, and changes in lean mass was strongly correlated with change in BMC/aBMD (Morris et al., 1997). The link between muscle and bone is not novel or surprising as these results have been reported consistently in both children (Morris et al., 1997) and adult (Heinonen et al., 1996) studies. It appears that muscles are responsible for tensile as well as compressive forces on bones during mechanical loading.. In animal studies, by changing only one feature of the loading environment, researchers have established a relationship between strain magnitude, rate, distribution and cycles and bone (re) modeling. Animal studies have shown that the most osteogenic activities are high in magnitude and unusual in their distribution. However, in a natural situation, the strain related stimulus is likely an amalgamation of the components of the dynamic strain environment (Lanyon, 1984).

Possible relationship between GRFs and mechanical loading at the hip

As previously stated, implant forces at the hip from gravitational force and muscle tension were 2.5 to 3.0 times the GRFs during *take-off* from the ground in a jump (Bassey et al., 1997). This was attributed to the contraction of the large extensor muscles of the knee, which are the source of power for take-off and protective braking force on landing. These muscles are attached across the femur and apply a compressive force to the shaft.

During *landing* from a jump, the implant forces exceeded the GRFs by 50%. They concluded that the body's centre of gravity is above the femur, so absorption of energy by soft tissues would contribute to the reduction of GRFs relative to implant force. Regression analysis for take off from slow jumps showed that 98% of the variance of the hip implant forces was due to GRF and action of the vastus lateralis (Bassey et al., 1997). It was also found in this study that wearing resilient trainers didn't reduce implant forces or rates of rise. In another study with hip prostheses, walking at 1 km/h produced 2.8 BW at the hip and 4.8 BW walking at 5 km/h (Bergmann et al., 1993). Walking normally produces GRF of >1 BW at the foot. They also found that jogging raised forces at the hip to about 5.5 BW. High GRFs, associated with DJs for example, will likely produce higher forces at the hip than jumps with lower GRFs.

As the hip is the clinically relevant site of osteoporotic fracture in older individuals, we briefly speculate as to likely GRFs at the hip in children performing jumps. GRFs are transmitted from the foot, along the lower limbs, and to the hips through a series of action-reaction forces. The transmission of these forces along the long bones of the leg has been modeled as a system of three rigid links (Figure 2.5). Based on this model and the two previous studies that looked at instrumented hip implants and GRFs, from our GRF data, we can conjecture that the forces at the hip would be in the range of 3 to 15 times BW, which may be beneficial to bone formation due to high forces. However, it must be noted that this model does not take into account the surrounding muscles and ligaments that span the joints, therefore our estimates provide a minimum value.

Although animal studies provide insight into the type of loading that is effective for increasing bone mineral accrual, the "optimal" osteogenic intervention program for children had yet to be clearly identified. In our study, we have seen maximum GRFs from 2 to over 5 times BW.

6.4 Summary

To recap and to take us back to the original hypotheses, the primary purpose of this study was to measure and describe the GRFs from a variety of jumps and the GRFs from the same jump at different levels of intensity in a group of normally active children aged 9 – 11.

Hypotheses:

1) DJ the higher jumps produced higher maximum GRFs, this is in agreement with the hypothesis. However, for the S-S and JJ jumps there were no differences in maximum GRFs, which disagrees with the hypothesis. There may be attributed to differences in landing strategies that for the same jump at different levels of intensity as previously discussed.
2) For different jumps there were different maximum GRFs, this is in agreement with the hypothesis (Table 5.1, page 49).
3) For different jumps there were different time to maximum GRFs, this is in agreement with the hypothesis (Table 5.1, page 49).
4) For time to maximum force and impulses there were differences between different jumps, supporting the hypothesis (Table 5.1, page 49).
5) There were no differences in height, mass, lean mass, and fat mass, in agreement with the hypothesis. It was observed that there were gender differences in dynamic power, maximum GRF and maximum rate of force, refuting the hypothesis. The explanation for the gender difference in dynamic power, maximum GRF, and maximum rate of force are not known
6) Loaded PA correlated positively with aBMD in agreement with the hypothesis.
7) PA correlated positively with dynamic measure of power in agreement with the hypothesis.

General

This study has demonstrated, that jumps with different levels of intensity do not necessary elicit different MFs. This may, in part, be due to different strategies and techniques for landing that affect the landing GRFs, rate of force, impulse, and time to maximum. These different variables would be expected to influence force transmission along the leg to the hip.

Landing GRFs vary significantly between jumps and range from 2 to 5 times BW. Maximum landing forces were, however, not significantly different for the JJ jumps and S-S jumps at different levels of intensity. In contrast, for the same jump at varying intensity, rates of force, and impulses varied, suggesting that landing characteristics did not remain constant.

Loaded PA times correlated significantly with measured subregions at the hip. Physical performance parameters (long jump) correlated significantly with BMD at the FN and for total PF sites, while vertical jump correlated significantly with BMD at the trochanter. Lean mass and long jump were significant predictors of the bone parameters. Others have shown that muscles are responsible for forces acting on bone during mechanical loading.

6.5 Conclusion

The optimal or most osteogenic intervention program for children has yet to be defined. Recently there has been evidence that increased activity during pre and early puberty stimulates bone mineral accretion. With minor changes to existing physical education programs, these intervention programs that prompt this response have already been put into place. This study measured the GRFs of various jumping activities. This is important step in determining effective bone-building programs. The biomechanical parameters assessed in the present study help determine if the activities are high in magnitude. In children, the 12 jumps evaluated have a variety of landing characteristics, and these novel data can be used in pediatric exercise and bone health research.

Future prospective intervention studies should be designed to focus on the loading characteristics, duration, and frequency of jumps that elicit an osteogenic response. Also future studies should concentrate on outcomes rather than bone mineral density as bone geometry, structure, size, shape, and material may also change as a result of bone loading programs.

References

1. AAHPERD. Youth fitness test manual. Reston, Va.: American Alliance for Health, Physical Education, Recreation and Dance, 1976.
2. Ashman, RB. Experimental techniques. In: *Bone Mechanics*. SC Cowin (ed). CRC: Boca Raton, FL. 1989: 75-95.
3. Ashman, RB, and Rho, JY. Elastic modulus of trabecular bone material. *Journal of Biomechics*, 1988; 21(3): 177-81.
4. Bailey, D, McKay, H, Mirwald, R, Crocker, P, and Faulkner, R. A six-year longitudinal study of the relationship of physical activity to bone mineral accrual in growing children: The University of Saskatchewan bone mineral accrual study. *Journal of Bone and Mineral Research*, 1999; 14: 1672-1679.
5. Bailey, D, Faulkner, R, and McKay, H. Growth, physical activity, and bone mineral acquisition. Exercise and Sport Sciences Reviews. J Holloszy (ed). Williams & Wilkins; 1996: 233-266.
6. Bailey D. The University of Saskatchewan Pediatric Bone Mineral Accrual Study: Bone mineral acquisition during the growing years. *International Journal of Sports Medicine*, 1997; 18: S191-S194.
7. Barr, SI and McKay, HA. Nutrition, exercise and bone status in youth. *International Journal of Sports Nutrition*, 1998; 8: 124-142.
8. Bass S, Bradney M, Pearce G, Hendrich E, Inge K, Stuckey S, Lo SK, Seeman E. Short stature and delayed puberty in gymnasts: influence of selection bias on leg length and the duration of training on trunk length. *Journal of Pediatrics*. 2000 Feb; 136(2):149-55.
9. Bassey, E, Littlewood, J, and Taylor, S. Relations between compressive axial forces in an instrumented massive femoral implant, ground reaction forces, and integrated electomyographs from vastus lateralis during various 'osteogenic' exercise. *Journal of Biomechanics*, 1997; 30: 212-223.
10. Bassey, RJ and Ramsdale, SJ. Increase in femoral bone density in young women following high-impact exercise. *Osteoporosis International*, 1994; 4: 72-75.
11. Beck, RJ, Andriacchi, TP, Kuo, KN, Fermier, RW, and Galante, JO. Changes in the gait pattern of growing children. *Journal of Bone and Joint Surgery*, 1981; 63A(9): 1452-1457.
12. Bergmann, G, Graichen, F, and Rohlmann, A. Hip joint loading during walking and running, measured in two patients. *Journal of Biomechanics*, 1993; 26(8): 969-990.
13. Biewener, AA, Swartz, SM, and Bertram, JE. Bone modeling during growth: Dynamic strain equilibrium in the chick tibiotarsus. *Calcified Tissue International*, 1986; 39: 390-395.
14. Bloomfield, S. Changes in musculoskeletal structure and function with prolonged bed rest. *Medicine and Science in Sports and* Exercise, 1997; 29:197-206.
15. Bobbert, MF, Huijing PA, Van Ingen Schenau GJ. Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine and Science in Sports and Exercise*, 1987; 19: 332-338.
16. Bobbert MF, Huijing PA, and GJ Van Ingen Schenau. Drop Jumping. II. The influence of dropping height on the biomechanics of drop jumping. *Medicine and Science in Sports and Exercise*, 1987; 19(4): 339-346.
17. Boppart, MD, Kimmel, DB, Yee, JA, Cullen, DM. Time course of osteoblast appearance after in vivo mechanical loading. *Bone*, 1998; 23(5): 409-15.
18. Bradney, M, Pearce, G, Naughton, G, Sullivan, C, Bass, S, Beck, T, Carlson, J, and Seeman, E. Moderate exercise during growth in prepubertal boys: Changes in bone mass, size,

volumetric density, and bone strength: a controlled prospective study. *Journal of Bone and Miner Research,* 1998; 13(12): 1814-1821.

19. Burdett, R. Forces predicted at the ankle during running. *Medicine and Science in Sports and Exercise*, 1992; 14: 308-318.
20. Burr, DB, Schaffler, MB, Yang, KH, Lukoschek, M, Sivaneri, N, Blaha, JD, Radin, EL. Skeletal change in response to altered strain environments: is woven bone a response to elevated strain? *Bone*, 1989; 10(3): 223-33.
21. Burr, DB, Schaffler, MB, Yang, KH, Wu, DD, Lukoschek, M, Kandzari, D, Sivaneri, N, Blaha, JD, Radin, EL. The effects of altered strain environments on bone tissue kinetics. *Bone*, 1989; 10(3): 215-21.
22. Burr, D. Orthopedic principles of skeletal growth, modeling and remodeling. Carlson, D and Goldstein, S (eds.). Bone dynamics in orthodontic and orthopedic treatment. Craniodacial growth series, Vol.27 Ann Arbor, MI: Center for Human Growth and Development, 1992, 15-19.
23. Burr, DB, Milgrom, C, Fyhrie, D, Forwood, M, Nyska, M, Finestone, A, Hoshaw, S, Saiag, E, and Simkin, A. In vivo measurement of human tibial strains during vigorous activity. *Bone*, 1996; 18(5): 405-410.
24. Caine, D, Howe, W, Ross, W, and Bergman, G. Does repetitive physical loading inhibit radial growth in female gymnasts? *Clinical Journal of Sports Medicine*, 1997; 7: 302-308.
25. Carter, D, Bouxsein, M and Marcus, R. New approaches for interpreting projected bone densitometry data. *Journal of Bone and Mineral Research*, 1992; 7: 137-145.
26. Carter, DR, Fyhrie, DP, and Whalen, RT. Trabecular bone density and loading history: Regulation of connective tissue biology by mechanical energy. *Journal of Biomechanics*, 1987; 20: 785-794.
27. Carter, DR and Hayes, WC. Bone compressive strength: The influence of density and strain rate. *Science*, 1976; 194: 1174-1176.
28. Cassell C, Benedict M, Specker, B. Bone mineral density in elite 7- to 9-yr-old female gymnasts and swimmers. *Medicine and Science in Sports and Exercise*, 1996; 28(10): 1243-1246.
29. Cavanaugh, DJ, and Cann, CE. Brisk walking does not stop bone loss in postmenopausal women. *Bone*, 1988; 9: 201-204.
30. Cavanagh, PR and Lafortune, MA. Ground reaction forces in distance running. *Journal of Biomechanic*, 1980; 13: 397-406.
31. Chow, JW, Wilson, AJ, Chambers, TJ, Fox, SW. Mechanical loading stimulates bone formation by reactivation of bone lining cells in 13-week-old rats. *Journal of Bone and Minereral Research*, 1998; 13(11): 1760-7.
32. Chow, R. Harrison, JE, and Notarius, C. Effect of two randomized exercise programmes on bone mass of healthy postmenopausal women. *British Medical Journal*, 1987; 295: 1441-1444.
33. Compston, JE. Bone density: BMC, BMD, or Corrected BMD? *Bone*, 1995; 16(1): 5-7.
34. Conroy, BP, Kraemer, WJ, Maresh, CM, Fleck, SJ, Stone, MH, Fry, AC, Miller, PD, and Dalsky, GP. Bone mineral density in elite junior Olympic weightlifters. *Medicine and Science in Sports and Exercise*, 1993; 25: 1103-1109.
35. Cullen, DM, Smith, RT, Akhter, MP. Time course for bone formation with long-term external mechanical loading. *Journal of Applied Physiology*, 2000; 88(6): 1943-8.
36. Currey, J. The mechanical adaptations of bone. Princeton NJ, Princeton University Press, 1984.
37. Duda, GN, Heller, M, Albinger, J, Schulz, O, Schneider, E, and L Claes. Influence of muscle forces on femoral strain distribution. *Journal of Biomechnics*, 1998; 31: 841-846.

38. Dufek, JS and Bates, BT. The evaluation and prediction of impact forces during landings. *Medicine and Science in Sports and Exercise*, 1990; 22(3): 370-377.
39. Duncan, R, and Turner, C. Mechanotransduction and the functional response of bone to mechanical strain. *Calcified Tissue International*, 1995; 57: 344-358.
40. Engsberg, JR, Lee, AG, Patterson, JL, and Harder, JA. External loading comparisons between able-bodied and below-knee-amputee children during walking. *Archives of Physical Medicine and Rehabilitation*, 1991; 72:657-661.
41. Eriksen, E, Gundersen, H, Melsen, F, and Mosekilde, L. Reconstruction of the formative site in iliac trabecular bone in 20 normal individuals employing a kinetic model for matrix and mineral apposition. *Metabolic Bone Disease & Related Research*. 1984; 5:243-252.
42. Faulkner, RA, Bailey, DA, Drinkwater, DT, Wilkinson, AA, Houston, CS, and McKay, HA. Regional and total body bone mineral content, bone mineral density and total body tissue composition in children 8-16 years of age. *Calcified Tissue International*, 1993; 53:7-12.
43. Fehling, P, Alelkel, L, Clasey, J, Rector, A, and Stillman, R. A comparison of bone mineral densities among female athletes in impact loading and active loading sports. *Bone*, 1995; 17: 205-210.
44. Figueroa-Colon, R, Mayo, MS, Treuth, MS, Aldridge, RA, and Weinser, RL. Reproducibility of dual-energy X-ray absorptiometry measurements in prepubertal girls. *Obesity Research*, 1998; 6: 262-267.
45. Forwood, M and Burr, D. Physical activity and bone mass: exercise in futility? *Bone* Mineral, 1993; 21: 89-112.
46. Forwood, MR and Turner, CH. Skeletal adaptations to mechanical usage: Results from tibial loading studies in rats. *Bone*, 1995; 17(4): s197-s205.
47. Frost, H. Why do marathon runners have less bone than weight lifters? A vital-biomechanical view and explanation. *Bone*, 1997; 20:183-189.
48. Frost, HM. Skeletal structural adaptations to mechanical usage: Redefining Wolff's Law: The bone modeling problem. *The Anatomical Record,* 1990; 226: 403-413.
49. Frost, HM. Skeletal structural adaptations to mechanical usage: Redefining Wolff's Law: The bone remodeling problem. *The Anatomical Record,* 1990; 226: 414-422.
50. Frost, HM. Vital biomechanics: proposed general concepts for skeletal adaptations to mechanical usage. *Calcified Tissue International*. 1988; 42: 145-156.
51. Frost, HM. Bone "mass" and the "mechanostat": A proposal. *The Anatomical Record*, 1987 219: 1-9.
52. Fukashiro, S and Komi, PV. Joint Moment and Mechanical Power Flow of the Lower Limb During Vertical Jump. *International Journal of Sports Medicine*, 1987; 8: s15-21.
53. Grimston, S, Wilows, N and Hanley, D. Mechanical loading regime and its relationship to bone mineral density in children. *Medicine and Science in Sports and* Exercise, 1993; 25: 1203-1210.
54. Heinonen A. Studies in sport, physical education and health. Exercise as an osteogenic stimulus. University Library of Jyvaskyla, 1997.
55. Heinonen, A, Sievanen, H, Kannus, P, and Oja P. High-impact exercise and bones of growing girls. *Osteoporosis International,* in press.
56. Heinonen, A, Oja, P, Kannus, P, Sievanen, H, Manttari, A, and Vuori, I. Bone mineral density of female athletes in different sports. *Bone Mineral,* 1993; 23: 1-14.
57. Heinonen, A, Oja, P, Sievanen, H, Pasanen, M, and Vuori, I. Effect of two training regimens on bone mineral density in healthy perimenopausal women: A Randomized Controlled Trial. *Journal of Bone and Mineral Research,* 1998; 13(3): 483-490.
58. Heinonen, A, Sievanen, H, Kannus, P, Oja, P, and Vuori, I. Effects of unilateral strength training and detraining on bone mineral mass and estimated mechanical characteristics of the

upper limb bones in young women. *Journal of Bone and Mineral Research,* 1996; 11(4): 490-501.

59. Hillam, RA and Skerry, TM. Inhibition of bone resorption and stimulation of formation by mechanical loading of the modeling rat ulna in vivo. *Journal of Bone and Mineral Research,* 1995; 10(5): 683-689.
60. Hoffman, JR, Liebermannm DM and Gusis, A. Relationship of leg strength and power to ground reaction forces in both experienced and novice jump trained personnel. *Aviation, Space, and Environmental Medicine,* 1997; 68(8): 710-714.
61. Hunter-Griffin, LY. Athletic Training and Sports Medicine. American Academy of Orthopaedic Surgeons, 2nd ed., Rosemont, IL, 1991.
62. Jarvinen, T, Kannus, P, Sievanen, H, Jolma, P, Heinonen, A and Jarvinen, M. Randomized controlled study of effects of sudden impact loading on rat femur. *Journal of Bone and Mineral Research*, 1998; 13(9): 1475-1482.
63. Jaworski, M, Lebiedowski, M, Lorenc, RS, and Trempe, J. Ultrasound bone measurements in pediatric subjects. *Calcified Tissue International*, 1995; 56: 368-371.
64. Johnston, C and Slemenda, C. Risk assessment: Theoretical considerations. *The American Journal of Medicine*, 1993; 5a: 2s-5s.
65. Jones, H, Priest, J, and Hayes, W. Humeral, hypertrophy in response to exercise. *The Journal of Bone and Joint Surgery,* 1977; 59a: 204-208.
66. Kannus, P, Haapasalo, H, Sankelo, M, Sievanen, H Pasanen, M, Heinonen, A, Oja, P, and Vuori, I. Effects of starting age of physical activity on bone mass in dominant arm of tennis and squash players. *Annals of Internal Medicine*, 1995; 23: 27-31.
67. Keaveny, TM, Wachtel, EF, Ford, CM, and Hayes, WC. Differences between the tensile and compressive strengths of bovine tibial trabeculaar bone depend on modulus. *Journal of Biomechanics*, 1994; 27: 1137-1146.
68. Keller, TS and Spengler, DM. Regulations of bone stress in the immature and mature rat femur. *Journal of Biomechanics*, 1989; 22: 1115-1127.
69. Kelly, P, Hopper, J, Macaskill, G, Pocock, N, Sambrook, P, and Eisman, J. Genetic factors in bone turnover. *The Journal of Clinical Endocrinology & Metabolism*, 1991; 72: 808-813.
70. Kimmel, DB. A paradigm for skeletal strength homeostasis. *Journal of Bone and Mineral Research*, 1993: 515-522.
71. Komi, PV. Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. in Terjung RL (ed): *Exercise and Sport Sciences Reviews*, Vol. 12. Lexington, Massachusetts, The Collamore Press, 1984; 81-121.
72. Kujala, UM, Viljanen, T, Taimela, S, and Viitasalo, JT. Physical activity, VO_{2max}, and jumping height in an urban population. *Medicine and Science in Sports and Exercise,* 1994; 26(7): 889-895.
73. Lanyon, LE and Rubin, CT. Static vs dynamic loads as an influence on bone remodeling. *Journal of Biomechanics*, 1984; 17(12): 897-905.
74. Lanyon, LE. Functional strain in bone tissue as an objective and controlling stimulus for adaptive bone remodeling. *Journal of Biomechanics*, 1987; 20: 1083-1093.
75. Lanyon, LE. Control of bone architecture by functional load bearing. *Journal of Bone and Mineral Research*, 1992; 7(2): s369-s375.
76. Lanyon, LE. Functional strain as a determinant for bone remodeling. *Calcified Tissue International*, 1984; 36: s56-s61.
77. Lanyon, LE. Using functional loading to influence bone mass and architecture: Objectives, mechanisms, and relationship with estrogen of the mechanically adaptive process in bone. *Bone,* 1996; 18(1): s37-s43.

78. Lanyon, LE, Magee, PT, and Baggott, DG. The relationship of functional stress and strain to the processes of bone remodeling. An experimental study on the sheep radius. *Journal of Biomechics*, 1979; 12(8): 593-600.
79. Lees, A. Methods of impact absorption when landing from a jump. *Engineering in Medicine*, 1981; 10: 207-211.
80. Lotz, J and Hayes, WC. The use of quantitative computed tomography to estimate risk of fracture of the hip in falls. *Journal of Bone and Joint Surgery (American volume)*, 1990; 72: 689-700.
81. Malina and Bouchard, *Growth, maturation, and physical activity*. Champaign, IL: Human Kinetics, 1991.
82. Martin, R and Burr, D. Structure, function, and adaptation of compact bone. New York: Raven Press. 1989.
83. Matkovic, V Jelic, T, Wardlaw, GM, Ilich, JZ, Goel, PK, Wright, JK, Andon, MB, Smith KT, Heaney, RP. Timing of peak bone mass in Caucasian females and its implication for the prevention of osteoporosis- inference from a cross-sectional model. *The Journal of Clinical Investigation,* 1994; 799-808.
84. McCulloch, RG, Bailey, DA, Whalen, R, Houston, CS, Faulkner, RA, and Craven, B. Bone density and bone mineral content of adolescent soccer athletes and competitive swimmers. *Pediatric Exercise and Science*, 1992; 4: 319-330.
85. McKay, HA, Petit, MA, Schutz, RW, Prior, JC, Barr, SI, and Khan, KM. Augmented trochanteric bone mineral density after modified physical education classes: A randomized school-based exercise intervention study in pre- pubescent and early- pubescent children. *The Journal of Pediatrics*, 2000; 136: 156-162.
86. McMahon T. Muscles, reflexes and locomotion. Princeton, NJ: University Press, 1984.
87. McNitt-Gray, JL. Kinetics of the lower extremities during drop jump landings from three heights. *Journal of Biomechanics*, 1993; 26: 1037-1046.
88. McNitt-Gray, JL. Kinematics and impulse characteristics of drop landings from three-heights. *International Journal of Sport Biomechanics*, 1991; 7: 201-224.
89. Michaud, TJ, Rodriguez-Zayas, J, Armstrong, C, and Hartnig, M. Ground reaction forces in high impact and low impact aerobic dance. *Journal of Sports Medicine and Physical Fitness*. 1993; 33(4): 359-366.
90. Milgrom, C, Finestone, A, Levi, Y, Simkin, A, Ekenman, I, Mendelson, S, Millgram, M, Nyska, M, Benjuya, N, and D Burr. Do high impact exercises produce higher tibial strains than running? *British Journal of Sports Medicine*. 2000; 34(3): 195-199.
91. Milgrom, C, Durr, D, Fyhrie, D, Hoshaw, S, Finestone, A, Nyska, M, Davidson, R, Mendelson, S, Giladi, M, Liebergall, M, Lehnert, B, Voloshin, A, and Simkin, A. A comparison of the effect of shoes on human tibial axial strains recorded during dynamic loading. *Foot & Ankle International*. 1998; 19(2): 85-90.
92. Morris, F, Naughton, G, Gibbs, J, Carlson, J and Wark, J. Prospective 10-month exercise intervention in pre-menarcheal girls: positive effects on bone and lean mass. *Journal of Bone and Mineral Research*, 1997; 12: 1453-1462.
93. Mosekilde, L. Vertebral structure and strength in vivo and in vitro. *Calcified Tissue International*. 1993; 53: s121-s126.
94. Mosley, JR and Lanyon, LE. Adaptive modeling in response to controlled non-invasive loading of the rat ulna in vivo. *Ophthalmological Society of the United Kingdom*, 1994; 19: 33.
95. Neil, JL, Demos, TC, Stone, JL, Hayes, WC. Tensile and compressive properties of vertebral trabecular bone. *Trans.* 29th ORS: 334.

96. Nigg, BM Biomechanics, load analysis and sports injuries in the lower extremities. *Sports Medicine,* 1985; 2: 367-379.
97. Nordin, M and Frankel, VH. Biomechanics of bone. Basic biomechanics of the musculoskeletal system. Edited by Nordin, N and Frankel, VH. Philadelphia, Lea & Febiger, 1989: 3-30.
98. O'Connor, JA, Lanyon, LE, and Macfie, H. The influence of strain rate on adaptive bone remodeling. *Journal of Biomechanics*, 1982; 15: 767-781.
99. Ogden, JA. Injury to the growth mechanisms of the immature Skeleton. *Skeletal Radiology*, 1981; 6: 237-253.
100. Ozguven, HN and Berme, N. An experiment and analytical study of impact forces during human jumping. *Journal of Biomechanics*, 1988; 21(12): 1061-1066.
101. Parfitt, A. The physiologic and clinical significance of bone histomorphometric data. bone histomorphometry: techniques and interpretations. R Recker (ed). CRC Press: Boca Raton. 1983: 143-152.
102. Parfitt, A. The cellular basis of bone remodeling: the quantum concept reexamined in light of recent advances in the cell biology of bone. *Calcified Tissue International*, 1984; 6: s37-s45.
103. Perttunen, J, Kyrolainen, H, Komi, P, and Heinonen, A. Biomechanical loading in the triple jump. *Journal of Sports Sciences*, 2000; 18: 363-370.
104. Raab DM, Smith, EL, Crenshaw, TD, and Thomas, DP. Bone mechanical properties after exercise training in young and old rats. *Journal of Applied Physiology*, 1990; 68(1): 130-134.
105. Raab-Cullen, DM, Akhter, MP, Kimmel, DB, and Recker, RR. Bone response to alternate-day mechanical loading of the rat tibia. *Journal of Bone and Mineral Research*, 1994; 9(2): 203-211.
106. Reilly, DT and Burstein, AH. The elastic and ultimate properties of compact bone tissue. *Journal of Biomechanics*, 1975; 8: 393-405.
107. Reilly, DT and Burstein, AM. The mechanical properties of cortical bone. *The Journal of Bone and Joint Surgery*, 1974; 56a: 1001-1022.
108. Ricard, MD and Veatch, S. Effect of running speed and aerobic dance jump height on vertical ground reaction forces. *Journal of Applied Biomechanics*, 1994; 10: 14-27.
109. Rice, S, Blimkie, CJR, Webber, CE, Levy, D, Martin, J, Parker, D, and Gordon, CL. Correlates and determinants of bone mineral content and density in healthy adolescent girls. *Journal of Physiology and Pharmacology*, 1993; 71: 923-930.
110. Rico H and Revilla M. Bone mass, body weight, and seasonal bone changes. *Calcified Tissue International.* 1994; 54: 523-524.
111. Riegger, CL. Mechanical properties of bone. In Orthopaedic and Sports Physical Therapy. Edited by JA Gould and GJ Davies. St. Louis, C.V. Mosby Co. 1985: 3-49.
112. Robinson, T, Snow-Harter, C, Taafe, D, Gillis, D, Shaw, J, and Marcus, R. Gymnast exhibit higher bone mass than runners despite similar prevalence of amenorrhea and oligomenorrhea. *Journal of Bone and Mineral Research*, 1995; 19(1): 26-35.
113. Romaines, GJ: Cunningham's Textbook of Anatomy. London, Oxford University Press, Inc., 1972: 172, 240-241, 663.
114. Rubin, CT and Lanyon, LE. Regulation of bone formation by applied dynamic loads. *The Journal of Bone and Joint Surgery*, 1984; 66A: 397-402.
115. Rubin, CT and Lanyon, LE. Regulation of bone mass by mechanical strain magnitude. *Calcified Tissue International*, 1985; 37: 411-417.
116. Rubin, CT and McLeod, KJ. Promotion of bony ingrowth by frequency specific, low amplitude mechanical strain. *Clinical Orthopaedics and Related Research,* 1994; 298: 165-174.

117. Sargent, DA. The physical test of a man. *American Physical Education Review*, 1921; 26(4): 188-194.

118. Sievanen, H, Kannus, P, Nieminen, V, Heinonen, A, Oja, P, and Vuori, I. Estimation of various mechanical characteristics of human bones using dual energy x-ray absorptiometry: methodology and precision. *Bone*, 1996; 18: 17s-27s.

119. Sievanen, H, Uusi-Rasi, K, Heinonen, A, Oja, P, and Vuori, I. Disproportionate, age-related bone loss in long bone ends: a structural analysis based on dual-energy X-ray absorptiometry. *Osteoporosis International,* 1999; 10(4): 295-302.

120. Simonsen, EB, Dyhre-Poulsen, P,Viogt, M, Aagaard, P, Sjogaard, G and Bojsen-Moller, F. Bone-on-bone forces during loaded and unloaded walking. *Acta Anatomica*, 1995; 152: 133-142.

121. Skerry, TM and Lanyon, LE. Interruption of disuse by short duration walking exercises does not prevent bone loss in the sheep calcaneous. *Bone*, 1995; 16: 269-274.

122. Sledge, C and Rubin, C. Formation and Resorption of bone. W. Kelley, E. Harris, S. Ruddy, and C. Sledge (eds.) Textbook of Rheumatology. Philadelphia: W.B. Saunders, 1989, 54-75.

123. Slemenda, CW and Johnston, CC. High intensity activities in young women: Site specific bone mass effects among figure skaters. *Bone Mineral*, 1993; 20:125-132.

124. Slemenda, CW, Reister, TK, Hui, SL, Miller, Z, Christian, JC, Johnston, CC. Influences on skeletal mineralization in children and adolescence: evidence for varying effects of sexual maturation and physical activity. *Journal of Pediatrics*, 1994; 125: 201-207.

125. Snow-Harter CM, Bouxsein, ML, Lewis, BT, Carter, DR, and Marcus, R. Effects of resistance and endurance exercise on bone mineral status of young women: A randomized exercise intervention trial. *Journal of Bone and Mineral Research*, 1992; 7(7): 761-769.

126. Sogaard, CH, Danielsen, CC, Thorling, EB, and Mosekilde, L. Long-term exercise of young and adult female rats- effect on femoral neck biomechanical competence and bone structure. *Journal of Bone and Mineral Research*, 1994; 9: 409-416.

127. Tanner JM. Growth at adolescence. Oxford: Blackwell Scientific Pub, 1955.

128. Turner, CH. Three rules for bone adaptation to mechanical stimuli. *Bone*. 1998; 23(5): 399-407.

129. Turner, CH and Burr, DB. Basic biomechanical measurements of bone: A Tutorial. *Bone*, 1993; 14: 595-608.

130. Turner, C, Takano, Y and Owan, I. Aging changes mechanical loading thresholds for bone formation in rats. *Journal of Bone and Mineral Research*, 1995; 10: 1544-1549.

131. Turner, CH, Forwood, MR, Rho, J, and Yoshikawa,T. Mechanical loading threshold for lamellar and woven bone formation. *Journal of Bone and Mineral Research*, 1994; 9: 87-97.

132. Turner, CH, Woltman, Ta, Belongia, DA. Structural changes in rat bone subjected to long term, in vivo, mechanical loading. *Bone,* 1992; 13:417-422.

133. Turner, CH. Homeostatic control of bone structure: An application of feedback theory. *Bone*, 1991; 12: 203-217.

134. Umemura, Y, Ishiko, T, Tsujimoto, H, Miura, H, Mokushi, N, and Suzuki, H. Effects of jump training on bone hypertrophy in young and old rats. *International Journal of Sports Medicine*, 1995; 16:364-367.

135. Wahner, H, Dunn, W, Brown, M, Moris, R, and Riggs, L. Comparison of dual-energy x-ray absorptiometry and dual photon absorptiometry for bone mineral measurements of the lumbar spine. *Mayo Clinic Proceedings*, 1988; 63: 1075-84.

136. Whalen, RT and Carter, DR. Influence of physical activity on the regulation of bone density. *Journal of Biomechanics*, 1988; 21: 825-837.

137. Witze, KA, and Snow, CM. Effects of plyometric jump training on bone mass in adolescent girls. *Medicine and Science in Sports and Exercise*, 2000; 32(6): 1051-1057.

138. Wolff, J. Das Gesetz der Transformation der Knochen. Berlin, Germany: A. Hirschwald.

139. Yoshikawa, T, Mori, S, Santiesteban, AJ, Sun, TC, Hafstad, E, Chen, J, and Burr, D. The effects of muscle fatigue on bone strain. *The Journal of Experimental Biology*, 1994; 188: 217-233.

140. Young, D, Hopper, JL, Nowson, CA, Green, RM, Sherwin, AJ, Kaymakci, B, Smid, M, Guest, CS, Larkins, RG and Wark, JD. Determinants of bone mass in 10 to 26 year-old females: A twin study. *Journal of Bone and Miner Research*, 1995; 10: 558-567.

Appendices

Appendix A

Pilot Study Methods and Results

Ground Reaction Force Analysis of a Variety of Jumping Activities in Growing Children

Pilot Data

Subjects

Four subjects (two males and two females) were recruited to participate in this preliminary study. Subjects were recruited from Community Sports at the University of British Columbia. The average age for the subjects was 9.54 ± 0.63 (SD) years. The average height of these subjects was 137.74 ± 4.83 cm, sitting height 74.53 ± 2.73 cm, and weight was 33.24 ± 4.54 kg. The children were all very active and participated in extra-curricular activities outside of school. All subjects were provided with full details of the testing procedures, and an expectation of the time required (approximately 1 ½ hours) for their participation. Subjects and parents had an opportunity to ask questions about the study. A written informed consent was completed before testing commenced (Appendix a), in compliance with the University of British Columbia ethics (Appendix b)

Pilot Study Methods

Measurements

Anthropometry: Height (without shoes) was recorded to the nearest (mm) using a stadiometer. Height measurements were taken as the distance from the floor to the vertex of the head when the head is held in the Frankfort plane. Two measurements were taken unless values are more than 0.4 cm for height, then a third measure were taken. The average of the two values were used or the median of the three values were used as the final value.

Ground Reaction Force: the same investigator acquired the ground reaction force data over two days. The force platform is a solid metal plate that rests on four piezoelectric transducers and is set into the floor so that its surface is flush with the surrounding surface. The ground reaction forces was measured on a Kistler 9251A force platform (Winterthur, Switzerland). The force platform was set to acquire data at 600 Hz for a total time of 4.5 seconds. The ground reaction force was converted by an analog/digital board (type DT2821 data translation, Marlboro, MA) and interfaced to the program Peak Motus – Motion Measurement System (Peak Performance Technology, Englewood, Colorado). Weight was recorded by having the subject stand motionless on the force platform.

Procedure

Participation in this project involved one testing session at the University of British Columbia Biomechanics Laboratory. Each subject was asked to wear their regular physical education clothing (preferably a T-shirt, shorts, sweat pants). The subjects were all tested with bare feet. Upon arrival at the biomechanics lab, the children were introduced to the investigators and to the lab equipment. Each subject completed an activity questionnaire (Appendix c). A data sheet was marked with an identification number; which was used to indicate each child's file on the computer. The name of each subject was marked on a separate data sheet. The child then completed the activity questionnaire. Anthropometry was taken prior to GRF testing.

Jumps:

For the measurement of ground reaction forces, each child was asked to perform a series of jumps. The ground reaction forces of these activities were measured with the Kistler force platform. The force platform is 40 x 60 cm in size. The child was shown how to perform the jump and was allowed to practice the jumps prior to data collection. On the force platform, the subject performed either a series of jumps or a single jump. The subjects performed the following jumps in random order:

1) A series frog-like jump (hopping in a crouched position)

2) A series of jumping on one foot (subject preference)

3) A series jumping on two feet

4) A series tuck jumps

5) Leaping from the force platform (performing a long jump)

6) Landing on the force platform

7) A single frog jump

8) A single one foot jump

9) A single two feet jump

10) A single tuck jump

11) A series of small jumps

Data Analysis

Vertical, medial lateral and anterior- posterior ground reaction forces of the 11 different jumps were recorded. The maximum forces during take-off and landing, the take-off and landing impulses, and flight time (vertical height) were calculated from the data. From the raw data, the data was normalized into a percentage of the jump cycle. From this we were able to determine the relative time to peak force during the take-off phase. The means and standard deviations for age, height, and weight are reported. From the ground reaction force data, several variables were examined including the vertical impulse and peak take-off and landing force for each jump.

Definition of Jump Phases

The jumps were divided into three phases: take-off, flight, and landing. For the jumps in a series, the take-off phase was defined as the point from the lowest displacement to the beginning of take-off. The flight phase consists of the aerial portion, while the landing phase begins at the point of contact to the point of lowest displacement. For single jumps, the take-off phase is defined as the time before the flight phase, while landing is the time after the flight phase.

The ground reaction force is the force applied from the ground to the feet while the subject is in contact with the force platform. The GRFs vary at different stages of the jump. By calculating the impulse (Ns), or the area under the GRF force curve we are able to determine the change in momentum of the subject through the following stages: 1) preparation (unloading), 2) air born, 3) landing. The height of the jumps can be calculated from the flight time of the jumps.

Results

The single counter movement jumps (single, double, and tuck jumps), have two distinct peaks of GRF. The first peak comes after the unloading phase associated with the push for take off. The second sharp peak is associated with the landing. In contrast, the repeated jumps are performed continuously so that the landing from one jump becomes the take off the next jump and there is only one peak ground reaction force per jump.

Ground Reaction Forces

All GRF are presented relative to body weight (bw). In general, over all jumps, the landing forces were two to four times greater than take off forces (Table 2). Another generality is that a single jump produced landing GRFs greater than repeated jumps, up to 2.25 times. This is to be expected as the subject performing single jumps has time to think about the movement and can concentrate on jumping higher, which would produce higher landing GRFs. This can be seen in the longer flight times and higher vertical heights in the single jumps (Table 3 and 4). The take off GRF for all jumps ranged from 0.83-1.87 bw, while landing GRF ranged from 2.37-4.22 bw.

The lowest take-off force for the repeated jumps was the one foot jumps at 1.23 ± 0.56 bw, this is expected. The repeated one foot jumps also had the lowest variability. The repeated jump that had the highest take-off force was the repeated frog jumps, 1.87 ± 1.17 bw which had the highest variability. Take-off forces for a leaping jump produced forces on average of 5.34 ± 2.66 bw, which is more than double the take-off forces of all

Table 1

Descriptive Data		
	Mean	Standard
		Deviation
Age (years):	9.5	0.6
Height (cm):	137.7	4.8
Sitting Height (cm):	74.5	2.7
Weight (kg):	33.2	4.5

Table 2 Normalized Take-off and Landing Maximum Forces

Normalized Data	Subject 1		subject 2		Subject 3		Subject 4		Average		Average	
	take off	landing	take off	landing	take off	landing	take off	landing	take off	Standard	landing	Stand
	max	max	max	max	max	max	max	max	max	deviation	max	deviation
Repeated Frog Jumps	0.9	2.8	2.3	2.6	3.4	3.3	1.0	1.5	1.9	1.2	2.5	0.8
Repeated 1 Foot Jumps	0.9	3.6	1.9	1.9	1.4	2.8	0.7	1.7	1.2	0.6	2.5	0.9
Repeated 2 Feet Jumps	1.9	2.9	3.0	3.1	1.4	1.7	1.1	2.0	1.8	0.8	2.4	0.7
Repeated Tuck Jumps	2.2	2.7	2.4	3.1	1.6	2.1	1.2	1.7	1.8	0.6	2.4	0.6
Leaping Only	3.6	none	4.4	none	4.0	none	9.3	none	5.3	2.7	none	none
Landing Only	none	6.7	none	4.7	none	4.5	none	5.6	none	none	5.4	1.0
One Frog Jump	1.1	2.9	0.7	2.7	0.9	1.2	0.9	3.5	0.9	0.1	2.6	1.0
One 1 Foot Jump	0.9	7.4	0.8	3.3	0.9	4.2	0.8	2.0	0.8	0.1	4.2	2.3
One 2 Feet Jump	1.1	4.1	1.2	4.7	1.4	2.8	1.3	2.6	1.3	0.1	3.6	1.0
One Tuck Jump	1.6	5.4	1.4	2.7	1.4	2.3	1.3	1.9	1.4	0.1	3.1	1.6
Small Jumps	1.9	2.3	2.7	2.8	4.3	4.5	1.9	1.8	2.7	1.1	2.8	1.2

Table 3 Flight Time

flight time (seconds)	Subject 1		Subject 2		Subject 3		Subject 4		Overall	
	mean	st dev	mean	st dev	mean	st dev	mean	st dev	mean	st dev
Repeated Frog Jumps	0.41	0.03	0.38	0.02	0.50	0.02	0.39	0.04	0.42	0.03
Repeated 1 Foot Jumps	0.29	0.01	0.21	0.02	0.32	0.04	0.28	0.02	0.28	0.02
Repeated 2 Feet Jumps	0.40	0.01	0.30	0.02	0.48	0.01	0.38	0.02	0.39	0.01
Repeated Tuck Jumps	0.38	0.06	0.41	0.00	0.54	0.01	0.40	0.02	0.43	0.02
Leaping Only	none		none		none		none			none
Landing Only	none		none		none		none			none
One Frog Jump	0.47		0.40		0.52		0.46		0.46	0.05
One 1 Foot Jump	0.35		0.32		0.37		0.31		0.34	0.03
One 2 Feet Jump	0.45		0.44		0.55		0.43		0.47	0.06
One Tuck Jump	0.45		0.44		0.58		0.46		0.48	0.06
Small Jumps	0.24	0.01	0.19	0.01	0.30	0.02	0.25	0.04	0.25	0.02

Table 4 Vertical Height

Jumps	(m)
Repeated Frog Jumps	0.21
Repeated 1 Foot Jumps	0.09
Repeated 2 Feet Jumps	0.19
Repeated Tuck Jumps	0.23
Leaping Only	none
Landing Only	none
One Frog Jump	0.26
One 1 Foot Jump	0.14
One 2 Feet Jump	0.27
One Tuck Jump	0.29
Small Jumps	0.07

other jumps. The order (hierarchy) of take-off GRF for repeated jumps do not correspond to single jumps. In other words, the highest take-off GRF for repeated jumps, frog jump, doesn't correspond to the highest take-off GRF for single jumps, and tuck jumps.

Landing forces was the greatest for the landing only, at 5.37 ± 1.03 bw. For this jump the subjects were allowed a short run-up and told to land on the force platform. The landing forces for single jumps were greater than the repeated jumps. The repeated jumps all produced similar landing forces ranging from 2.37-2.53 bw. (average standard deviation of 0.73). The single jumps had higher landing GRF, but also greater variability. The greatest landing force for a single jump is a one foot jump, 4.22 ± 2.28 bw, but note the high amount of variability (subject 1 had a landing force of 7.35 bw). The single two foot jump had the next highest landing GRF at 3.57 ± 1.01 bw. The lowest single jump landing force was the frog jump, 2.58 ± 0.99 bw. The frog jump landing GRF is less than the two feet and tuck jumps even though there have similar flight times (vertical height). Obviously, the landing of the frog jump allows a subject to catch him or herself as they land, reducing impact forces. For the frog jump, the subject started in a crouched position and landed in a crouched position. This requires the subject to catch him or herself as they land, reducing the impact forces. The landing impulses are also spread out over a longer period of time, as we will see later. The jump that produced the lowest GRF was the repeated tuck jump 2.37 ± 0.64 bw.

Repeated take off forces were greater than the single take off forces. While the reverse is true for the landing, the singles jumps are greater than the repeated jumps. However, the highest repeated take off forces do not correspond to the highest single take off jumps in both take off and landing cases. This may be due to the low number of subjects (increased variability).

Flight time

The aerial times ranged from 0.25 s for small jumps to 0.48 s for single tuck jumps (Table 3). The jumps with the longest flight times were the single two feet jump, the single tuck jump, and the single frog jump. From $V_2 = V_1 + a\,t$ and $V_2^2 = V_1^2 + 2\,a\,d$, we can estimate the vertical height from flight time (Table 4). The vertical heights were calculated from the average flight times of each jump. The previous three jumps had the greatest vertical height. This partially explains the higher landing GRF data. These single jumps had the greatest peak vertical jump heights and relatively higher landing GRF, although this relationship is not linear. The highest jump was a single tuck jump (0.29 m), followed by the single two feet jump (0.27 m), and single frog jump (0.26 m). For the repeated jumps, the tuck jump was also the highest jump, but this time the frog jump was higher than the two feet jump. The repeated small jumps had an average height of 0.07 m, with a flight time of 0.25 s.

Impulses

Take-off and landing impulses were calculated from the GRF data and compared between jumps and between single and multi-jumps (Tables 5 and 6). The greatest take-off impulse was with the leaping jump, the average impulse was 117.38 ± 22.60 Ns. The small jumps produced the smallest overall impulse 34.61 Ns. In general, the impulses of single jumps were greater than repeated jumps.

The jumps have a distinct period of time for maximum take-off force. The one foot jump had the earliest peak in maximum take-off force for all subjects ranging from 56-73 % of the take-off cycle. The frog jump had the latest peak for all subjects, at 89-91% of the take off cycle. While the tuck jump and two feet jump range between 69-82% of the take-off cycle.

The take-off impulse for the frog, tuck, and two feet jumps were significantly higher than the one-foot jump for both repeated and single jumps. Of the four jumps, the one foot

Table 5 Take-off Impulse (Ns)

	Subject 1		Subject 2		Subject 3		Subject 4		Overall	
	mean	st dev	mean	st dev	mean	st dev	mean	st dev	mean	st dev
Repeated Frog Jumps	54.2	3.6	67.2	0.1	86.5	2.5	55.9	8.3	66.0	3.6
Repeated 1 Foot Jumps	37.7	1.8	35.4	7.5	61.8	2.2	37.2	0.7	43.0	3.1
Repeated 2 Feet Jumps	48.9	4.1	51.3	5.0	80.4	1.5	54.2	3.4	58.7	3.5
Repeated Tuck Jumps	51.1	7.8	64.7	2.4	88.0	3.9	54.8	4.3	64.7	4.6
Leaping Only	87.1		116.4		141.0		125.0		117.4	22.6
Landing Only	none		none		none		none		none	none
One Frog Jump	57.6		74.7		92.1		61.7		71.5	15.5
One 1 Foot Jump	37.4		46.5		56.7		48.3		47.2	7.9
One 2 Feet Jump	54.3		74.8		98.0		61.6		72.2	19.2
One Tuck Jump	56.5		74.5		98.7		63.4		73.3	18.5
Small Jumps	25.7	4.4	29.6	4.4	50.7	3.6	32.4	7.8	34.6	5.1

Table 6 Landing Impulse (Ns)

	Subject 1		Subject 2		Subject 3		Subject 4		Overall	
	mean	st dev	mean	st dev	mean	st dev	mean	st dev	mean	st dev
Repeated Frog Jumps	60.6	4.3	70.6	7.8	96.8	2.8	55.3	5.7	70.8	5.2
Repeated 1 Foot Jumps	44.9	0.8	39.4	5.9	60.6	9.7	39.6	10.7	46.1	6.8
Repeated 2 Feet Jumps	66.8	5.7	54.8	6.1	93.8	4.1	56.4	3.3	68.0	4.8
Repeated Tuck Jumps	54.6	14.9	85.2	4.6	106.3	2.2	53.3	15.4	74.8	9.3
Leaping Only	none		none		none		none		none	none
Landing Only	73.9		90.2		105.1		63.4		83.2	18.3
One Frog Jump	66.4		81.8		103.7		79.1		82.7	15.5
One 1 Foot Jump	91.2		67.5		72.1		51.5		70.6	16.3
One 2 Feet Jump	57.5		88.1		110.1		65.6		80.3	23.7
One Tuck Jump	105.6		87.7		112.7		69.0		93.8	19.6
Small Jumps	45.6	12.4	37.0	2.9	54.8	6.5	41.5	5.0	44.7	6.7

jumps (both repeated and single) produce a much smaller take off impulse with lower variability than the three other jumps (two feet, tuck and frog). These three latter jumps all had similar take off impulses and similar vertical heights. The single jumps that produce the highest take-off impulses are the single frog and single tuck jumps (65.95 ± 3.63 Ns and 64.65 ± 4.62 Ns).

The highest landing impulse was the repeated single jump, 93.75 ± 19.58 Ns, which is true also for the repeated jumps. The repeated tuck jumps produced a landing impulse of 74.83 ± 9.28 Ns. However, the repeated frog and two feet jumps were also similar at 70.82 ± 5.17 Ns and 67.97 ± 4.82 Ns. This may be due to the time it takes to tuck and extend the legs, this would result in less time to catch oneself. The lowest landing impulses are the small jumps (44.72 ± 6.68 Ns) and repeated one foot jumps(46.12 ± 6.78 Ns). The repeated jumps were generally smaller in landing and take- off impulse than the single jumps. The single jumps tended to elicit higher landing response than repeated jumps, but with a greater variability. This is also expected, as during repeated jumps the subject has to land and prepare for the next jump in one motion. For both repeated and single jumps the tuck jumps had the highest landing impulse, followed by the frog, two feet, and one foot jumps. It must be noted that the variability of the two feet, frog and tuck jumps are high and are not significantly different Table 5 and 6). The small jumps had an impulse of less than 50% of the single tuck jump.

The landing impulses for the single two feet and one-foot landing appear similar with one big spike followed by a gradual decrease in positive impulse. While the frog jump landing produces the initial contact spike then a second spike at approximately 40% of the initial impact. The tuck jumps have a variable landing pattern, some resemble two feet jumps and some look like the frog landings.

Looking at the characteristics of the singles jumps, we find that the frog jump has the most unique properties compared to the other three jumps. The take-off impulse is positive throughout the take-off phase (Appendix A, Figure 1). The frog jump begins with a small impulse followed by a larger impulse. During take off, there is no negative impulse, unlike the three other single jumps, where there are distinct negative impulse during the take off phase. The negative impulses can be seen as a counter movement. The landing impulse of the frog jump is also distinct (Appendix A, Figure 2). The landing impulse has a much lower peak force and occurs later in the landing cycle compared to the other three jumps. This uniqueness of the frog jump is seen in both single and repeated jumps (Appendix A, Figures 1 to 4). The take-off impulse for the two feet, one foot, and tuck jumps were all similar. They begin with a small negative impulse followed by a larger positive impulse. The landing for the two feet and one foot jump was fairly consistent, with a sharp landing impact followed by a secondary spike. The landing for the tuck jumps was highly variable between subjects. There is considerable inter-subject variability with tuck jumps. Since this is a complex movement, there are many variations to the jump. For example, a higher tuck during the jump would mean less time to catch oneself during the landing.

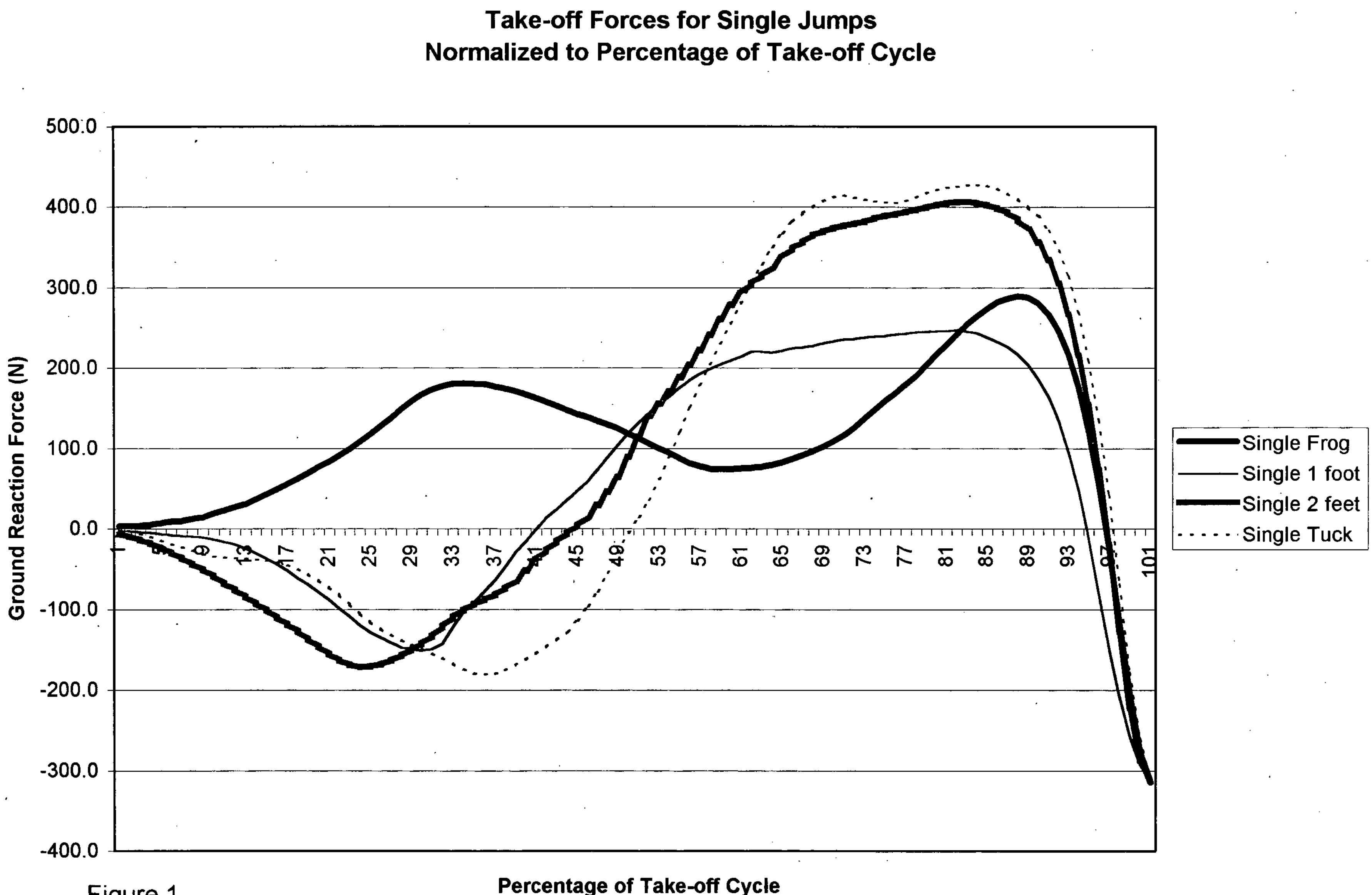

Take-off Forces for Single Jumps
Normalized to Percentage of Take-off Cycle
Ground Reaction Force (N)
500.0
400.0
300.0
200.0
100.0
0.0
-100.0
-200.0
-300.0
-400.0
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
85
89
93
97
101
Percentage of Take-off Cycle
Single Frog
Single 1 foot
Single 2 feet
Single Tuck

Figure 1

Landing Forces for Single Jumps
Normalized to Percentage of Landing Cycle

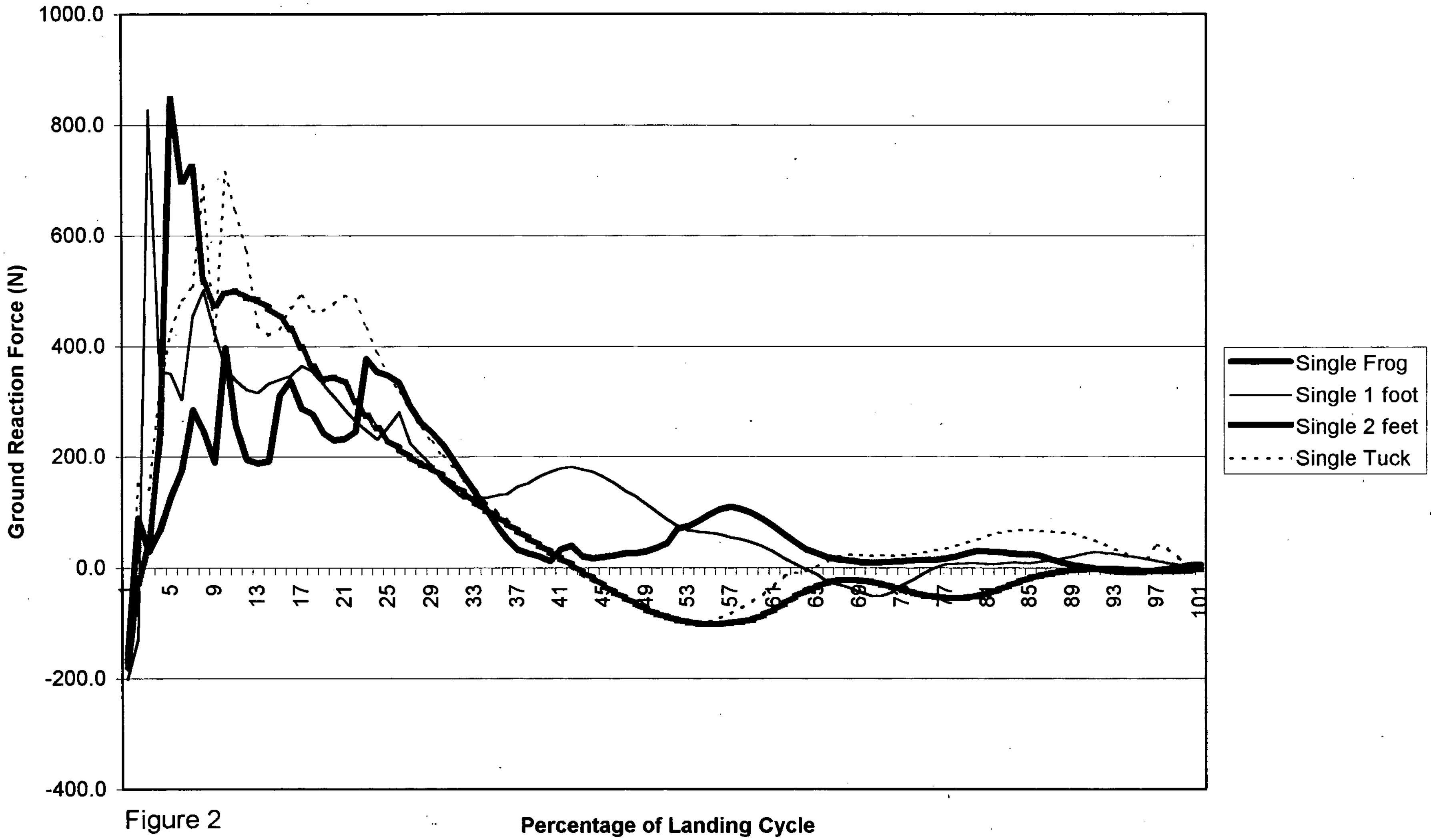


Figure 2

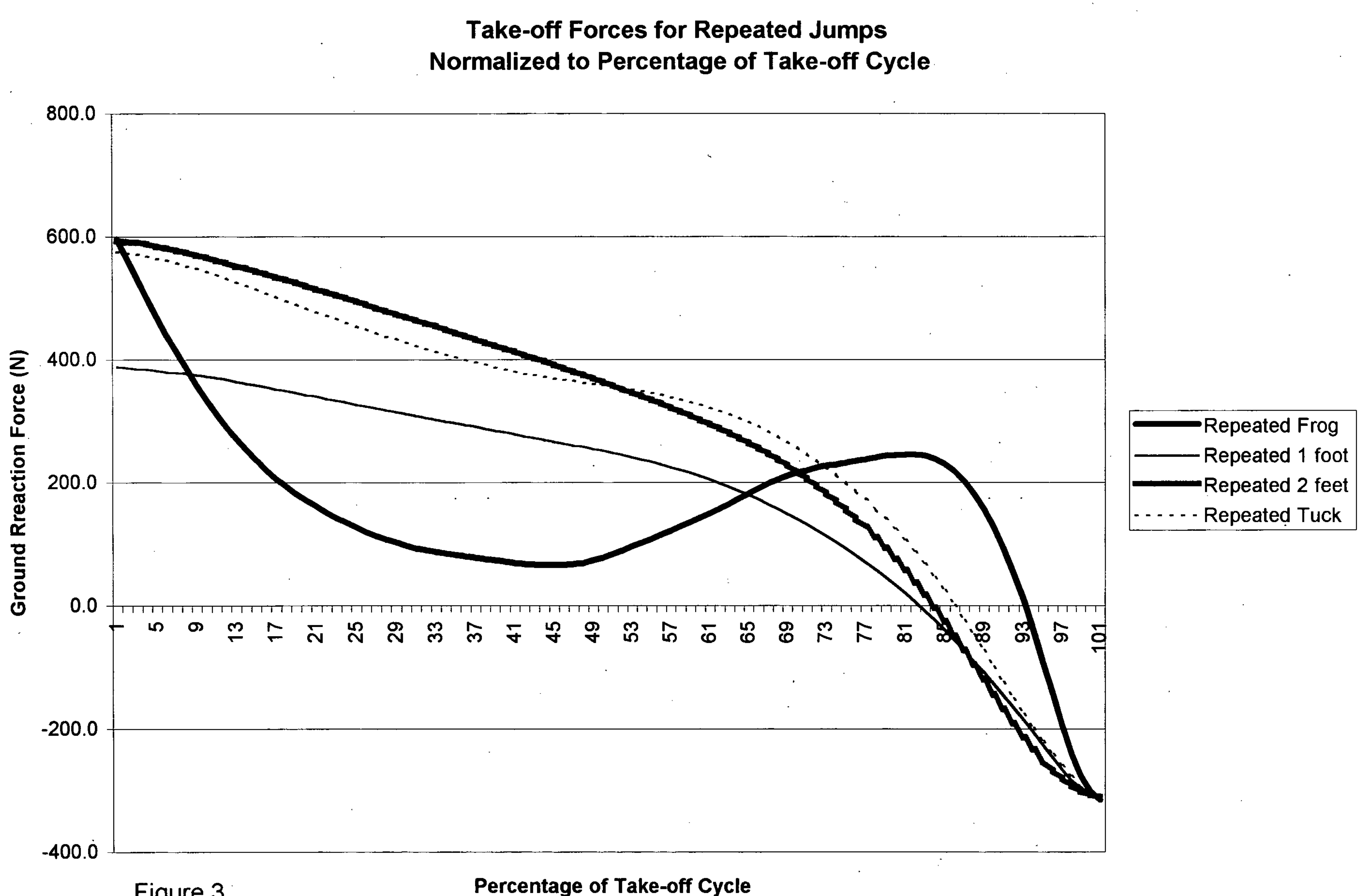

Take-off Forces for Repeated Jumps
Normalized to Percentage of Take-off Cycle
800.0
600.0
400.0
200.0
0.0
-200.0
-400.0
Ground Rreaction Force (N)
1
5
9
13
17
21
25
29
33
37
41
45
49
53
57
61
65
69
73
77
81
85
89
93
97
101
Percentage of Take-off Cycle
Repeated Frog
Repeated 1 foot
Repeated 2 feet
Repeated Tuck

Figure 3

Landing Forces for Repeated Jumps Normalized to Percentage of Landing Cycle

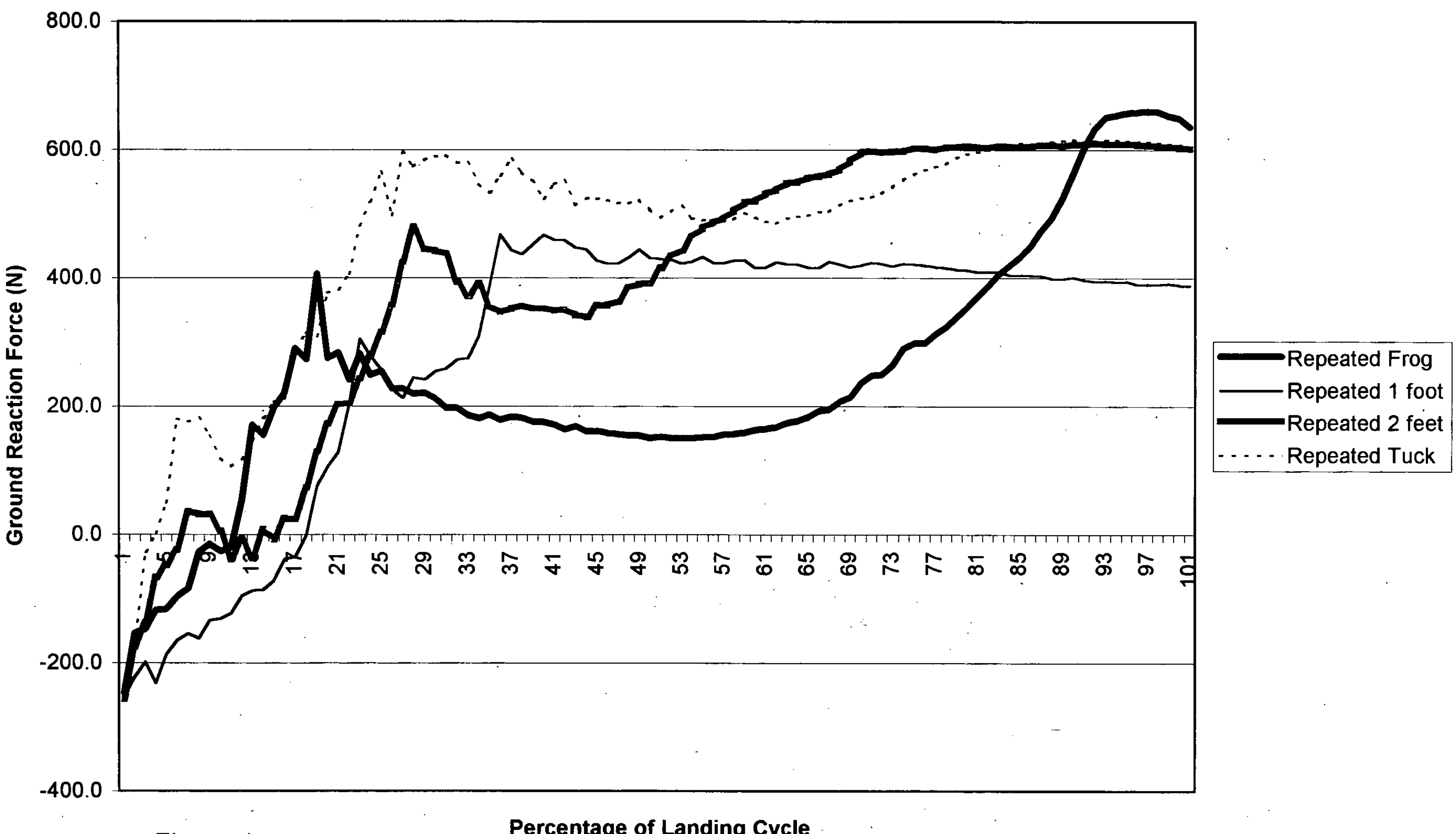


Figure 4

Appendix A_1

Consent Form

Osteoporosis is the degeneration of bone, which may predispose, primarily older, individuals to fractures. However, as more than 90% of peak skeletal mass is present by the age of 18, the attainment of optimal bone mass during childhood may be one of the preventative measures for osteoporosis.

A list of the study procedures is presented below.

Study Procedures:

Your child's participation in this project will involve one testing session at the University of British Columbia Biomechanics Laboratory. We ask that your child wear their regular physical education clothing (preferably a T-shirt, shorts, sweat pants, and runners). Under the supervision of a research assistant, your child will be transported from the Community Sports program at U.B.C. to the Biomechanics Laboratory at War Memorial Gym, 6081 University Boulevard. Parents may also transport their child to the University of British Columbia at the appointed time. The session will include the following:

1. Upon arrival at the biomechanics lab, the children will be introduced to investigators and to the lab equipment. The name and age of each child will be recorded on a separate data sheet. The data sheet will be marked with an identification number; this number will be used to indicate each child's file on the computer.
2. Height and weight will be measured with a wall stadiometer and weigh scale. Calf circumference will be measured with a tape measure and limb lengths with a caliper will also be measured.
3. For the measurement of ground reaction forces, each child will be asked to perform a series of jumps that are a part of their regular physical education programs. The ground reaction forces of these jumps will be measured by a force platform. The force platform is 40 x 60 cm in size and is mounted level with the floor. The first jump will be a trial and the ground reaction forces will be recorded after the initial trial jump.

The nine jumps are:

1) Drop jump at a low level
2) Drop jump at a medium level
3) Drop jump at a high level
4) Maximal jumping jacks
5) Submaximal jumping jacks
6) Alternating feet
7) Counter movement jump
8) Side to side over a 10 cm foam barrier
9) Side to side over a 20 cm foam barrier

The total time commitment for each child will be one half-hour, including transportation and measurement. The children will be under adult supervision at all times. The children will be free to withdraw at any time without jeopardizing educational opportunities.

Confidentiality:

Any information resulting from this study will be kept strictly confidential. All documents will be identified only by code number and kept on a password-protected computer. Participants will not be identified by name in any reports of the completed study.

Contact:

Please be assured that you may ask questions at any time. Should you have any concerns about this study or wish further information please contact Dr. Heather McKay (822-3120) or Garry Tsang (322-1975). Should you wish to contact the Biomechanics laboratory on the day of the measurement please call 822-4361. If you have any concerns about your child's treatment as a research subject, please contact Dr. Richard Spratley at the office of Research Services and Administration at UBC (822-8598).

<u>**Ground Reaction Force Analyses of a**</u>

<u>**Variety of Jumping Activities in Growing Children**</u>

University of British Columbia
Research Project Consent Form

<u>**Parent's Statement**</u>:

I,____
(please print the name of the parent/ guardian)
understand the purpose and procedures of this study as described and I voluntarily agree to allow my child to participate. I understand that at any time during the study we will be free to withdraw without jeopardizing any educational opportunities. I understand the contents of the consent form, the proposed procedures and possible risks.

I have received a copy of this consent form for my own records.

I consent/I do not consent (circle one) to my child's participate in this study.

__________________________ ____________________
Signature of Parent/Guardian Date

__________________________ ____________________
Signature of Witness Date

__________________________ ____________________
Signature of Investigator Date

Child's Statement:

I understand the purpose and procedures of this study as described and I voluntarily agree to participate. I understand that at any time during the study, I will be free to withdraw without jeopardizing any educational opportunities. I understand the contents of the consent form, the proposed procedures and possible risks.

I have had the opportunity to ask questions and have received satisfactory answers to all inquiries regarding this study.

________________________ __________________

Signature of Child Date

Appendix A_2

Ethical Approval

16. SUMMARY OF METHODOLOGY AND PROCEDURES. NOTE: IF YOUR STUDY INVOLVES DECEPTION, YOU MUST ALSO COMPLETE PAGE 7, THE 'DECEPTION FORM':

Parents will be provided with an approved measurement schedule for the study two weeks prior to testing. The subjects will be asked to go to the University of British Columbia Biomechanics Lab for testing at the scheduled time. The subjects will be tested in their regular physical education clothing and foot wear (T-shirt, shorts, and runners). Each subject will have a data sheet. The name, height, weight, calf girth, and limb lengths (outlined in C97-0121) of the subjects will be measured using standard techniques and recorded on the data sheet. Each data sheet will have an identification number which will be entered in the computer. The subjects will then be asked to perform seven different jumps on the Kistler force platform (40 x 60 cm) that is mounted flush to the floor.

Each subject will perform the following jumps:

1) frog-like jump (hopping in a crouched position, 2) jumping on one foot, 3) jumping on two feet, 4) tuck jumps, 5) skipping alternating legs, 6) skipping with both feet together, 7) leaping (like performing a basketball lay-up)

Each jump will be performed three times. The first jump will be a trial jump. The ground reaction forces for the second and third jumps will be recorded using the Kistler force platform interfaced with a computer acquisition system. After the completion of measurement the parents will pick up the subjects. The subjects will be under adult supervision at all times by the investigators and/or the study staff. The estimated participation time for each subject is one hour

Several variables will be examined including the vertical impulse, peak force, vertical height, forces in the vertical, horizontal, and medial lateral planes. These data will be used to assess the relative loading pattern for each jumping style.

As an additional descriptive measure, bone mineral density of the calcaneus will be assessed by quantitative ultrasound (QUS) on a Lunar Achilles unit (Lunar, WI). This is a completely painless, non-invasive procedure that simply involves the measurement of the attenuation of sound waves as they pass through bone. The child will submerge the heel area in water of room temperature, and must remain still for approximately 10 minutes. QUS is ideally suited to pediatric studies as the measurement involves no radiation.

DESCRIPTION OF POPULATION

17. HOW MANY SUBJECTS WILL BE USED? 80 HOW MANY IN THE CONTROL GROUP? 0

18. WHO IS BEING RECRUITED, AND WHAT ARE THE CRITERIA FOR THEIR SELECTION?

Children aged 10-12 participating in recreational programs administered by Community Sports or Athletics at the University of British Columbia.

19. WHAT SUBJECTS WILL BE EXCLUDED FROM PARTICIPATION?

Subjects with known medical problems, injuries, or who are taking medication known to effect physical activity or bone metabolism.

20. HOW ARE THE SUBJECTS BEING RECRUITED? IF THE INITIAL CONTACT IS BY LETTER OR IF A RECRUITMENT NOTICE IS TO BE POSTED, ATTACH A COPY. NOTE THAT UBC POLICY DISCOURAGES INITIAL CONTACT BY TELEPHONE. HOWEVER, SURVEYS WHICH USE RANDOM DIGIT DIALING MAY BE ALLOWED. IF YOUR STUDY INVOLVES SUCH CONTACT, YOU MUST ALSO COMPLETE PAGE 8, THE 'TELEPHONE CONTACT' FORM.

A list of registrants in U.B.C sports programs will be obtained and potential participants will be sent a letter describing the project and inviting them to participate. Interested participants then will receive the consent forms, which outlines the purpose and procedure of the study. The participants will be contacted by phone to answer any questions and to schedule testing times. An copy of the letter is included.

21. IF A CONTROL GROUP IS INVOLVED, AND IF THEIR SELECTION AND/OR RECRUITMENT DIFFERS FROM THE ABOVE, PROVIDE DETAILS:

n/a

PROJECT DETAILS

22. WHERE WILL THE PROJECT BE CONDUCTED? (ROOM OR AREA)

Biomechanics Lab in War Memorial Gym, Room 30

23. WHO WILL ACTUALLY CONDUCT THE STUDY AND WHAT ARE THEIR QUALIFICATIONS?

Dr. Sanderson. Associate Professor, School of Human Kinetics, University of British Columbia.
Garry Tsang, Master's candidate.
Kerry MacKelvie, PhD candidate, School of Human Kinetics, trained on Lunar Achilles Quantitative Ultrasound (Lunar, WI).

24. WILL THE GROUP OF SUBJECTS HAVE ANY PROBLEMS GIVING INFORMED CONSENT ON THEIR OWN BEHALF? CONSIDER PHYSICAL OR MENTAL CONDITION, AGE, LANGUAGE, AND OTHER BARRIERS.

The subjects will have problems giving consent due to their age and thus parental consent is required.

25. IF THE SUBJECTS ARE NOT COMPETENT TO GIVE FULLY INFORMED CONSENT, WHO WILL CONSENT ON THEIR BEHALF?

The parent or guardian of the child will provide consent.

26. WHAT IS KNOWN ABOUT THE RISKS AND BENEFITS OF THE PROPOSED RESEARCH? DO YOU HAVE ADDITIONAL OPINIONS ON THIS ISSUE?

The activities being performed are among those undertaken by children during the course of leisure time play. There are no known risks associated with these activities, or with qualitative ultrasound techniques of bone density measurement.

27. WHAT DISCOMFORT OR INCAPACITY ARE THE SUBJECTS LIKELY TO ENDURE AS A RESULT OF THE EXPERIMENTAL PROCEDURES?

none

28. IF MONETARY COMPENSATION IS TO BE OFFERED TO THE SUBJECTS, PROVIDE DETAILS OF AMOUNTS AND PAYMENT SCHEDULES:

n/a

29. HOW MUCH TIME WILL A SUBJECT HAVE TO DEDICATE TO THE PROJECT?

The subjects will dedicate one hour to the project.

30. HOW MUCH TIME WILL A MEMBER OF THE CONTROL GROUP, IF ANY, HAVE TO DEDICATE TO THE PROJECT?

n/a

DATA

31. WHO WILL HAVE ACCESS TO THE DATA?

Only Drs. Sanderson and McKay and Garry Tsang, Master's candidate, will have access to the data

32. HOW WILL THE CONFIDENTIALITY OF THE DATA BE MAINTAINED?

The data will be stored in Dr. Sanderson's office on a password protected computer. All hard copies of the data will be locked in a file cabinet. Subjects will be given an identification number and all data analysis will be performed using subject identification numbers only. Access to research investigators and assistants only.

33. WHAT ARE THE PLANS FOR THE FUTURE USE OF THE RAW DATA BEYOND THAT DESCRIBED IN THIS PROTOCOL? HOW AND WHEN WILL THE DATA BE DESTROYED?

The data will be considered for publication in a peer-reviewed journal. The data will also be used to establish a more comprehensive data base on ground reaction forces in children. Once our study is completed, the identification of the subjects will be shredded and destroyed.

34. WILL ANY DATA WHICH IDENTIFIES INDIVIDUALS BE AVAILABLE TO PERSONS OR AGENCIES OUTSIDE THE UNIVERSITY?

No.

35. ARE THERE ANY PLANS FOR FEEDBACK TO THE SUBJECT?

No.

36. WILL YOUR PROJECT USE:

- ☐ QUESTIONNAIRES (SUBMIT A COPY);
- ☐ INTERVIEWS (SUBMIT A SAMPLE OF QUESTIONS);
- ☐ OBSERVATIONS (SUBMIT A BRIEF DESCRIPTION);
- ☐ TESTS (SUBMIT A BRIEF DESCRIPTION).

37. FUNDING INFORMATION

AGENCY / SOURCE OF FUNDS:
National Institutes of Health (US)

FUNDS ADMINISTERED BY:
○ UBC ○ VHHSC ○ SPH ○ BCWH ○ BCCH ○ BCCA

UBC OR HOSPITAL ACCOUNT NUMBER:

○ INTERNAL ○ EXTERNAL

STATUS: ○ AWARDED ◉ PENDING

PEER REVIEW: ○ YES ○ NO

START DATE:

FINISH DATE:

INFORMED CONSENT

38. WHO WILL CONSENT?

☐ SUBJECT.

☒ PARENT OR GUARDIAN. (WRITTEN PARENTAL CONSENT IS ALWAYS REQUIRED FOR RESEARCH IN THE SCHOOLS AND AN OPPORTUNITY MUST BE PRESENTED EITHER VERBALLY OR IN WRITING TO THE STUDENTS TO REFUSE TO PARTICIPATE OR WITHDRAW. A COPY OF WHAT IS WRITTEN OR SAID TO THE STUDENTS SHOULD BE PROVIDED FOR REVIEW BY THE COMMITTEE.)

☐ AGENCY OFFICIAL(S).

39. IN THE CASE OF PROJECTS CARRIED OUT AT OTHER INSTITUTIONS, THE COMMITTEE REQUIRES WRITTEN PROOF THAT AGENCY CONSENT HAS BEEN RECEIVED. PLEASE SPECIFY BELOW:

☐ RESEARCH CARRIED OUT IN A HOSPITAL - APPROVAL OF HOSPITAL RESEARCH OR ETHICS COMMITTEE.

☐ RESEARCH CARRIED OUT IN A SCHOOL - APPROVAL OF SCHOOL BOARD AND/OR PRINCIPAL. EXACT REQUIREMENTS DEPEND ON INDIVIDUAL SCHOOL BOARDS; CHECK WITH FACULTY OF EDUCATION COMMITTEE MEMBERS FOR DETAILS.

☐ RESEARCH CARRIED OUT IN A PROVINCIAL HEALTH AGENCY - APPROVAL OF DEPUTY MINISTER.

☐ OTHER, SPECIFY:

QUESTIONNAIRES (COMPLETED BY SUBJECTS)

40. QUESTIONNAIRES SHOULD CONTAIN AN INTRODUCTORY PARAGRAPH OR COVERING LETTER WHICH INCLUDES THE FOLLOWING INFORMATION. PLEASE CHECK EACH ITEM IN THE FOLLOWING LIST BEFORE SUBMISSION OF THIS FORM TO INSURE THAT THE INSTRUCTION CONTAINS ALL NECESSARY ITEMS:

☐ UBC LETTERHEAD.

☐ TITLE OF PROJECT.

☐ IDENTIFICATION OF THE INVESTIGATORS, INCLUDING A TELEPHONE NUMBER.

☐ A BRIEF SUMMARY THAT INDICATES THE PURPOSE OF THE PROJECT.

☐ THE BENEFITS TO BE DERIVED.

☐ A FULL DESCRIPTION OF THE PROCEDURES TO BE CARRIED OUT IN WHICH THE SUBJECTS ARE INVOLVED.

☐ A STATEMENT OF THE SUBJECT'S RIGHT TO REFUSE TO PARTICIPATE OR WITHDRAW AT ANY TIME WITHOUT JEOPARDIZING FURTHER TREATMENT, MEDICAL CARE OR CLASS STANDING AS APPLICABLE. NOTE: THIS STATEMENT MUST ALSO APPEAR ON EXPLANATORY LETTERS INVOLVING QUESTIONNAIRES.

☐ THE AMOUNT OF TIME REQUIRED OF THE SUBJECT MUST BE STATED.

☐ THE STATEMENT THAT IF THE QUESTIONNAIRE IS COMPLETED IT WILL BE ASSUMED THAT CONSENT HAS BEEN GIVEN. THIS IS SUFFICIENT IF THE RESEARCH IS LIMITED TO QUESTIONNAIRES; ANY OTHER PROCEDURES OR INTERVIEWS REQUIRE A CONSENT FORM SIGNED BY THE SUBJECT.

☐ AN EXPLANATION OF HOW TO RETURN THE QUESTIONNAIRE.

☐ ASSURANCE THAT THE IDENTITY OF THE SUBJECT WILL BE KEPT CONFIDENTIAL AND A DESCRIPTION OF HOW THIS WILL BE ACCOMPLISHED; E.G. 'DON'T PUT YOUR NAME ON THE QUESTIONNAIRE'

☐ FOR SURVEYS CIRCULATED BY MAIL SUBMIT A COPY OF THE EXPLANATORY LETTER AS WELL AS A COPY OF THE QUESTIONNAIRE.

CONSENT FORMS

41. UBC POLICY REQUIRES WRITTEN CONSENT IN ALL CASES OTHER THAN THOSE **LIMITED** TO QUESTIONNAIRES WHICH ARE COMPLETED BY THE SUBJECT. (SEE ITEM #40 FOR CONSENT REQUIREMENTS.) PLEASE CHECK EACH ITEM IN THE FOLLOWING LIST BEFORE SUBMISSION OF THIS FORM TO ENSURE THAT THE WRITTEN CONSENT FORM ATTACHED CONTAINS ALL NECESSARY ITEMS. IF YOUR RESEARCH INVOLVES INITIAL CONTACT BY TELEPHONE, YOU DO NOT NEED TO FILL OUT THIS SECTION.

- [x] THE CONSENT FORM MUST BE ON UBC LETTERHEAD.
- [x] TITLE OF PROJECT.
- [x] IDENTIFICATION OF INVESTIGATORS, INCLUDING A TELEPHONE NUMBER. RESEARCH FOR A GRADUATE THESIS SHOULD BE IDENTIFIED AS SUCH AND THE NAME AND TELEPHONE NUMBER OF THE FACULTY ADVISOR INCLUDED.
- [x] BRIEF BUT COMPLETE DESCRIPTION IN LAY LANGUAGE OF THE PURPOSE OF THE PROJECT AND OF ALL PROCEDURES TO BE CARRIED OUT IN WHICH THE SUBJECTS ARE INVOLVED. INDICATE IF THE PROJECT INVOLVES A NEW OR NON-TRADITIONAL PROCEDURE WHOSE EFFICACY HAS NOT BEEN PROVEN IN CONTROLLED STUDIES.
- [x] ASSURANCE THAT THE IDENTITY OF THE SUBJECT WILL BE KEPT CONFIDENTIAL AND DESCRIPTION OF HOW THIS WILL BE ACCOMPLISHED, I.E. DESCRIBE HOW RECORDS IN THE PRINCIPAL INVESTIGATOR'S POSSESSION WILL BE CODED, KEPT IN A LOCKED FILING CABINET, OR UNDER PASSWORD IF KEPT ON A COMPUTER HARD DRIVE.
- [x] STATEMENT OF THE TOTAL AMOUNT OF TIME THAT WILL BE REQUIRED OF A SUBJECT.
- [x] DETAILS OF MONETARY COMPENSATION, IF ANY, TO BE OFFERED TO SUBJECTS.
- [x] AN OFFER TO ANSWER ANY INQUIRIES CONCERNING THE PROCEDURES TO ENSURE THAT THEY ARE FULLY UNDERSTOOD BY THE SUBJECT AND TO PROVIDE DEBRIEFING, IF APPROPRIATE.
- [x] A STATEMENT THAT IF THEY HAVE ANY CONCERNS ABOUT THEIR RIGHTS OR TREATMENT AS RESEARCH SUBJECTS, THEY MAY CONTACT DR. RICHARD SPRATLEY, DIRECTOR OF THE UBC OFFICE OF RESEARCH SERVICES AND ADMINISTRATION, AT 822-8598.
- [x] A STATEMENT OF THE SUBJECT'S RIGHT TO REFUSE TO PARTICIPATE OR WITHDRAW AT ANY TIME AND A STATEMENT THAT WITHDRAWAL OR REFUSAL TO PARTICIPATE WILL NOT JEOPARDIZE FURTHER TREATMENT, MEDICAL CARE OR INFLUENCE CLASS STANDING AS APPLICABLE. NOTE: THIS STATEMENT MUST ALSO APPEAR ON LETTERS OF INITIAL CONTRACT. FOR RESEARCH DONE IN THE SCHOOLS, INDICATE WHAT HAPPENS TO CHILDREN WHOSE PARENTS DO NOT CONSENT. THE PROCEDURE MAY BE PART OF CLASSROOM WORK BUT THE COLLECTION OF DATA MAY BE PURELY FOR RESEARCH.
- [x] A STATEMENT ACKNOWLEDGING THAT THE SUBJECT HAS RECEIVED A COPY OF THE CONSENT FORM INCLUDING ALL ATTACHMENTS FOR THE SUBJECT'S OWN RECORDS.
- [x] A PLACE FOR SIGNATURE OF SUBJECT CONSENTING TO PARTICIPATE IN THE RESEARCH PROJECT, INVESTIGATION, OR STUDY AND A PLACE FOR THE DATE OF THE SIGNATURE.
- [x] PARENTAL CONSENT FORMS MUST CONTAIN A STATEMENT OF CHOICE PROVIDING AN OPTION FOR REFUSAL TO PARTICIPATE, E.G. "I CONSENT / I DO NOT CONSENT TO MY CHILD'S PARTICIPATION IN THIS STUDY." ALSO, VERBAL ASSENT MUST BE OBTAINED FROM THE CHILD, IF THE PARENT HAS CONSENTED.
- [x] IF THERE IS MORE THAN ONE PAGE, NUMBER THE PAGES OF THE CONSENT, E.G. PAGE 1 OF 3, 2 OF 3, 3 OF 3.

ATTACHMENTS

42. CHECK ITEMS ATTACHED TO THIS SUBMISSION, IF APPLICABLE. INCOMPLETE SUBMISSIONS WILL NOT BE REVIEWED.

- [x] LETTER OF INITIAL CONTACT. (ITEM 20)
- [ ] ADVERTISEMENT FOR VOLUNTEER SUBJECTS. (ITEM 20)
- [x] SUBJECT CONSENT FORM. (ITEM 41)
- [ ] CONTROL GROUP CONSENT FORM. (IF DIFERENT FROM ABOVE)
- [x] PARENT/GUARDIAN CONSENT FORM. (IF DIFFERENCT FROM ABOVE)
- [ ] AGENCY CONSENT. (ITEM 39)
- [ ] QUESTIONNAIRES, TESTS, INTERVIEWS, ETC. (ITEM 36)
- [ ] EXPLANATORY LETTER WITH QUESTIONNAIRE. (ITEM 40)
- [ ] DECEPTION FORM. (INCLUDING A COPY OF TRANSCRIPT OF WRITTEN OR VERBAL DEBRIEFING)
- [ ] TELEPHONE CONTACT FORM.
- [ ] OTHER, SPECIFY:

DECEPTION FORM

IF YOUR STUDY INVOLVES DECEPTION, COMPLETE ITEMS 1 TO 3. IF NOT, SKIP TO THE NEXT PAGE.

1. DECEPTION UNDERMINES INFORMED CONSENT. INDICATE (A) WHY YOU BELIEVE DECEPTION IS NECESSARY TO ACHIEVE YOUR RESEARCH OBJECTIVES, AND (B) WHY YOU BELIEVE THAT THE BENEFITS OF THE RESEARCH OUTWEIGH THE COST TO THE SUBJECTS:
2. EXPLAIN WHY YOU BELIEVE THERE WILL BE NO PERMANENT DAMAGE AS A RESULT OF THE DECEPTION:
3. DESCRIBE HOW YOU WILL DEBRIEF SUBJECTS AT THE END OF THE STUDY:

TELEPHONE CONTACT FORM

IF YOUR STUDY INVOLVES TELEPHONE CONTACT, COMPLETE ITEMS 1 TO 4. IF NOT, YOU ARE AT THE END OF THE FORM.

1. TELEPHONE CONTACT MAKES IT IMPOSSIBLE FOR A SIGNED RECORD OF CONSENT TO BE KEPT. INDICATE WHY YOU BELIEVE THAT SUCH CONTACT IS NECESSARY TO ACHIEVE YOUR RESEARCH OBJECTIVES:

2. INCLUDE A COPY OF THE PROPOSED 'FRONT END' SCRIPT OF YOUR TELEPHONE INTERVIEW. PLEASE CHECK EACH ITEM ON THE FOLLOWING LIST BEFORE SUBMISSION OF REQUEST FOR REVIEW TO ENSURE THAT THE FRONT END COVERS AS MUCH AS POSSIBLE OF THE NORMAL CONSENT PROCEDURES:

- ☐ IDENTIFICATION OF FIELDWORK AGENCY, IF APPLICABLE.
- ☐ IDENTIFICATION OF RESEARCHER.
- ☐ BASIC PURPOSE OF PROJECT.
- ☐ NATURE OF QUESTIONS TO BE ASKED, ESPECIALLY IF SENSITIVE QUESTIONS ARE TO BE ASKED.
- ☐ GUARANTEE OF ANONYMITY AND CONFIDENTIALITY.
- ☐ INDICATION OF RIGHT OF REFUSAL TO ANSWER ANY QUESTION.
- ☐ AN OFFER TO ANSWER ANY QUESTIONS BEFORE PROCEEDING. (SEE BELOW, ITEM 3)
- ☐ A SPECIFIC INQUIRY ABOUT WILLINGNESS TO PROCEED.

3. INDICATE HOW INTERVIEWERS WILL BE TRAINED TO ANSWER RESPONDENTS' QUESTIONS. INVESTIGATORS SHOULD PREPARE AND SUBMIT 'SCRIPTED REPLIES', WHICH MAY COVER, BUT ARE NOT NECESSARILY LIMITED TO:

(A) MEANS BY WHICH RESPONDENT WAS SELECTED.

(B) AN INDICATION OF THE ESTIMATED TIME TO BE REQUIRED FOR THE INTERVIEW.

(C) THE MEANS BY WHICH GUARANTEES OF ANONYMITY AND CONFIDENTIALITY WILL BE ACHIEVED.

(D) AN OFFER TO PROVIDE THE NAME AND TELEPHONE NUMBER OF A PERSON WHO CAN VERIFY THE AUTHENTICITY OF THE RESEARCH PROJECT. THIS PERSON SHALL NOT BE THE RESEARCH ADMINISTRATION OFFICER OR ANY PERSON IN THE OFFICE OF RESEARCH SERVICES AND ADMINISTRATION. (NOTE: INVESTIGATORS SHOULD BE PREPARED, SHOULD POTENTIAL RESPONDENTS REQUEST IT, TO PROVIDE THE NAME OF A PERSON OUTSIDE THE RESEARCH GROUP, AS REQUIRED BY SECTION 9 OF THE SSHRC GUIDELINES.)

4. SENSITIVE SUBJECT MATTER: RESPONDENTS SHOULD BE FOREWARNED OF SUCH QUESTIONS. IT IS NOT ALWAYS PRACTICAL TO DO SO AS PART OF THE INTERVIEW'S FRONT END. WARNINGS CAN BE PLACED LATER IN THE INTERVIEW AND CAN TAKE A NATURALISTIC FORM AS LONG AS THEIR CONTENT SPECIFICIALLY REFERS TO THE SENSITIVE MATTER. INDICATE HOW YOU PROPOSE TO DEAL WITH SENSITIVE ITEMS, IF ANY, IN YOUR INTERVIEW.

Appendix A_3

Physical Activity Questionnaire

Healthy Bones Activity Questionnaire: Spring 2000

Name:______________________________ Age:________
Sex: M___ F___ Grade:_______

We would like to know about the physical activity you have done in the last 7 days. This includes sports or dance that make you sweat or make your legs feel tired, or games that make you huff and puff, like tag, skipping, running, and climbing.

Remember:

A. There are no right or wrong answers – this is not a test.

B. Please answer all questions as honestly and accurately as you can – this is very important.

---

1. PHYSICAL ACTIVITY IN YOUR **SPARE TIME (this <u>does not</u> include P.E classes)**.
Have you done any of the following activities in the **past 7 days**? If yes, how many times and for how long?

Tick only one circle per row	No	1-2	3-4	5-6	7 or more times	time per session
Skipping	O	O	O	O	O	________
Four Square	O	O	O	O	O	________
Creative Playground	O	O	O	O	O	________
Tag	O	O	O	O	O	________
Walking for exercise	O	O	O	O	O	________
Bicycling	O	O	O	O	O	________
Jogging or running	O	O	O	O	O	________
Aerobics	O	O	O	O	O	________
Swimming	O	O	O	O	O	________
Baseball, softball	O	O	O	O	O	________
Dance	O	O	O	O	O	________
Football	O	O	O	O	O	________
Badminton	O	O	O	O	O	________
Skateboarding	O	O	O	O	O	________
Soccer	O	O	O	O	O	________
Street Hockey	O	O	O	O	O	________
Volleyball	O	O	O	O	O	________
Floor Hockey	O	O	O	O	O	________
Basketball	O	O	O	O	O	________
Ice skating	O	O	O	O	O	________
Cross-country skiing	O	O	O	O	O	________
Ice hockey/ringette	O	O	O	O	O	________
Other:____________	O	O	O	O	O	________
________________	O	O	O	O	O	________

2. In the last 7 days, during your **PHYSICAL EDUCATION (PE) CLASSES**, how often were you very active (playing hard, running, jumping and throwing)? Check only one.

O I don't do PE
O Hardly ever
O Sometimes
O Quite often
O Always

3. In the last 7 days, what did you do most of the time at **RECESS?** Check only one.

O Sat down (talking, reading, doing school work)
O Stood around or walked around.
O Ran or played a little bit.
O Ran around and played quite a bit.
O Ran and played hard most of the time.

4. In the last 7 days, what did you normally do **AT LUNCH** (besides eating lunch)? Check only one.

O Sat down (talking, reading, doing school work)
O Stood around or walked around.
O Ran or played a little bit.
O Ran around and played quite a bit.
O Ran and played hard most of the time.

5. In the last 7 days, on how many days **RIGHT AFTER SCHOOL**, did you do sports, dance, or play games in which you were very active? Check only one.

O None.
O 1 time last week.
O 2 or 3 times.
O 4 times last week.
O 5 times last week.

6. In the last 7 days, on how many **EVENINGS** did you do sports, dance, or play games in which you were very active? Check only one.

O None.
O 1 time last week.
O 2 - 3 times.
O 4 - 5 times last week.
O 6 - 7 times last week.

7. How many times did you do sports, dance, or play games in which you were very active **LAST WEEKEND?** Check only one.

- O None.
- O 1 time.
- O 2 - 3 times.
- O 4 - 5 times.
- O 6 or more times.

8. Which **ONE** of the following five statements describes you best for the last 7 days? Read all 5 before deciding on the one answer that describes you.

O All or most of my free time was spent doing things that involved **little physical effort** (e.g. watching TV, homework, playing computer games, Nintendo).

O **I sometimes (1-2 times last week) did physical things** in my free time (e.g. played sports went running, swimming, bike riding, did aerobics).

O **I often (3-4 times last week) did physical things** in my free time.

O **I quite often (5-6 times last week) did physical things** in my free time.

O **I very often (7 or more times last week) did physical things** in my free time.

9. How many hours per day did you watch television or play Nintendo last week? (each show is usually a half hour or 30 minutes). Check only one.

- O I watched less than 1 hour or have no TV.
- O I watched more than 1 hour but less than 2.
- O I watched more than 2 hours but less than 3.
- O I watched more than 3 hours but less than 4.
- O I watched more than 4 hours.

10. Were you sick last week, or did anything prevent you from doing your normal physical activities?

- O Yes
- O No

If yes, what prevented you?____

11. Mark how often you did physical activity (like playing sports, games, doing dance or any other physical activity) for each day last week (this includes P.E, lunch, recess, after school, evenings, spare time, etc).

	None	Little Bit	Medium	Often	Very Often
Monday	O	O	O	O	O
Tuesday	O	O	O	O	O
Wednesday	O	O	O	O	O
Thursday	O	O	O	O	O
Friday	O	O	O	O	O
Saturday	O	O	O	O	O
Sunday	O	O	O	O	O

12. Do you participate in **organized sport** or **activities** (music lessons, Chinese school, tutoring, girl guides, boy scouts) outside of school?

O Yes

O No

If yes, what sport(s) or activities do you do?

____

____

How many nights during the week do you do these activities? (If you have swimming lessons on 2 nights of the week, check the circle beside "2" and write swimming lessons on the line. You can have more than one activity on a line).

O 1 activity: ____________________

O 2 activity: ____________________

O 3 activity: ____________________

O 4 activity: ____________________

O 5 activity: ____________________

O 6 activity: ____________________

O 7 activity: ____________________

Appendix B

Standardized Instructions for the Jumps

Jumping Instructions

Jumping Jacks/ side splits

I. Practice Jumps

1) *First we are going to do Jumping Jacks/ side splits.*

a) They look like this (demo).

b) Start by standing on the middle of the white square (force platform), with feet together, hands on hips.

c) Let's do a practice jump.

d) Jump moving feet apart and then bring the feet together

e) Jump at a steady pace.

II. Measured Jumps

1) *Now we are going to measure your jumps.*

a) *Starting position.*

b) Please do 5 jumps in a row ending with your feet on the white square. I'll count for you.

c) After the final jump please stand quietly on the white square for a few seconds

Jumping Jacks/ side splits (maximal)

d) Next we are going to do maximal Jumping Jacks/ side splits this time the jumps will be as high as you can

Alternating Feet (no obstacle)

d) Jump side to side with a steady rhythm (no hops in the middle)

Counter Movement Jump

d) ***Jump as high as you can (bending knees)***

e) Kelly will tell you when to start jumping

Two feet Side-to-side (10 cm barrier)

> ***d) Jump over the barrier keeping the feet together and jump back onto the force platform***

Two feet Side-to-side (15 or 20 cm barrier)

> **d) *This is the same jump as before, but with a higher piece of foam.***

Drop Jump/ Plyometric Jump (Green platform)

> **d) *You will drop off of the green platform onto the force platform followed by a quick jump as high as you can***

Drop Jump/ Plyometric Jump (Green platform with two purple lifts)

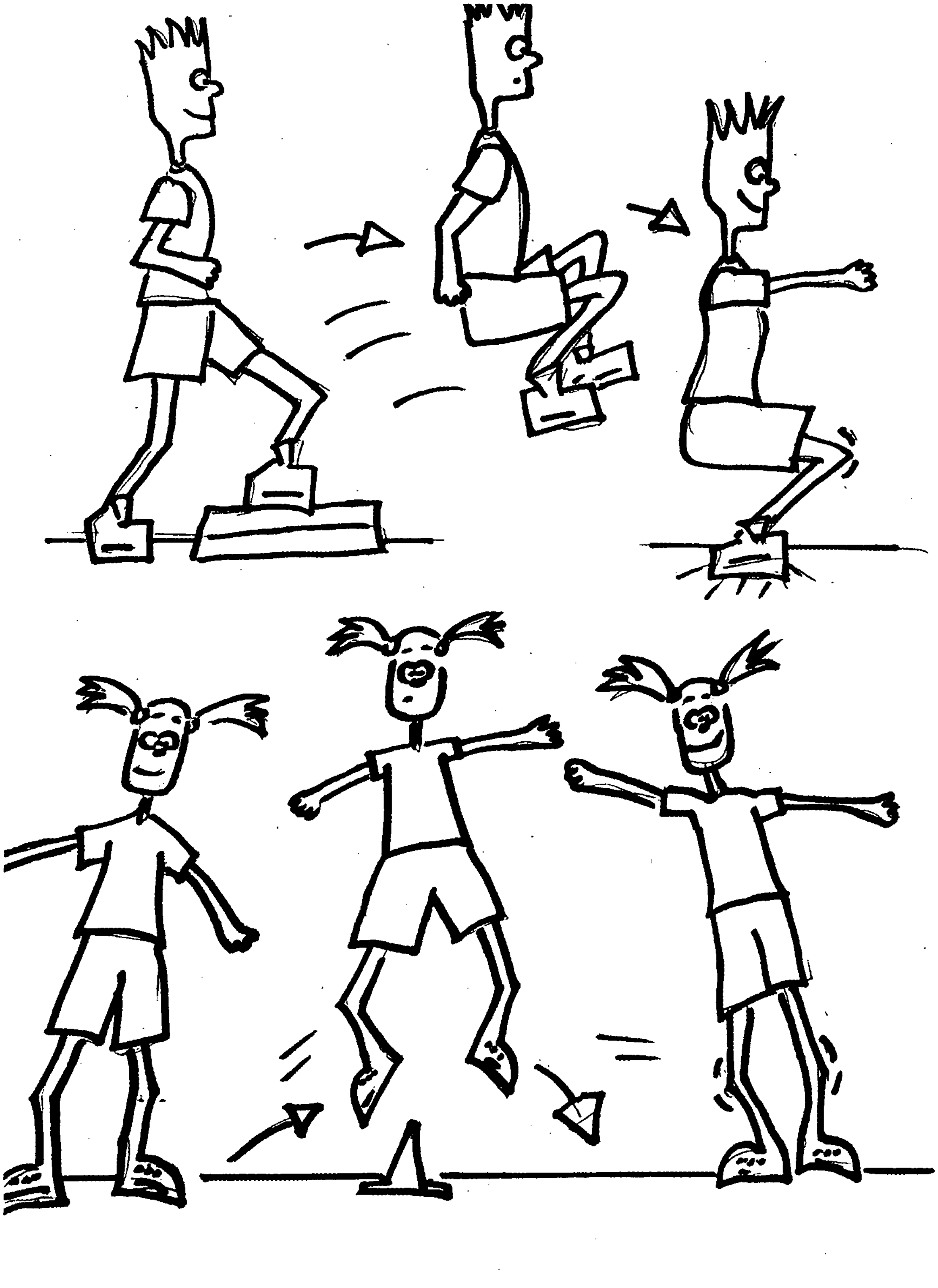
> ***d) Same as the previous jump***

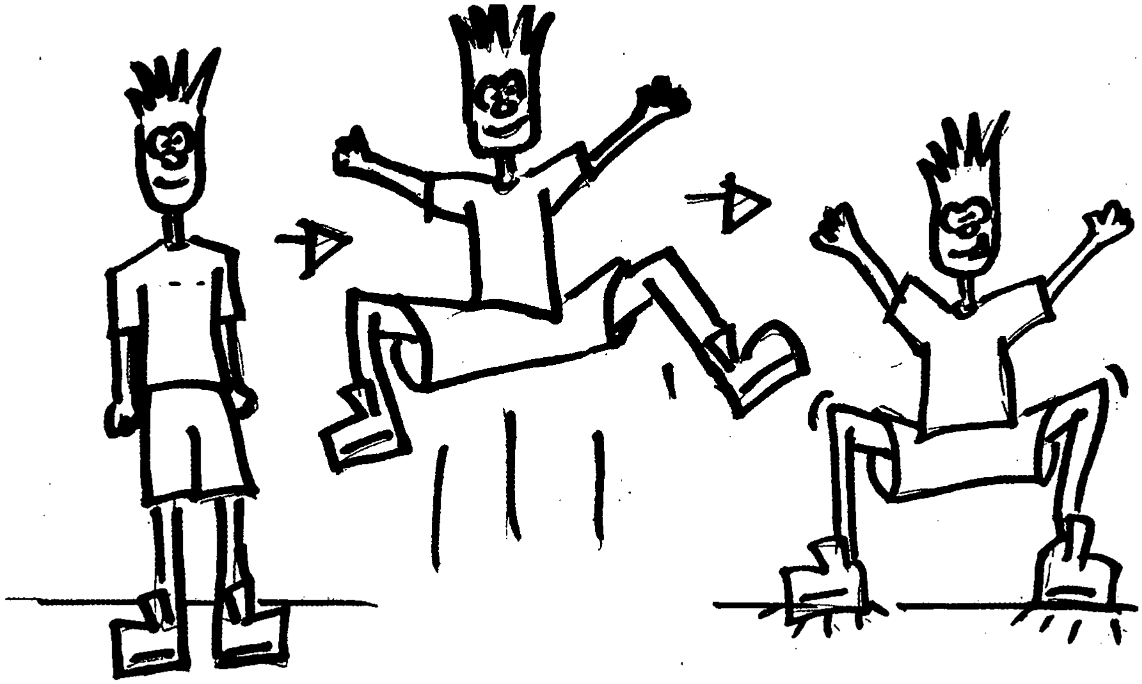
Drop Jump/ Plyometric Jump (Green platform with four purple lifts)

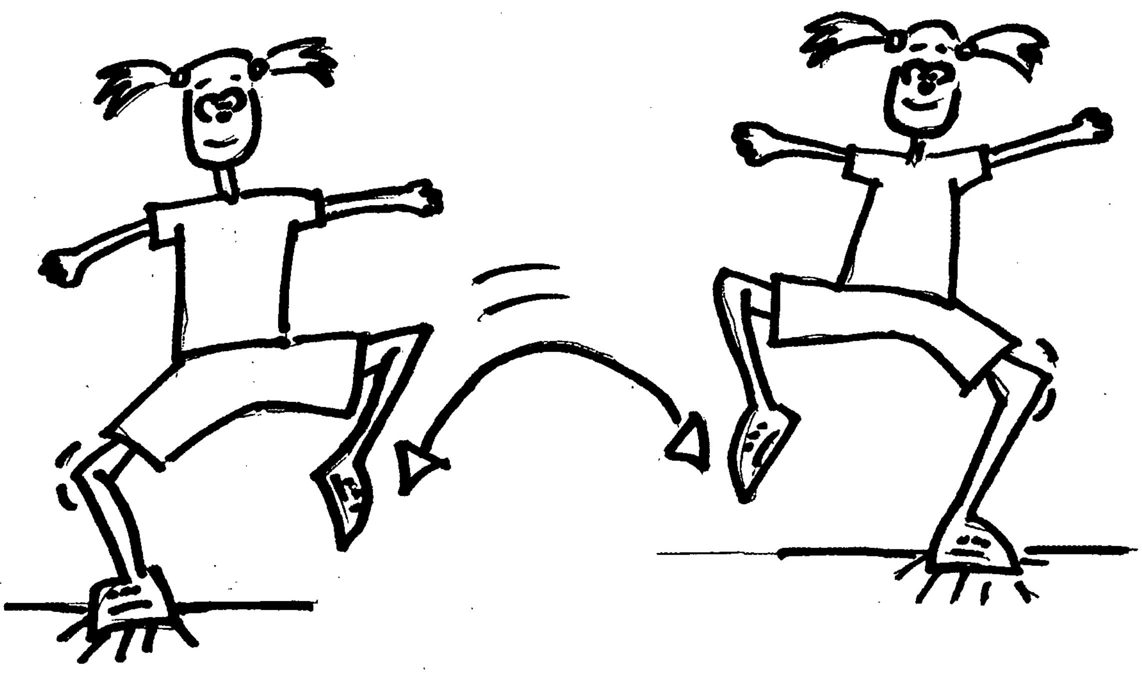
> ***d) Same as the previous two jumps***

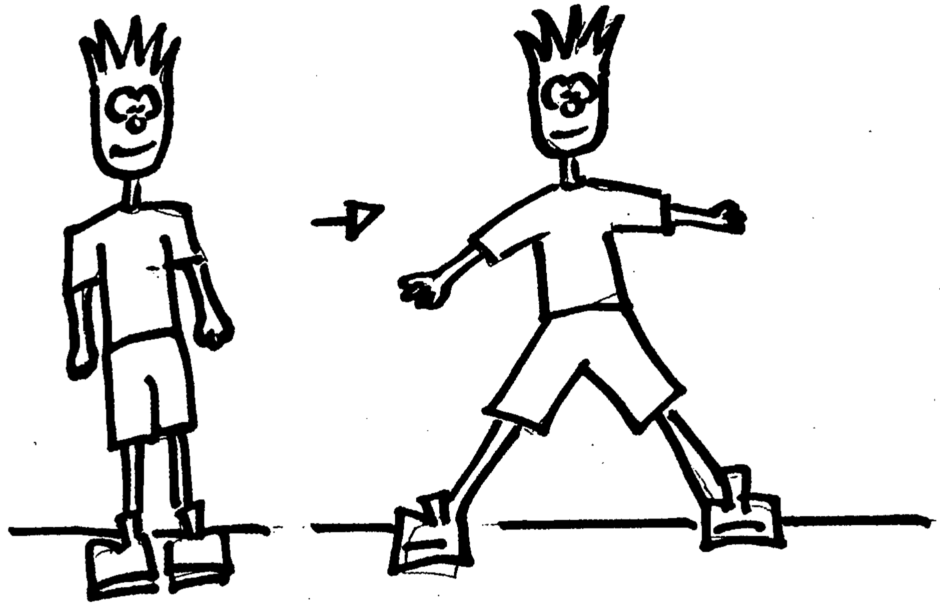
Appendix C

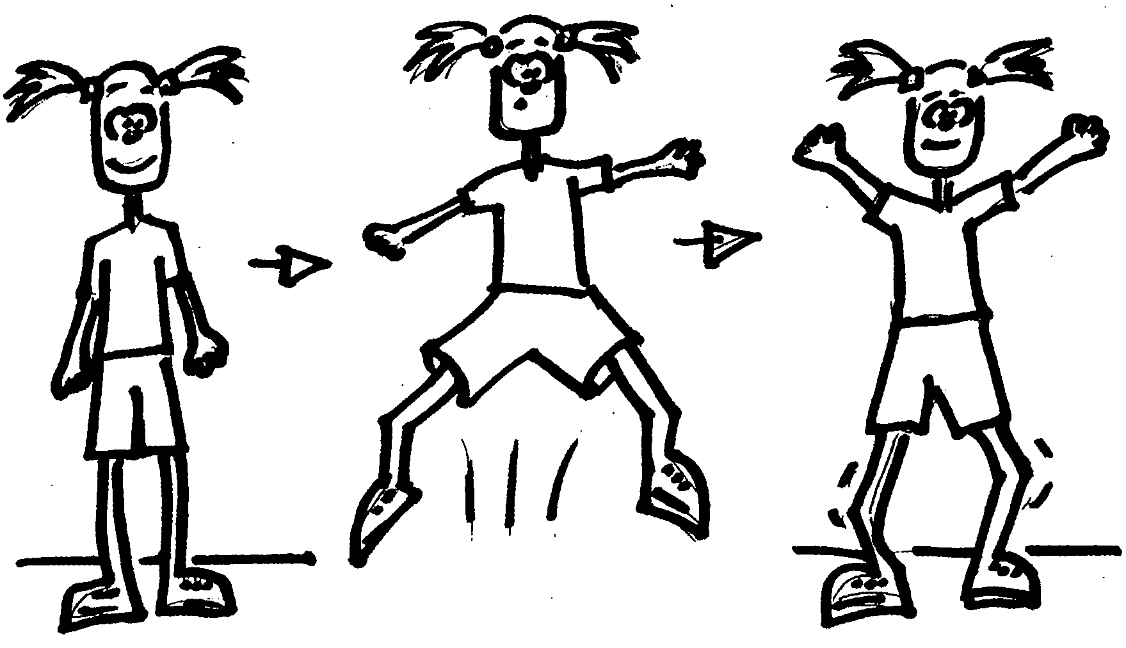
Illustration of the Jumps







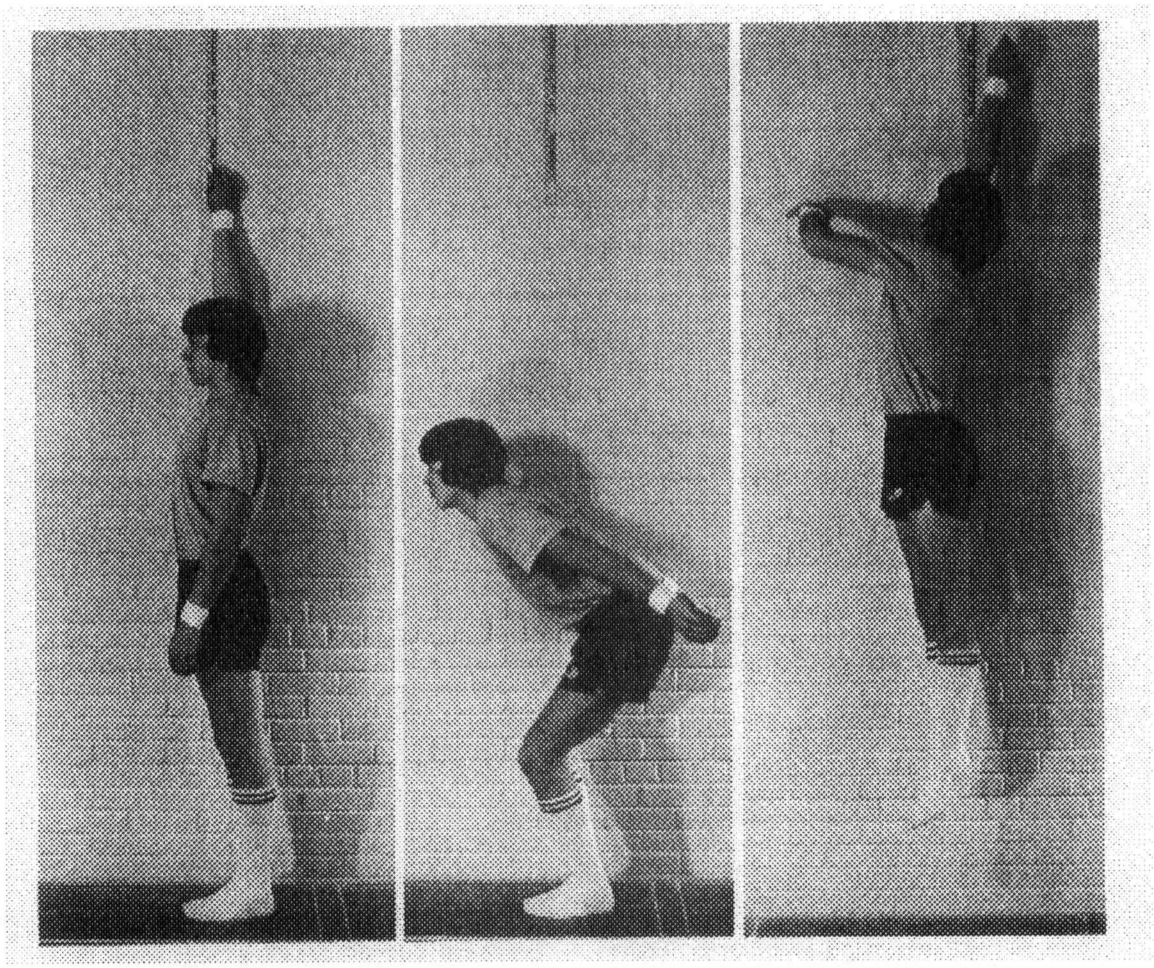




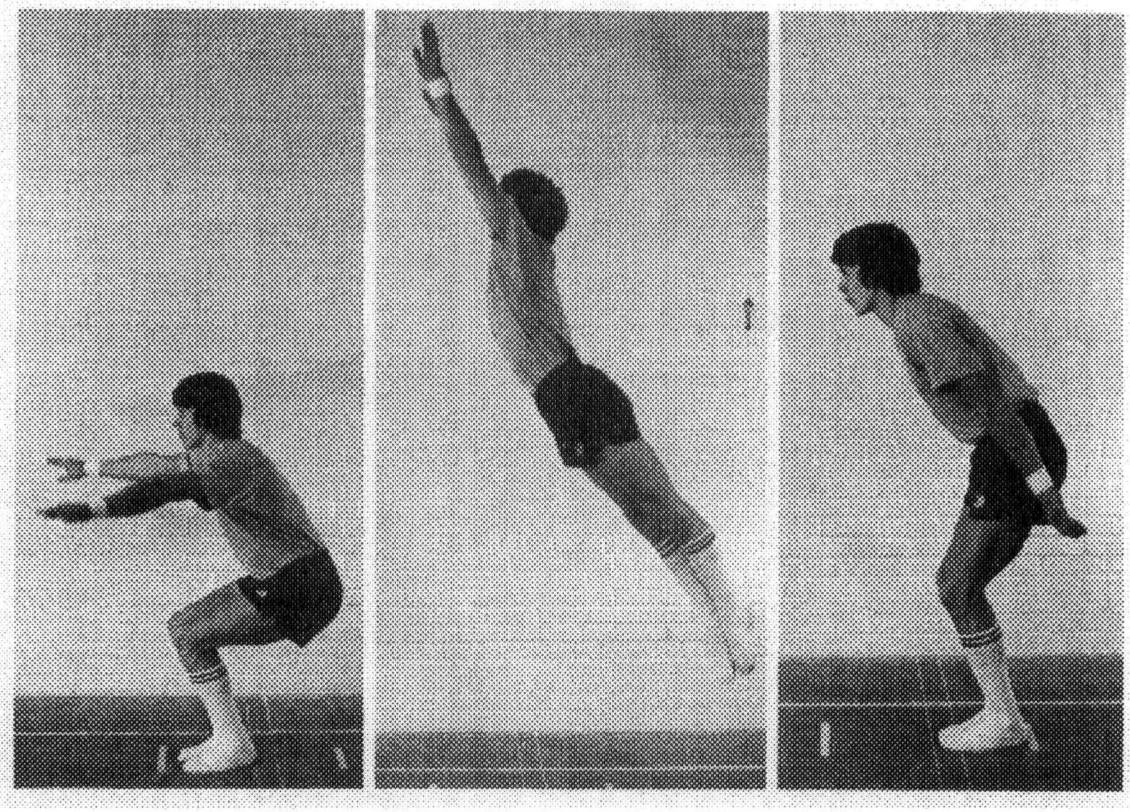
Appendix D

Dynamic Power Measures (Vertical and Standing Long Jump)

Vertical Jump Test



Standing Long Jump

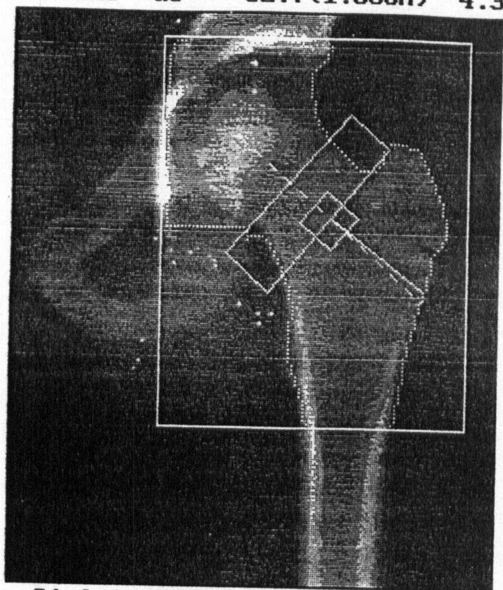


Appendix E

DXA Scan

U.B.C.

k = 1.139 d0 = 52.7(1.000H) 4.365



·21.Oct.1999 14:22 [81 x 101]
Hologic QDR-4500W (S/N 48346)
Left Hip V8.23a:5

01021991X Thu 21.Oct.1999 13:06
Name:
Comment:
I.D.: 2239 Sex: F
S.S.#: - - Ethnic: W
ZIPCode: Height: 153.10 cm
Operator: KM Weight: 33.60 kg
BirthDate: 31.Dec.88 Age: 10
Physician:
Image not for diagnostic use

TOTAL BMD CV 1.0%

Region	Est.Area (cm2)	Est.BMC (grams)	BMD (gms/cm2)
C.F.	1.043	1.025	1.000
Neck	4.77	2.86	0.599
Troch	6.87	3.34	0.487
Inter	13.87	9.09	0.655
TOTAL	25.51	15.29	0.599
Ward's	1.27	0.78	0.609

Midline (88,106)-(136, 64)
Neck -49 x 15 at [24, 14]
Troch 4 x 31 at [0, 0]
Ward's -11 x 11 at [5, 5]

HOLOGIC