AN ABSTRACT OF THE THESIS OF

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Title: Effect of Jumping On Growing Bones: Forces During Different Landings

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In order to develop a stimulating yet effective school-based program which elicits a positive bone growth response, we need to understand the forces acting on the bones of children during various high-impact activities. One activity found to promote bone growth is drop landings from a height. We determined whether there are other jumping activities that exhibit similar loading properties to those of a drop landing and identified the effects of number of feet used, continuity, and direction on loading.

Twenty-one healthy children (11 boys, 10 girls; age 7-9 years) were recruited from the local population. After warming up, each child performed five trials of 13 types of jumps as motion capture and ground reaction force data were collected. One type of jump was a drop landing from a 61 cm-high platform. The other 12 types were performed from the ground and comprised all possible combinations of three factors: direction (vertical as high as possible, forward a distance of 80% body height, sideways a distance of 55% body height), feet used (1-footed hops, 2-footed jumps), and continuity (discrete,
continuous). The average peak force and peak loading rate at the hip of the dominant limb over five trials were computed and normalized to body weight for analysis. Three-way ANOVA identified loading differences across direction, feet used, and continuity among the 12 jump types. Paired t-tests with a Bonferroni correction compared the loading for each activity to that of the drop landings.

In general, peak forces and loading rates during landing were greater for hops than for jumps, greater for discrete than for continuous hops/jumps, and greater for forward than for vertical hops/jumps. However, peak forces did not differ between sideways hops and jumps, nor did peak loading rates differ between vertical hops and jumps. Peak forces during the drop landings exceeded those during all other jumping activities except the discrete forward hop, which had peak forces similar to the drop landing. Although discrete forward hops had greater peak loading rates than the other 11 activities from the ground, the rates were less than those during the drop landings. Likely, the need to arrest the body’s large forward momentum using a single limb upon landing of the discrete forward hop elevated loading over the other 11 conditions and made it comparable to that of the drop landing.

Knowing what factors influence impact forces and loading rates on the hip, specifically that discrete forward hops have high forces similar to those for drop landings, will aid in developing a stimulating and effective jumping program for improved bone development in children.
Effect of Jumping On Growing Bones: Forces During Different Landings

by
Bradley A. Black

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Bradley A. Black, Author
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Effect of Jumping On Growing Bones: Forces During Different Landings

INTRODUCTION

By their mid-to-late 20's, men and women achieve their peak bone mass, at which point bone commences to depreciate and weaken into old age (Henry et al., 2004). Osteoporosis is said to be responsible for more than 1.5 million fractures annually, including over 300,000 hip fractures and approximately 700,000 vertebral fractures, and these numbers are expected to double by the year 2050 (National Osteoporosis Foundation, 2004).

Many treatments have been tried to treat osteoporosis in older adults. The most common treatment uses hormone replacement therapy and other drugs to reduce the rate of bone absorption. The problems with this treatment are that it is costly and there are side effects that may not outweigh the benefits. Also, the bone that remains may not maintain the suitable structure to prevent fractures due to a lack of loading stimulus on the bone (Burr et al. 2002). Therefore, increased emphasis has recently been put on the prevention, rather than the treatment, of osteoporosis to help curtail the burden mentioned above. Of particular interest are interventions with exercises that apply impact forces to the bones.

Bone adapts to loading, and the loading characteristics that increase bone mass have been revealed from animal model studies. It has been reported that dynamic loads with high peak force magnitude and rate of loading are determining factors of bone adaptation. Particularly, strain rate has been shown to be associated with a greater bone response than strain magnitude and it is more important to have loads that are applied
quickly than high magnitude loads (Burr et al., 2002; Turner, 1998). Also, there is a saturation effect where bone cells accommodate to a mechanical loading situation, making them less responsive to the usual loading signals (Smith & Gilligan, 1996; Turner & Pavalko, 1998). This is the reason that most routine activities such as walking and running do not increase bone, even if you do more of them. Based on this knowledge, it has been hypothesized that osteoporosis might be prevented through a varied program of high-impact exercises, such as jumping.

It is becoming clearer that the most suitable time to intercede is with exercise intervention during the growing years of childhood, when the majority of bone mineralization occurs (Modlesky & Lewis, 2002). Low peak bone mass may be a more important determinant of low bone density and risk of osteoporotic fracture later in life than is age-related bone loss (Henry et al. 2004). Therefore, finding ways to increase peak bone mass may be a practical way to reduce osteoporosis risk.

Exercise interventions involving jumping exercises have been found to increase bone mass in children. Fuchs and colleagues (2001) found that prepubertal children who performed 100 drop landings per day, three times per week, from a 60 cm box had significantly higher bone mineral density after 7 months than controls. Also, following 7 months of detraining, the children retained the new bone (Fuchs & Snow, 2002). In addition, a randomized school-based jumping intervention that also lasted for 7 months but did various jumping activities in circuit style for 10-12 minutes a day, two times per week, found small but significant increases in bone mineral density (Petit et al. 2002). Increased peak force magnitude and strain rate of drop landings and jumping activities over children’s “normal” daily activity is likely the cause of increased bone mass. This is
noteworthy because the extra bone created from relatively small amounts of specific exercises during youth may last into adulthood. According to Mackelvie and colleagues, the take-home message to gleam from the current literature is,

"During the very early stages of puberty, bone may be particularly responsive to weight-bearing, high impact exercise, attainable in a range of youth sports and activities or in brief sessions of jumping activity" (Mackelvie et al., 2002, p. 256).

However, unlike other health factors such as cardiovascular and muscle fitness, there are no exercise prescription guidelines for improving peak bone mass in normally active children. It is known that drop landings from a 61cm box produce adequate loading on the hip to increase bone mass, yet these became monotonous for children. Thus, in order to develop a stimulating yet effective school-based program that elicits a positive bone response, we need to understand the differences in loading on the bones with varying high-impact activities.

It is currently unknown what characteristics about ground level jumping activities maximize loading, especially at the hip, where bone mass is needed to protect against fracture in older age. Based on a review of a widely used curriculum text (Pangrazi, 2003), characteristics of jumping activities performed by children in physical education classes were identified. The jumping activities were found to differ in the number of feet used (i.e. hops vs. jumps), in direction, and in whether jumps were performed discretely or continuously. Thus, the purpose of this study was to evaluate the effects on the peak force and peak rate of loading at the hip of a) one-legged versus two-legged landings, b) continuous versus discontinuous hops/jumps, and c) forward, vertical, or sideways directed landing activities. In addition, the loading at the hip associated with each
combination of these factors was compared to the loading characteristics of the 61 cm drop landing.
LITERATURE REVIEW

By their mid-to-late 20's, men and women achieve their peak bone mass, at which point bone commences to depreciate and weaken into old age (Henry et al., 2004). Osteoporosis (porous bone) is caused by a decrease in bone tissue that leads to fragility and increased risk of fractures. Known as the “silent killer”, this disease is said to be responsible for more than 1.5 million fractures annually, including over 300,000 hip fractures and approximately 700,000 vertebral fractures, 250,000 wrist fractures, and 300,000 fractures at other sites (National Osteoporosis Foundation, 2004). These numbers are expected to double by the year 2050 (National Osteoporosis Foundation, 2004). The estimated national direct expenditures (hospitals and nursing homes) for fractures associated with osteoporosis was $17 billion in 2001 ($47 million each day) and the cost is rising (National Osteoporosis Foundation, 2004). In addition to bone fractures, other common health consequences of osteoporosis are related to quality of life and daily activities. These consequences include frailty and difficulty with balance, weakness, cognitive decline, depression, poor perceived health, less social support, and not enjoying free time as much (Kotz et al., 2004).

Many treatments have been tried to treat osteoporosis in older adults. The most common treatment uses hormone replacement therapy and other drugs to reduce the rate of bone absorption. The problems with this treatment are that it is costly and there are side effects that may not outweigh the benefits. The “Women’s Health Initiative Study” on women and hormone replacement therapy was ended three years early because the side effects include a 26% increased risk for invasive breast cancer, 41% increased risk of
having a stroke, a 100% increased risk of blood clots, and a 29% greater risk of heart attack (Nelson et al., 2002).

Recently, increased emphasis has been put on the prevention of osteoporosis to help curtail the burden mentioned above. It is becoming clearer that the most suitable time to intercede is with exercise intervention during the growing years of childhood, when the majority of bone mineralization occurs (Modlesky & Lewis, 2002). Low peak bone mass may be a more important determinant of low bone density and risk of osteoporotic fracture later in life than is age-related bone loss (Henry et al., 2004).

Therefore, finding ways to increase peak bone mass may be a practical way to reduce osteoporosis risk. Fuchs and colleagues (2001) found that prepubertal children who performed 100 drop landings per day, three times per week, from a 60 cm box had significantly higher bone mineral density after 7 months than controls. Also, following 7 months of detraining, the children retained the new bone (Fuchs & Snow, 2002). In addition, a randomized school-based jumping intervention that also lasted for 7 months but did various jumping activities in circuit style for 10-12 minutes a day, two times per week found small but significant increases in bone mineral density (Petit et al., 2002). This is noteworthy because the extra bone created from relatively small amounts of specific exercises during youth may last into adulthood.

Small gains in bone mineral density (BMD) can have a considerable impact on the mechanical strength of bone. Robling and colleagues (2002) showed that a 5.4% increase in areal BMD resulted in a 64% increase in the maximum amount of compressive force the bone could support before failing. However, unlike other health factors such as cardiovascular and muscle fitness, there are no exercise prescription
guidelines for improving peak bone mass in normally active children. Thus, it is important to understand the factors that affect the accumulation of bone so that we can identify ways to increase peak bone mass. The objective is to determine and manipulate the modifiable factors of bone augmentation to an extent that is significant, thereby producing an increase in peak bone mass that is maintained into old age; at which time osteoporotic fractures are curtailed. Factors that may affect the accumulation of peak bone mass are: response to mechanical loading, genetics, nutrition, activity level, sex, and ethnic differences (Mora & Gilsanz, 2003).

**Mechanical Loading and Bone**

Understanding how mechanical loading affects bone modeling is a vital piece in developing an effective protocol to enhance peak bone mass. Wolff (1892) first proposed that bone is a dynamic tissue that adapts to environmental stimulus (also known as “form follows function”). There is a minimum and maximum threshold to the mechanical strain at which bone adaptation occurs, strain that is below the minimum threshold will prompt bone mass to decrease, whereas bone mass will increase if strain is above the maximum threshold. Only in the last few decades have we begun to understand how this happens.

Studies using animal models have revealed many of the mechanical stress properties that affect bone modeling. Recently, Burr and colleagues (2002) have followed up previous studies, confirming and exposing the characteristics of mechanical stress that influence bone modeling. First, it has been shown that dynamic, but not static loads drive bone adaptation (Turner & Pavalko, 1998). In a recent study, Burr and colleagues (2002) applied two static compressive loads of 8.5 N and 17 N and dynamic
loads of 17 N to the ulnae of growing male rats for 10 min/day for two weeks. The results confirmed that dynamic loading increased bone modeling significantly; static loading at either load magnitude had no effect on endocortical bone formation rate and suppressed periosteal bone formation (Robling et al., 2001).

Dynamic loads all have a magnitude, frequency, and rate, which are related to how the bone responds. The more "abnormal" these factors of the dynamic load are within physiological limits, the faster the bone will respond. Strain magnitude of the dynamic load is recognized as important in disrupting equilibrium of the bone modeling equation. Additionally, strain rate has been shown to be associated with a greater bone response than strain magnitude and it is more important to have loads that are applied quickly than high magnitude loads (Burr et al., 2002; Turner, 1998). It is unclear how effective higher frequency (cycles per second) loading is at increasing bone strength. Rubin and colleagues (2001) conducted a study using sheep and found that, as the loading frequency increases, the mechanical load required to initiate new bone formation decreases. Small loads were applied to hind limbs at 30 Hz for 20 min per day for one year. Trabecular bone volume was increased by more than 30% in the femur, but there was no increase in bone mass at any cortical bone site. Recent studies were completed on human subjects using high-frequency vibration loads. Verschueren and colleagues (2004) studied postmenopausal women using whole body vibration along with strength training and found that the vibration group's bone mineral density was 1.51% greater than the control group, which also completed the strength-training program. When vibration loads were applied just to the feet, the bone modeling response was only in the
tibia, suggesting that the small loads did not reach the hip due to the dampening that occurs at the joints and tissues of the lower limb (Ward et al., 2004).

Second, lengthening the loading duration has a diminishing effect on further bone adaptation. Thus, splitting loading sessions will have a greater osteogenic effect than one longer session. In a recent study, Robling et al. (2002) administered identical mechanical inputs to rats on two different schedules, one in a single session of 360 load cycles, the other in four sessions of 90 cycles with a few hours in between. With splitting the loading session into four sessions, the rats’ bone energy to fatigue was 75% greater than in the single-session rats. Therefore, by allowing a recovery period between loading bouts, the desensitizing affect is minimized, which allows the bone to further adapt.

Third, as proposed by Wolff (1892), there is a saturation effect where bone cells accommodate to a mechanical loading situation, making them less responsive to the usual loading signals, which means that the mechanical loading must be altered often to keep eliciting a bone modeling response (Smith & Gilligan, 1996; Turner & Pavalko, 1998). This is the reason that most routine activities such as walking and running do not increase bone, even if you do more of them. For example, a person who has played soccer most of his or her life may have a greater bone density than a sedentary person who never participated in a high impact activity, but playing more soccer will produce no additional increase in osteogenic activity in the soccer player.

Other factors may alter the response to mechanical loading, such as genetics, hormones, and nutrition. It was determined from twin sibling studies that approximately half of the variation in bone mineral density is attributed to genetic factors (Cowell & Tao, 2002). It is unknown how genetics affect bone response to mechanical loading.
Most studies have used a method that recognizes genes involved in regulating modeling and remodeling of bone. The regulation of bone modeling (formation and absorption) is the primary mode for creating new bone in response to loads; therefore, genetics may play a role in this process. While much information on genetic factors influencing bone modeling has been assessed in adults, these factors have yet to be examined in children (Brown et al., 2001). Hormones such as estrogen may alter how bones respond to mechanical loading, especially in adolescence when 40% of bone mass is obtained in females. Estrogen deficiency in adolescent girls has been shown to cause a severe reduction in peak BMD (Bailey et al., 1999). Many studies have addressed the issue of calcium and its relationship to bone mineralization, and it is still controversial whether calcium supplementation increases BMD (French et al., 2000). Studies have shown an increase in BMD of 1-4% during supplementation but, once discontinued, the gains in bone normalized to that of the controls (French et al., 2000; Lloyd et al., 2002). Interaction effects may exist between nutrition and mechanical loading on bone growth and mineralization. Specker and Binkley (2003) found that calcium intake alone did not influence total bone mass accretion and that physical activity without calcium supplementation resulted in very little increase in BMD. However, when calcium intake was combined with a physical activity program there were significant gains in BMD. Although genes play a significant role in peak BMD, we cannot ignore other variables in the osteoporosis equation. Even though a person may be more genetically prone to fracture risk later in life, peak bone mass may be enhanced by other factors, including high loading exercises and healthy lifestyle, to decrease the threat of fracture in old age.
In summary, evidence points to an optimal combination of magnitude, rate, frequency, and loading schedule of dynamic bone loading that will have maximum effect on bone formation and integrity. Also, it may be necessary to periodically alter the combination of the dynamic stimulus to avoid the saturation effect and the limiting of peak bone mass. Unfortunately, this optimal combination for dynamic loading has yet to be found in humans. Better understanding of how Wolff’s law of “form follows function” governs bone response to mechanical loading is fundamental to developing ways to increase peak bone mass in humans.

**Exercise and Bone**

It is hypothesized that various exercise modes and frequencies during childhood will result in a significant increase in peak bone mass, ultimately leading to greater bone strength and decreased fracture risk in old age. Although longitudinal studies that have implemented an intervention program in children and followed them into old age have yet to be completed, there is evidence to support this hypothesis. It is clear that the human skeleton responds to mechanical loading during exercise (Lloyd et al., 2002). According to Mackelvie et al., the take home message to gleam from the current literature is,

“During the very early stages of puberty, bone may be particularly responsive to weight-bearing, high impact exercise, attainable in a range of youth sports and activities or in brief sessions of jumping activity” (Mackelvie, 2002, p. 256).

Cross-sectional and intervention studies support this conjecture and may give us some direction in designing a program that can reduce the burden of osteoporosis later in life. Studies of athletes who participated in high-impact sports show evidence of increased
BMD having residual benefit compared to their controls. Gymnasts show greater BMD than athletes in other, non-high-impact sports such as biking, swimming, and even running, and retired gymnasts have been found to have residual BMD enhancement later in life (Bass et al., 1998). Studies of young and old tennis players have shown significantly greater bone mass in the dominant arm than in the non-dominant arm (Bass et al., 2002). This strongly supports the notion that the bone gains are from the exercise and not from other factors such as genetics or nutrition. This and another study also found that tennis players at the same competitive level who started playing just before puberty had significantly greater BMD in the playing arm than players who started post puberty (Kontulainen et al., 2003). This is strong evidence that exercise before and during puberty is the best time to illicit the greatest bone response. Also, these studies have shown that gains in bone mass due to exercise are proportional to the applied load specific to the sport and the level of competition (Bass et al., 2002; Kontulainen et al., 2003). For example, elite gymnasts have greater bone growth than recreational soccer players.

Recent longitudinal studies are confirming the findings from previous cross-sectional studies. Moisio and colleagues (2004) estimated that up to 40% of the variance in peak bone mass at the proximal hip can be explained by the history of dynamic loading. A recent longitudinal study that followed gymnasts for 3 years and accounted for factors such as biological age, body size, and energy and protein intake found a 13-18% higher BMD in the gymnasts than in the controls (Nurmi-Lawton et al., 2004). In a five year follow-up study, retired elite racquet sport athletes maintained more bone mineral, even with greatly reduced training, compared to controls (Kontulainen et al.,
Kontulainen and colleagues (2003) found that moderate physical activity after an 18-month high-impact intervention had lasting benefits for bone. The subjects in the training group maintained their greater bone accumulation after 3.5 years of detraining, during which most subjects participated in low-impact physical activity such as cycling and swimming. The study examined women in their 40's, which demonstrates that it may be possible for mature bone to have residual benefits following a high-impact training period. Conversely, Winters and Snow (2000) found that a comparable 12-month protocol on women of similar age increased BMD, but the gains were lost after 6 months of detraining. It is well accepted that exercise, especially high-impact activities that are sustained from youth to adulthood, is beneficial to bone health, but it is still unclear whether short-term interventions in youth will result in greater peak bone mass. It seems likely, however, that the benefits of a high-impact loading phase in youth will be maintained if it is following up by regular moderate exercise into old age.

In contrast to studying athletes, the “Iowa Bone Development Study” examined the effects of usual everyday activity on bone accretion in young, non-athletic children. They found that minutes spent in vigorous physical activity tended to be the variable most associated with bone measures, and their categorical analysis found approximately a 12% difference in mean hip bone mineral content between the least and most vigorously active children (similar for boys and girls) (Janz et al., 2001). Moreover, results from this study suggested that as little as a 10-minute increase in daily vigorous physical activity would result in an increase equivalent to three percent of mean bone mineral content at the hip and two percent at the spine. This is important because ten additional minutes of vigorous physical activity per day is practical and attainable for children.
A common hypothesis regarding exercise and bone is a connection between increased muscle size and increased bone mass, the idea that muscle stimulated by exercise would lead directly to a balanced increase in bone mass. Current data suggest otherwise, attributing gains to maturing factors of bone during growth, rather than muscle size and strength conditioning (Daly et al., 2004). I presume that this is because neither strengthening exercises nor increased muscle size stimulate bone with the appropriate mechanical loading combination to achieve bone modeling that augments bone strength through increased formation or enhanced structure.

In conclusion, it is clear that certain modes of exercise for men and women influence bone development and subsequent loss of bone. If done at particular stages of development during the growing years, the bone formed may be maintained. High impact weight-bearing exercise interventions with children that include jumping activities may be a practical means of increasing bone mass. This simple intervention during youth may lead to higher peak bone mass and reduce the chance for an osteoporotic fracture in later life, even if the high impact exercise is not continued.

**Biomechanical Factors of Landings**

When studying the possible beneficial aspects of landings, it is important to consider the many factors that affect the kinematics and kinetics of landings. Some factors to consider are: technique, landing surfaces/shoes, effect of instructions/training, learning effects, fatigue, landing height, body orientation, sex, skill level, specificity, and history of injury. These factors attribute to individual differences in kinematics and
kinetics of landings, thus it is difficult to study and make generalizations about group landing characteristics.

Loading rates and forces can be influenced by the technique used when performing a landing from a height. Peak forces generally increase with greater height and with less knee flexion upon landing, even though subjects perform landings using individual strategies (Dufek & Bates, 1991). The ground reaction force (GRF) curve for a landing is typically a bimodal curve (has two peaks), one pertaining to toe contact and the other to heel contact, the latter contributing most of the force to the body. Foot contact pattern, knee angle, and hip angle all influence this bimodal curve. Researchers have identified two primary foot contact patterns: toe-heel and flatfoot techniques. The flatfoot technique will produce a unimodal ground reaction curve, but toe-heel is most widely observed (Dufek & Bates, 1990). Upon ground contact, individuals tend to control knee flexion and ankle plantarflexion while actively extending the hip to resist the forward and downward rotation of the trunk (Devita & Skelly, 1992). Because the work by the hip is used to counteract the accelerated trunk motion, the hip is less involved in reducing GRF’s (Devita & Skelly 1992). Manipulating knee joint flexion/extension at landing tends to be the factor that influences ground reaction forces the most, with more flexion resulting in lower forces and extension (i.e. straight-leg landing) resulting in higher forces (Dufek & Bates, 1991).

Research that observed differences in take-off techniques in a jump found that this does not influence the kinematics or kinetics of landing behavior (McKinley & Pedotti, 1992). They found two take-off techniques that most people will generally use: roll-off and push-off. McKinley and Pedotti (1992) also found that skill level did not influence
which technique individuals chose, although their study had a low sample size. Thus it is
difficult to make predictions regarding skill level, technique, kinetic, and kinematic
properties from these data.

According to Prapavessis and colleagues (2003), verbal instructions have an
impact on landing technique and thus the kinetics and kinematics of a landing. They
found that, by using verbal cues with children, they could alter the landing technique of
the children and influence GRF forces. The children assimilated the instructions in one
session and were able to repeat the technique over multiple trials for a week. The learned
technique appeared to be temporary; after 3 months with no practice, the children were
not able to perform the altered landing technique without relearning the verbal cues
(Prapavessis et al., 2003).

Motor behavior and mechanical loading are also influenced by restrictions
imposed by the task and the orientation of the body (McNitt-Gray et al., 2001). The
mechanical demand and thus the associated motor control in gymnasts differed between a
front salto landing and a rear salto landing. The gymnasts altered muscle activations
prior to landing differently between the two landings, suggesting that there is some form
of feedforward control to prepare for anticipated differences in mechanical demand after
contact. These differences also varied between individuals; this may suggest that
personal preferences or skill level may vary for each person (McNitt-Gray et al., 2001).

A past injury may also influence landing technique. Decker and associates (2002)
conducted a study with subjects with prior anterior cruciate ligament (ACL)
reconstruction but who were fully recovered. They found that the previously injured
group had greater ankle range of motion, with an increased ankle angular velocity and a
more restrained use of the hip flexors, leading to a more erect body posture. This accounted for decreased loading rates of the bimodal vertical ground reaction forces. They hypothesized that the ACL reconstruction group were protecting their knee by limiting the amount their hamstring muscles contributed to the landing. This could be a practiced effect from when they were injured and being careful to protect their knee while undergoing rehabilitation. Also, this might be due to muscle imbalances from inadequate rehabilitation or insufficient muscle strength.

Although there were no significant differences found by Lephart and colleagues (2002) between sexes for the vertical ground reaction forces for a single-leg landing, there were significant kinematic differences. Women had significantly less knee flexion and lower leg internal rotation after impact than men. This resulted in a more abrupt absorption of the impact forces of landing by the women (Lephart et al., 2002). Also, the women had more hip internal rotation with lower leg external rotation. This knee-extended position, combined with internal hip rotation, makes women vulnerable for anterior cruciate ligament loading. The kinematic differences were attributed to skill/training and muscle strength differences, especially the hamstring-to-quadriceps ratio (Lephart et al., 2002). Chappell and colleagues (2002) also looked at kinetic and kinematic differences for a stop-jump task and found similar results. They found that women also exhibited a greater peak proximal tibia anterior shear force and a greater peak knee extension moment than men did. An important finding also related to the knee is that female athletes had valgus moments at the knee, whereas males had varus moments at the knee during the landing phase of a backward jump. Hewett and colleagues (1996) studied the effects of plyometrics training on female athletes and
landing kinematics. They found that training increased eccentric muscle strength and increased the hamstring-to-quadriceps strength ratio to that of males. Landing forces were significantly reduced and the females increased their knee flexion at landing. In adduction-dominant subjects, the adduction moment decreased and abduction-dominant subjects showed a similar decrease in abduction moment (Hewett et al., 1996).

Landing kinetics and kinematics are also influenced by fatigue. Madigan and Pidco (2003) found that lower extremity fatigue decreased ground reaction force, decreased plantar flexor moment, and increased knee joint flexion during landing. These changes suggest a distal-to-proximal extensor moment, possibly allowing the larger proximal muscles in the lower extremity to contribute more to the shock absorption. This study only looked at one mode of inducing fatigue; different methods of achieving fatigue may elicit a different motor/joint control behavior.

Studies have shown that individuals will uniquely adjust to various surfaces and shoes. Dufek and colleagues (1991) demonstrated that some shoes may work better for some than others and that shoes can make a significant difference in ground reaction forces. Surfaces can also alter individuals' techniques. McKinley and Pedotti (1992) compared skilled and unskilled subjects in a landing task on hard and soft surfaces. The skilled subjects altered their performance more efficiently than the unskilled subjects according to the performance index developed for the study.

In general, we can conclude that there is a difference in landing kinetics and kinematics between individuals and that it is very difficult to attain data applicable to all groups, especially with the low sample size of most studies. However, McNair and Prapaessis (2003) conducted a study with 234 adolescents and found no significant GRF
differences in landing and no interaction effects across sex, activity level, and type of activity regularly performed. The large sample size gives this study statistical power and appears to show that different activities which have varying kinematics have no effect on GRF’s for adolescents. The factors that seem to influence loading rate and force the most are the height from which the landing occurs and knee joint flexion at landing. Landing performance and ability seems to be very task specific and generally follows the law of specificity, where people who practice a basketball rebound will have a better landing technique for that task than that of a runner (Devita & Skelly, 1992; Dufek & Bates, 1991; Dufek & Bates, 1990). In most instances, reducing the amount of ground reaction force and strain on the musculoskeletal system is the goal of manipulating technique for a landing and this is what is considered when considering “better technique”. For “soft” landings, more of the impact force is dissipated into the muscle tissue, whereas in “stiff” landings more of the force is dissipated into the skeletal system. The loading rate and force on the skeletal system is important to bone health. Now the challenge is to find safe landing activities that elicit a bone growth response at the hip.

In order to develop a stimulating yet effective school-based program that elicits a positive bone response, we need to understand the differences in forces on the bones with varying high-impact activities (Turner & Robling, 2003). Studies on factors that influence high-impact activities such as direction, one-foot versus two-foot landings, and continuous versus discrete jumping and landing have yet to be conducted. Therefore, there is no strong basis for developing a set of landing exercises that promote bone growth.
Rationale

Weight-bearing physical activity in childhood is documented as a significant determinant of peak bone mass, and physical activity intervention may be a feasible strategy for primary prevention of osteoporosis. Significant increases in bone density have been identified in children who performed 100 drop landings from a 61 cm box three times per week for 7 months in previous school-based exercise. However effective, drop landings proved to be monotonous for the young participants. In order to develop a stimulating yet effective school-based program that elicits a positive bone response, we need to understand the differences in forces on the bones with varying high-impact activities. One purpose of this study is to compare the peak impact forces and rate of loading at the hip resulting from a 61 cm drop landing to those among: one-leg versus two-leg landing, continuous versus discontinuous jumping, and forward, vertical, or sideways landing activities derived from 2nd and 3rd grade physical education classes. Secondly, we will determine the effects of jump direction, number of feet used in landing, and continuous versus discrete jumping on the peak resultant forces and loading rates at the hip.

Hypotheses

A review of the literature led to the hypothesis that the resulting impact force and peak loading rate at the hip from a 61 cm drop landing would be greater than those for 12 other types of jumps, comprising different combinations of direction, feet used, and continuity, derived from common jumping activities.
In addition to comparing the peak force and loading rate at the hip for each jump type to those of the drop landing, the effects of jump direction, number of feet used in landing, and continuity will be tested. It is hypothesized that one-legged landing activities will have greater forces and loading rates than two-legged landings. It is also hypothesized that single, discrete jumps will have higher peak forces and loading rates than repeated jumps and that this will be consistent across directions and number of feet used.
METHODS

Subjects

Twenty-three apparently healthy prepubescent children (12 boys, 11 girls; mean ± SD age: 8.22 ± 0.6 years [range: 7-9]; mass: 32.05 ± 8.41 kg; height: 1.37 ± 0.07 m) with no disability were recruited from the population of local second and third grade children. A parent of each subject completed a brief health history questionnaire to confirm that the subject was currently healthy and able to perform the tasks with minimal risk (Appendix B). Children were excluded from the study if they had a condition or history of injury/illness that put them at risk of injury or might limit their ability to perform. Parents and children provided written informed consent before participating (Appendix C & D). This study was approved by the Oregon State University Institutional Review Board.

Instruments and Apparatus

In the jumping activities performed, the children would land with one or two feet on each of two 40 x 60 cm force plates (Bertec, Columbus, OH) mounted flush with the floor, 5 mm apart. Ground reaction forces were sampled from the force plates at 1080 Hz. A six-camera optoelectronic motion capture system (Vicon Motion Systems, Lake Forest, CA), sampling at 120 Hz and synchronized with the force plate data, recorded the positions of 33 reflective markers (9 mm diameter) placed on the body at various landmarks. Markers were placed bilaterally at the 5th metatarsal head, 2nd metatarsal head, heel, ankle (lateral malleolus), lateral leg, knee (lateral femoral epicondyle), lateral thigh, anterior superior iliac spine (ASIS), lateral pelvis, acromion, elbow, and wrist.
Markers were also placed at the right greater trochanter, sacrum, C7 spinous process, T10 vertebra, and right back-of-torso. Four markers were placed on the head.

**Procedures**

Participants wore athletic shoes, Lycra shorts, and a tank top shirt during data collection. All participants wore the same make and model of athletic shoe. Prior to the jumping activities, a measurement of body height was made using a wall-mounted stadiometer. One static trial was conducted in which the subject stood on the force plates in a known static position while motion capture data was gathered for 2 seconds. In this known position, the subject stood facing directly in the global “forward” direction with the feet side-by-side, approximately shoulder width apart, and in neutral abduction-adduction. After a 2-3 minute warm-up of brisk walking, each child performed five trials each of 13 jumping activities (Appendix E), completing all five trials before proceeding to the next jump type. Verbal instructions and a demonstration were given immediately prior to each new jumping task and the children were given an opportunity to practice each jump one to three times before proceeding with data collection. If the child failed to jump the appropriate distance or did not follow the protocol for the jumping task, the trial was repeated. Participants were allowed to rest as much as desired between trials.

Each jumping activity was derived from Pangrazi’s (2003) physical education curriculum for second and third grade children (Appendix A). Three factors changed between different jump types:

1) *Feet Used in Take-Off and Landing*: participants took off with and landed on either (a) both feet, or (b) their dominant foot. A two-footed take-off and
landing constituted a jump, whereas a one-footed take-off and landing was a hop.

2) Jump direction: participants either (a) jumped/hopped upward as high as they could, (b) jumped/hopped forward a distance of approximately 80% of body height, or (c) jumped/hopped sideways a distance of approximately 55% of body height in the direction of their dominant foot.

3) Discrete vs. Continuous Jumps (i.e. Single vs. Repeated): after landing from a jump/hop, subjects either (a) remained standing still, or (b) immediately performed a second jump/hop that was identical to the first. For the continuous sideways jumps/hops, the second jump/hop was in the direction opposite the first (i.e. back to the initial take-off position).

All combinations of the three factors were tested, making a total of 12 jumping activities. In addition, drop landings from a 61-cm box were performed making a total of 13 jumping activities. With the exception of the drop landings, subjects started from a standing position on the floor. The desired take-off and landing sites for the forward and sideways jumps/hops were marked on the ground with tape. All hopping activities started and ended on the dominant leg, which was determined during the instruction period by asking the subject which leg he or she prefers when kicking a ball. In each jump trial, the initial landing was on the force plates (one foot on each plate where applicable).

A cool-down of 2-3 minutes of walking was performed upon completion of the data collection. Body dimensions were measured during standing, using an anthropometer and a tape measure. These dimensions included: foot length, ankle width,
knee width, pelvis-to-waist height, and arm width at the shoulder. All data were collected in a single session of approximately 1.5-2 hours.

**Experimental Design**

In order to compare the peak forces and loading rates at the hip between the different jump types (excluding the drop from the 61 cm box), a completely within factorial design with repeated measures was used: 3 x 2 x 2 (Direction x Feet x Continuity). In order to counteract for fatigue, practice, and carry-over effects, counterbalancing was used and each ordering was randomly assigned. The 13 interventions were counterbalanced using the formula: 1, 2, n, 3, (n-1), 4, (n-2), etc. Since all combinations were not covered and perfect counterbalancing could not be achieved with 20 subjects, the formula was also calculated in reverse starting with 13. This made 26 total combinations. The testing order for each of the 20 subjects was then randomly selected without replacement from the 26 combinations. A separate one-way completely within design was used to compare the means between the 61 cm drop landing and the remaining 12 combinations.

**Data Analysis**

Motion analysis software (Vicon Motion Systems, Lake Forest, CA) was used to reconstruct the 3-dimensional trajectory of each marker and to synchronize the marker position and ground reaction force data. In order to utilize the 1080 Hz force data with the 120 Hz motion data, cubic spline interpolation of the marker trajectories and
downsampling of the force data were performed to a common frequency of 540 Hz (the highest frequency allowed by the software). Subsequently, the marker position data were filtered using a fourth-order Butterworth recursive digital filter to exclude high-frequency noise. A cut-off frequency of 12 Hz was used, based on the results of a residual analysis procedure (Winters, 1990, page 41).

Bodybuilder version 3.6 (Vicon Motion Systems, Lake Forest, CA) was used to calculate the resultant forces and moments at the hip of the dominant limb. Instantaneous joint center locations were identified using fixed offsets within a set of marker-defined segment coordinate systems. These offsets were derived from the marker positions and known body orientation in the static trial. The location of the ankle joint center was found from the malleolus marker based on a displacement of half the ankle width along the subtalar joint axis reported by Isman and Inman (1969), as expressed in the coordinate system of the leg. The knee joint center location was computed in the coordinate system of the thigh by taking half the knee width medial to the knee marker. Hip joint center location was estimated using a fixed displacement from the ASIS marker in a marker-defined coordinate system of the pelvis, the displacement determined as percentages of inter-ASIS distance (Bell et al., 1989). Missing ASIS data were extrapolated from the positions of the remaining pelvis markers using the average relative position of the ASIS marker in the other frames of data.

Instantaneous body segment orientations were given by anatomical coordinate systems that were derived from the marker positions and computed joint center positions, using the known segment orientations in the static trial. Segment coordinate axes were defined as: X pointing anteriorly, Y pointing left along the mediolateral axis, and Z
pointing proximally along the longitudinal axis. In particular, the longitudinal axis of the thigh was directed from the knee joint center to the hip joint center, and the mediolateral axis was assumed to be aligned with the frontal plane of the body during the static trial. To correct for errors in the placement of the lateral thigh marker, a fixed rotation about the thigh's longitudinal axis was used to properly align the anatomical coordinate system, this rotation angle determined from the static trial. Similar procedures were used for the other body segments.

Three-dimensional inverse dynamics methods were used to calculate the joint reaction forces and moments at the hip of the dominant limb from the measured ground reaction forces and the computed segment position and acceleration data. In these calculations, the lower extremity was modeled as three rigid segments: foot, leg, and thigh. Body segment mass, segment center-of-mass location, and moments of inertia specific to children were used (Jensen, 1986; Jensen & Nassas, 1988). The components of the hip reaction forces and moments were expressed with respect to the anatomical coordinate system of the thigh. Forces and moments were normalized to body weight and body weight times body height, respectively.

The peak resultant forces at the hip of the dominant limb during landing were extracted for analysis. In previous studies of landings from a 61 cm box (Bauer et al., 2001); the first two force peaks of the force-time curve were analyzed. However, in the present study, many jumps from the ground did not have two distinct force peaks. Therefore, the average values across the five trials of the single largest peak of each force-time curve were analyzed. Matlab version 7.0 (MathWorks, Natick, MA) was used to compute the magnitude of the resultant force at the hip and to identify the peak force
magnitude during landing for each trial. For continuous jumps/hops, only the first
landing of the trial was analyzed.

The direction of the peak resultant force acting on the thigh at the hip was
expressed by the direction cosines of the peak force with respect to the anatomical axes
of the thigh. Direction cosines were defined to be positive when the reaction force on the
thigh was directed anteriorly, laterally, and inferiorly, respectively. The direction cosines
of the peak resultant force were determined for each trial and averaged across the five
trials of each type. These provided some indication of the manner in which the femur
was being loaded.

The average value of the peak loading rate at the hip of the dominant limb across
the five trials was also calculated. The rate of change of the resultant force at the hip
was found by finding the slope of the corresponding force-time curve across a moving
window of 5.6 milliseconds, and the largest rate of increase was identified. The period of
5.6 milliseconds closely corresponds to the time required for the resultant force to
increase from 20% to 80% of its peak value during a drop landing, which was the period
used by Bauer et al. (2001).

Finally, the hip joint angles and moments at the instant of peak force were
identified. Hip joint angles were determined from the orientation of the coordinate
system of the thigh with respect to that of the pelvis, according to the convention of
Grood and Suntay (1983). Rotation of the thigh at the hip was assumed to occur about its
axes in the sequence: flexion/extension, abduction/adduction, and then external/internal
rotation. As described, hip moments were expressed relative to the anatomical coordinate
system of the thigh. The flexion/extension, abduction/adduction, and external/internal
rotation moments at the hip were defined to be those components of the hip moment that acted about the mediolateral, anteroposterior, and longitudinal axes, respectively. These moments provided a gross measure of the muscle forces acting across the hip joint. The joint angles and moments at the instant of peak force were determined for each trial and averaged across the five trials of each type.

**Statistical Analysis**

Two of the 23 subjects were excluded from analysis. One subject was excluded due to missing ground reaction force data, which made it impossible to compute peak forces and loading rates at the hip. The other subject was excluded due to an inability to jump the required distances forward and sideways.

Three-way repeated-measures ANOVA analyzed the differences in the means of the peak forces, direction cosines of the peak forces, and loading rates at the hip across three factors: direction, feet used, and continuity, in the 3 x 2 x2 design. The alpha value was set at 0.05. Paired t-tests were used for post hoc testing of significant interaction effects, with Bonferroni corrections used to maintain a familywise error rate of 0.1. Multiple paired t-tests were used to compare the means for the drop landing from a 61 cm box to the means from each of the other 12 jumping conditions across all subjects; the error rate was adjusted to accommodate the multiple tests with an alpha value of 0.1, with each t-test having an alpha of 0.0083. SPSS version 13.0 was used to compute all statistics (SPSS Inc., Chicago, IL). By means of a regression equation by Park and Schutz (1999), an estimate was made for power and effect size. With an average mean correlation between jumping combinations of 0.8, to be able to detect a medium effect
size among means, 20 subjects provided a statistical power of approximately 0.9 at alpha 0.05.
RESULTS

**Peak Force at the Hip**

The peak resultant forces at the hip during the drop landings were greater than for all other types of hops and jumps (p < .001), with the exception of the discrete, one-footed, forward hop (p = 0.056; Figure 1). Mean peak forces at the hip were 4.5 ± 1.1 body weights and 4.0 ± 0.6 body weights for drop landings and discrete forward hops, respectively. In comparison, mean peak forces for the other jump types ranged from 2.1 to 3.2 body weights.

![Figure 1: Rank ordering of the mean peak force at the hip during landing as a function of jump type. Jump types include drop landings (DL) and all combinations of direction (F=forward; V=vertical; S=sideways), number of feet used (1=hop; 2=jump), and continuity (D=discrete; C=continuous). BW=body weight. Error bars represent ± 1 standard deviation.](image)

Peak forces at the hip for one-footed hops exceeded those for two-footed jumps for all directions, whether discrete or continuous (p < .001; Figure 2). The ANOVA
revealed a significant interaction between the effects of hop/jump direction and continuity on the peak forces (p < .001). In both the vertical and forward directions, discrete hops or jumps had greater peak forces than did continuous ones (p < .001). However, peak forces did not differ between discrete and continuous hops/jumps in the sideways direction. Peak forces during forward hops and jumps were always larger than for vertical hops/jumps. Peak forces during sideways hops/jumps varied in relative size; they were similar to those for vertical hops/jumps in the discrete case, but were similar to those for forward hops/jumps in the continuous case.

Figure 2: Condition effect of mean peak force at the hip during landing as a function of jump type. Effects of direction (F=forward; V=vertical; S=sideways), number of feet used (1=hop; 2=jump), and continuity (D=discrete; C=continuous) are shown. BW=body weight. Error bars represent ± 1 standard deviation.
Direction of the Peak Force at the Hip

For all jump types, the direction cosines revealed that the majority of the peak resultant force at the hip was directed inferiorly along the thigh (i.e. a compressive force on the femur) (Figure 3). The mediolateral component of the peak force at the hip was negligible for all cases, with direction cosines ranging between -0.1 and 0.05. The remainder of the peak force at the hip was directed posteriorly relative to the thigh.

Figure 3: Direction Cosines of the peak force at the hip, relative to the anatomical axes of the thigh, as a function of jump type. Abbreviations are same as in Figure 1. Error bars represent ± 1 standard deviation.

In comparison to the peak resultant forces at the hip during drop landings, those for discrete forward hops, vertical hops, sideways hops, and discrete sideways jumps were directed more inferiorly along the thigh (p ≤ .007). Also, the peak resultant force
was less posterior-directed for discrete forward and vertical hops, and more posterior-directed for continuous forward jumps, than for drop landings (p ≤ .005).

The direction of the peak resultant force at the hip was slightly affected by the continuity, number of feet used, and direction of the hop or jump. The peak force was more inferior- and less posterior-directed relative to the thigh for discrete than for continuous hops/jumps (p ≤ .001). The exception was that the posterior-directed proportion of force did not differ between discrete and continuous sideways hops/jumps. The peak force was also more inferior- and less posterior-directed for forward and vertical hops than for corresponding jumps (p ≤ .001). The direction of the peak force did not differ between sideways hops and jumps.

With respect to hop/jump direction, peak resultant forces at the hip were more inferior- and less posterior-directed relative to the thigh for vertical than for forward hops and jumps (p ≤ .003). The exception was that the posterior-directed proportion of force did not differ between discrete vertical and forward hops. The relative directions of the peak forces during sideways hops and jumps varied. For sideways hops, the peak forces were similarly directed to those for forward hops whereas, for sideways jumps, they were similarly directed to those for vertical jumps. An exception was that the posterior-directed proportion of force for discrete sideways hops exceeded that for discrete vertical and forward hops.

**Peak Rate of Loading at the Hip**

The peak loading rates at the hip for the drop landings were greater than for all other jump types (p ≤ .001; Figure 4). The mean peak loading rate at the hip was 547.1 ±
165.4 body weights per second for drop landings, whereas the mean peak loading rates for the other jump types ranged only from 177.7 to 404.9 body weights per second.

Figure 4: Rank ordering of the mean peak loading rate at the hip during landing as a function of jump type. Jump types include drop landings (DL) and all combinations of direction (F=forward; V=vertical; S=sideways), number of feet used (1=hop; 2=jump), and continuity (D=discrete; C=continuous). BW=body weight; S=seconds. Error bars represent ± 1 standard deviation.

Peak loading rates at the hip for discrete hops and jumps exceeded those for continuous hops and jumps, regardless of direction (p = .001; Figure 5). The ANOVA revealed a significant interaction between the effects of hop/jump direction and number of feet used on the peak loading rates (p = .001). In both the forward and sideways directions, hops had greater peak loading rates than jumps (p ≤ .002). However, peak loading rates did not differ between vertical hops and jumps. Peak loading rates during forward hops and jumps were greater than those for vertical and sideways hops/jumps (p ≤ .012), which did not differ.
Figure 5: Condition effect of mean peak loading rate at the hip during landing as a function of jump type. Effects of direction (F=forward; V=vertical; S=sideways), number of feet used (1=hop; 2=jump), and continuity (D=discrete; C=continuous) are shown. BW=body weight; S=seconds. Error bars represent ±1 standard deviation.

Hip Moments at Peak Hip Force

For each jump type tested, there was a large hip extension moment at the instant at which the peak hip force occurred (Figure 6). In contrast, the corresponding hip abduction/adduction and internal/external rotation moments were near zero on average (Table 1). The hip extension moment at the instant of peak force did not differ between drop landings and forward hops/jumps. This moment for drop landings was greater than for vertical and sideways hops/jumps, however (p ≤ .003), with the exception of the discrete sideways hop. There was a complex three-way interaction between the effects of hop/jump direction, number of feet used, and continuity on the hip extension moment at the instant of peak force (p = .001). It was beyond the scope of this study to analyze this
interaction in detail. In general, hip extension moments at the instant of peak force tended to be greater for forward than for vertical and sideways hops/jumps. An exception was that the extension moments for forward and sideways hops did not differ. Finally, extension moments tended to be greater for sideways hops than for sideways jumps.

![Graph showing hip extension moments during landing, as a function of jump type.](image)

**Figure 6**: Rank ordering of the hip extension moments at the instant of peak hip force during landing, as a function of jump type. Jump types include drop landings (DL) and all combinations of direction (F=forward; V=vertical; S=sideways), number of feet used (1=hop; 2=jump), and continuity (D=discrete; C=continuous). BW=body weight; BH=body height. Error bars represent ± 1 standard deviation.

**Hip Angle at Peak Hip Force**

For each jump type tested, the peak resultant force at the hip typically occurred with the hip flexed, in slight abduction, and in slight external rotation (Table 2). Although no statistical analyses were performed on these angles, the hip angles at the instant of peak force for the drop landings were comparable to those for the vertical hops/jumps. Hip flexion at the instant of peak force tended to be greater for sideways hops/jumps and the greatest for forward hops/jumps, whereas hip abduction at the instant of peak force tended to be the greatest for sideways hop/jumps. Continuous hops/jumps tended to have
**Table 1:** Mean ± SD hip moments at the instant of peak hip force during landing, as a function of jump type

<table>
<thead>
<tr>
<th>Jump Type</th>
<th>Extension (% BW·BH)</th>
<th>Abduction (% BW·BH)</th>
<th>Internal Rotation (% BW·BH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1D</td>
<td>37.7 ± 21.3</td>
<td>2.9 ± 13.6</td>
<td>0.4 ± 2.1</td>
</tr>
<tr>
<td>F1C</td>
<td>44.1 ± 19.2</td>
<td>1.3 ± 9.4</td>
<td>0.1 ± 1.8</td>
</tr>
<tr>
<td>F2D</td>
<td>44.4 ± 17.7</td>
<td>2.2 ± 11.9</td>
<td>1.7 ± 3.2</td>
</tr>
<tr>
<td>F2C</td>
<td>37.1 ± 16.4</td>
<td>0.4 ± 9.2</td>
<td>0.1 ± 2.5</td>
</tr>
<tr>
<td>V1D</td>
<td>26.4 ± 11.6</td>
<td>5.9 ± 7.2</td>
<td>0.5 ± 0.7</td>
</tr>
<tr>
<td>V1C</td>
<td>26.5 ± 10.0</td>
<td>4.1 ± 7.9</td>
<td>0.9 ± 0.8</td>
</tr>
<tr>
<td>V2D</td>
<td>23.2 ± 11.1</td>
<td>2.0 ± 9.1</td>
<td>0.6 ± 1.2</td>
</tr>
<tr>
<td>V2C</td>
<td>20.4 ± 8.9</td>
<td>3.1 ± 10.9</td>
<td>0.3 ± 1.4</td>
</tr>
<tr>
<td>S1D</td>
<td>33.5 ± 10.8</td>
<td>3.2 ± 9.1</td>
<td>0.5 ± 1.7</td>
</tr>
<tr>
<td>S1C</td>
<td>31.3 ± 7.0</td>
<td>0.7 ± 7.7</td>
<td>0.9 ± 1.3</td>
</tr>
<tr>
<td>S2D</td>
<td>21.3 ± 8.0</td>
<td>1.3 ± 4.5</td>
<td>1.3 ± 1.1</td>
</tr>
<tr>
<td>S2C</td>
<td>25.3 ± 6.7</td>
<td>3.9 ± 5.6</td>
<td>1.3 ± 1.2</td>
</tr>
<tr>
<td>DL</td>
<td>48.6 ± 26.8</td>
<td>4.4 ± 12.5</td>
<td>0.5 ± 1.9</td>
</tr>
</tbody>
</table>

BW = body weight; BH = body height.

* F=forward; V=vertical; S=sideways; 1=hop; 2=jump; D=discrete; C=continuous; DL=drop landing.

greater hip flexion at the instant of peak force than discrete hops/jumps. Finally, jumps tended to have greater hip flexion and abduction at the instant of peak force than hops, except for sideways hops/jumps where hip flexion was similar.
Table 2: Mean ± SD hip angle at the instant of peak hip force during landing, as a function of jump type

<table>
<thead>
<tr>
<th>Jump Type</th>
<th>Flexion (deg)</th>
<th>Abduction (deg)</th>
<th>External Rotation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FID</td>
<td>50.7 ± 9.3</td>
<td>4.0 ± 5.0</td>
<td>7.9 ± 10.6</td>
</tr>
<tr>
<td>F1C</td>
<td>58.0 ± 10.3</td>
<td>1.2 ± 5.1</td>
<td>11.4 ± 13.1</td>
</tr>
<tr>
<td>F2D</td>
<td>57.9 ± 7.9</td>
<td>6.6 ± 5.4</td>
<td>3.8 ± 12.6</td>
</tr>
<tr>
<td>F2C</td>
<td>66.6 ± 8.7</td>
<td>4.9 ± 5.0</td>
<td>7.7 ± 14.0</td>
</tr>
<tr>
<td>V1D</td>
<td>30.1 ± 7.1</td>
<td>1.7 ± 4.7</td>
<td>9.1 ± 13.7</td>
</tr>
<tr>
<td>V1C</td>
<td>37.4 ± 7.1</td>
<td>0.1 ± 4.3</td>
<td>15.7 ± 14.8</td>
</tr>
<tr>
<td>V2D</td>
<td>35.3 ± 10.8</td>
<td>6.0 ± 5.0</td>
<td>10.9 ± 14.1</td>
</tr>
<tr>
<td>V2C</td>
<td>46.4 ± 9.0</td>
<td>6.2 ± 5.2</td>
<td>12.8 ± 14.1</td>
</tr>
<tr>
<td>S1D</td>
<td>43.6 ± 9.7</td>
<td>11.2 ± 6.9</td>
<td>17.7 ± 15.0</td>
</tr>
<tr>
<td>S1C</td>
<td>45.4 ± 8.6</td>
<td>10.6 ± 5.3</td>
<td>22.2 ± 14.5</td>
</tr>
<tr>
<td>S2D</td>
<td>40.0 ± 7.8</td>
<td>15.3 ± 3.8</td>
<td>11.4 ± 10.3</td>
</tr>
<tr>
<td>S2C</td>
<td>45.0 ± 8.0</td>
<td>15.7 ± 3.7</td>
<td>16.8 ± 12.7</td>
</tr>
<tr>
<td>DL</td>
<td>39.3 ± 7.7</td>
<td>5.1 ± 5.8</td>
<td>13.8 ± 14.7</td>
</tr>
</tbody>
</table>

* F=forward; V=vertical; S=sideways; 1=hop; 2=jump; D=discrete; C=continuous; DL=drop landing
DISCUSSION

This study compared peak resultant forces and rates of loading at the hip among different hopping and jumping activities to those of drop landings, and investigated the effect of one foot versus two feet, continuity, and direction on loading at the hip during landing. It has been reported that, among children who performed drop landings from a height of 61 cm, 300 times per week, enough stress was produced at the hip upon landing to elicit bone augmentation (Fuchs et al., 2001). With that in mind, this study hoped to reveal which ground-level jumping activities might cause a similar response. Among a set of 12 jumping activities derived from elementary physical education activities, it was found that the discrete forward hop was the only activity that did not have significantly lower peak forces at the hip. However, the peak loading rates for all 12 activities were significantly lower than for the drop landing. Also, it was found that discrete hops/jumps had higher peak forces and loading rates than continuous hops/jumps, hops tended to have higher forces and rates than jumps, and forward hops/jumps generally had higher forces and rates than both sideways and vertical hops/jumps.

We hypothesized that hops would have greater peak forces and loading rates at the hip than jumps for all directions. Consistent with our hypothesis, forces and rates at the hip for hops exceeded those for jumps in almost all cases; peak loading rates did not differ between vertical hops and jumps. Interestingly, peak forces for hops were, on average, 1.3 times greater than jumps, not two times greater, even though jumps allow the sharing of impact forces between two limbs. One possibility is that the maximum height from the ground was greater for jumps than for hops, perhaps because of the capability of two legs to create more kinetic energy at take-off. Another possibility is that the subjects
adjusted their motor behavior during 1-footed landings to aid in reducing the impact forces at landing. Previous studies looking at ground reaction forces during different landings by gymnasts suggest there is some form of feedforward control to prepare for anticipated differences in mechanical demand at contact, and that this control is influenced by restrictions imposed by the task (McNitt-Gray et al., 2001). In addition, during the present data analysis, it was noted that ankle plantar flexion characteristics for hops were different than for jumps, with hops having more plantar flexion at landing. Typically, force-time curves for landings have a bimodal curve due to the toe-heel landing, one peak associated with toe contact, the other with heel contact. The magnitude of the first peak will, arguably, increase with greater plantar flexion at landing. Consistent with this, there was a more distinctly bimodal force-time curve for hops, with a relatively larger first peak compared to jumps (Figure 7). The exceptions were the forward hops/jumps, where there were little or no bimodal characteristics for either hops or jumps and initial landing was made with the heel rather than the forefoot (Figures 7 and 8). On average, there were greater hip flexion angles at the instant of peak hip force for 2-footed landings than for 1-footed landings, suggesting that subjects were altering their motor behavior between tasks. I speculate that, in order to maintain stability and reduce soft tissue vibrations when landing on one foot, adjustments are made to body segment orientations at landing, thereby mitigating the ground reaction forces and consequently the resultant forces and rates at the hip (Wakeling et al., 2001). Nevertheless, peak forces at the hip during 1-footed landings remained significantly greater than those for 2-footed landings.
Figure 7: Representative force-time graphs of the resultant force at the hip for various jumping conditions from the same subject. a) Drop Landing, b) Discrete Forward Hop, c) Continuous Sideways Hop, d) Continuous Forward Hop, e) Discrete Vertical Hop, f) Discrete Vertical Jump. The same scale is used for all graphs. BW=body weight.
Figure 8: Body position at the instant of peak hip force of the same subject for 3 different landings. From right to left: a) drop landing, b) discrete forward hop, c) discrete forward jump. The arrow indicates the direction and magnitude of the ground reaction force at the instant of peak force.

We also hypothesized that discrete hops/jumps would have greater peak forces and loading rates at the hip than continuous hops/jumps in all cases. Peak forces at the hip for discrete hops/jumps were, on average, 0.45 body weights greater than for continuous hops/jumps. Also, peak loading rates were 44.8 body weights per second greater, on average, for discrete than for continuous hops/jumps. The effect of continuity was dependent on direction though; in both the forward and vertical directions, discrete hops/jumps had significantly greater peak forces and loading rates at the hip than continuous hops/jumps. However, we found no significant difference in peak forces between discrete and continuous sideways hops or jumps. For the discrete forward hop/jump the children had to fully arrest their momentum upon landing whereas, in the continuous forward hop/jump, the forward momentum was maintained into the second jump. This likely reduced the braking impulse needed in the continuous case, causing the peak force and loading rate to be reduced (Figures 7b and 7d). In the continuous vertical
hop/jump, the jumpers likely had a greater countermovement (i.e. more knee flexion at landing) than in the discrete case, in preparation for the subsequent hop/jump. Therefore, the braking impulse at landing will be spread over a longer period of time, causing the peak force and loading rate to be reduced. The continuous sideways hop/jump was different from the forward case because, to reduce the risk of injury, the second hop/jump was performed in the opposite direction, back to the starting location, instead of continuing in the same direction. Therefore, subjects had to completely arrest their lateral momentum in order to change directions during both the discrete and the continuous hops/jumps, resulting in similar peak force magnitudes. I also hypothesize that the balance requirements upon landing from the sideways hop limited the jumpers’ ability to perform a countermovement, as in the vertical case.

Hop and jump direction was a contributing factor to the magnitude of the peak force and rate of loading at the hip. Peak forces and loading rates for forward-directed hops/jumps were always larger than for vertical hops/jumps. Peak forces during sideways hops/jumps were similar to those for vertical hops/jumps in the discrete case, but were similar to those for forward hops/jumps in the continuous case. Peak loading rate was similar between vertical and sideways-directed hops/jumps. Likely, the variation between the discrete and continuous cases in the relative sizes of the hip loading during the vertical and sideways hops/jumps is due to the varied balance requirements and direction changes of these hops/jumps, as mentioned above. Plus, for the discrete sideways and vertical conditions, similar take-off velocities and knee flexion angles at landing may have caused the similar loading rates. Several factors may have been responsible for the high peak forces and loading rates during the forward hops/jumps. As
mentioned above, the forward hops/jumps typically involve only one distinct force peak, confirming our observations of either flat-footed or heel landing (Figures 7b and 7d). This would act to reduce the loading duration during landing, leading to higher forces. Also, the forward hop/jump distance was 80% of body height, whereas the sideways distance was only 55%. The greater distance of the forward hops/jumps compared to sideways was chosen because it is much easier to jump forward than sideways and our goal was to have similar effort for each condition from the ground, in order to obtain estimates of maximal hip joint loading. Incidentally, it has been shown that increasing jumping distance has little effect on ground reaction forces (Dufek and Bates, 1989). A third possible contributor to the greater loading at the hip for most of the forward jumps might have been that more upper body movement was used to generate extra momentum and thus greater takeoff velocity. Possibly, the ability to create more momentum with the upper body in the forward-directed conditions was because it was not required to land back in the same place, thus there was more opportunity to make corrections in the air during the forward hops/jumps.

Finally, we hypothesized that the drop landing would have greater peak forces and loading rates at the hip during landing than all the other jumping combinations. Our present study found this to be true in all conditions, except that the discrete forward hop had similar peak forces at impact to the drop landing. Dufek and Bates (1989) found that ground reaction forces during landings are influenced most by landing height and the amount of knee flexion. The results from this study make sense because landing from a vertical or sideways hop/jump was not from as high as the drop landing was. The potential energy at take-off of the drop landings was greater than the
kinetic energy that the subjects could generate in taking off from the ground (since the children could not jump 61 cm into the air from the ground). I assume that only the discrete forward hop and none of the other forward hops/jumps were similar to the drop landing because, during the discrete forward hop, the jumper must fully stop his or her forward and vertical momentum with one leg extended in front of him or her (Figure 8). Consequently, the jumper is unable to utilize changes in motor behavior or take advantage of a toe-heel landing technique to spread the force over two separate peaks, as in the other directions, and therefore the forces are amplified (Devita and Kelly, 1992).

Although, it is unknown how much the direction of the applied force will influence bone adaptations, there were small but significant differences in the direction of the peak force at the hip between the different hop/jump conditions and the drop landing. Most notably, the discrete forward hop had more inferior-directed, compressive force at the hip and the drop landing had more posterior-directed force, as can be inferred from Figure 8. This is due to the different body segment orientations in relation to the direction of the hop/jump. It may be seen that the ground reaction force is directed more anteriorly relative to the longitudinal axis of the thigh during the drop landing (Figure 8a) than during the discrete forward hop (Figure 8b). Because the reaction force on the thigh at the hip must oppose the loading applied by the ground reaction force, this induces a more posterior-directed reaction force at the hip during the drop landing. When bone is subjected to bending stress, most bone augmentation occurs on the compressive side of the normal axis (Burr et al., 2002). However, little is known about what the best loading direction at the hip would be or where the best site for bone growth is to prevent hip fractures. Both posterior-directed and inferior-directed loads will place bending stress on
the neck of the trochanter. More research is needed to determine what the best directed forces are to prevent osteoporosis.

Some limitations of this study should be mentioned. First, there was no control over experience differences of the children, except that children were excluded from the study if they had participated in prior drop landing studies. From observation, there was high variability in jumping ability among the children. Some children were very "athletic" and able to complete each task to the specified distances, while others had some difficulty and missed the marked distances (particularly during the forward and sideways hops). Nevertheless, it has been reported that take-off technique does not influence ground reaction forces during landing (McKinley & Pedotti, 1992). Also, this study's relatively low variability between subjects suggests that observed skill differences did not significantly interact with the resultant joint reaction forces. A second limitation is that muscle forces were not measured. These forces may cause the resultant joint force to differ in direction from, and most likely underestimate, the total bone contact force at the hip. Therefore, hip joint moments were reported to aide in assessing the effects of muscle activity. In general, abduction and internal rotation moments were negligible. The hip extension moment data suggested that the extension moments were similar between the vertical and sideways hops/jumps and between the discrete forward hops and drop landings at the instant of peak hip resultant force. This is important because it has been shown that muscle activity accounts for a large proportion of the bending moments on bones and the hip moment data imply that discrete forward hops involve similar hip muscle activity to the drop landing (Lu et al., 1997). Third, there were only five trials for each task, which may have limited our ability to get a representative mean peak resultant
force and loading rate at the hip for each landing task. However, with a couple of practice trials in addition to the 5 trials for each of 13 conditions, having more trials would not have been suitable for children. This number seems to have been enough for rank ordering the jump types, though. This order could potentially have been altered by differences in skill. However, Prapaessis (2003) found no significant main or interaction effects of sex, activity level, and type of activity on the GRF during landing by children. Although not reported here, there was also no effect of sex on the peak resultant forces and loading rates at the hip in the present study. Lastly, we can’t directly measure the forces at the hip, thus we only computed an estimate based on ground reaction forces and body motion. This makes it difficult to conclude if there are differences in force or loading rate between activities, especially if the measures are very close. However, a study using prosthetic implants by Bassey et al. (1997), found that ground reaction forces and hip joint contact forces are significantly correlated for both peak force and loading rate. Typically measured values of the contact force are about twice the magnitude of the resultant joint force because the muscle force effect is accounted for (Bassey et al., 1997).

In order to develop the most effective jumping program to illicit bone augmentation in children, it is imperative to understand what kind of physical activity best for this purpose. Petit et al. (2002) reported small bone gains from a 7-month circuit style jumping program. Fuchs et al. (2001) found larger gains after 7 months of drop landings from a 61 cm box. The common factor in these studies shown to cause bone to grow include: dynamic loads that have high loading rates and magnitudes, and short intense bouts with more than 4 hours between each session (Burr et al., 2002; Turner, 1998). Daily activities such as walking, jogging, or even jump rope do not demonstrate
measurable changes in hip bone mass (Snow-Harter et al., 1992; Taaffe et al., 1997). Gains found in landing activities are attributable largely to the “abnormally” high loading rates and muscle moments (Burr et al., 2002; Bassey et al., 1997; Turner, 1998). The relative effects of high loading rates versus high peak forces are not completely understood, however. Nor is the effect of the total amount of time during loading fully understood. For instance, does the fact that the drop landing has two peaks, each with relatively high loading rates, increase the bone response over the other jumps which do not have a significant first peak? Typically the first peak of the drop landing is much smaller than the second peak, however, and may not be above the threshold to play a role in bone adaptation (Figure 7a).

Our long-term objective is to find activities that children currently perform in physical education that produce a stimulus to bone formation that is similar to drop landings. Children could then perform more of these activities, or a jumping program could be developed in physical education, as a preventative measure for osteoporosis. This study found which properties of jumping activities produce the largest peak resultant forces and loading rates at the hip. In general, hops were superior to jumps; forward directed hops/jumps were better than sideways- and vertical-directed hops/jumps; and discrete hops/jumps were better than continuous. Combining the best of each property, it was found that the discrete forward hop is the optimal activity among all the ground-level jumping conditions tested. This was followed by the remaining forward hops and jumps, then the sideways hops, and, finally, vertical hops and jumps. Although, the loading rates at the hip of the discrete forward hop (405 ± 82 body weights per second) did not quite equal those of the drop landing (547 ± 165 body weights per second), they far exceeded
those of the continuous 2-foot jump (178 ± 74 body weights per second), which were the lowest. I therefore consider the discrete forward hop to have much greater loading rates than "normal" daily activities. Combining this with the peak force magnitudes and muscle moments that were comparable to those of the drop landing leads me to conclude that the discrete forward hop is the best overall ground-level jumping activity that we derived from the physical education curriculum.

It has been found that performing 100 drop landings, three times per week will produce increases in bone mass over a 7-month period (Snow, 2001). Also, it has been shown that as little as 10 minutes of vigorous physical activity can increase bone mass and that lengthening the loading duration has a diminishing effect on further bone adaptation. Interestingly, splitting loading sessions will have a greater osteogenic effect than one longer session (Robling et al., 2002). Therefore, 10-minute increments of jumping activity that include up to 100 discrete forward hops, such as hop-scotch, may assist in the prevention of osteoporosis beginning with children aged 7-9 years.
CONCLUSION

In conclusion, the present findings show that, in general, hops have larger peak forces and loading rates at the hip than jumps, discrete have larger than continuous, forward have larger than vertical, and vertical have larger than sideways. Notably, the present results show that other landing activities besides the drop landing could potentially produce positive gains in bone mass, a discrete forward hop in particular. Further research, particularly looking at loading characteristics of the specific activities performed in physical education, is needed to confirm these results. Subsequently a bone loading program that includes forward hops might be developed and its effects assessed in longitudinal studies on changes in bone mass in children. Potentially, findings from this study may contribute to the prevention of osteoporosis in older adults.
BIBLIOGRAPHY


Appendices
Appendix A

Jumping Activities Derived From Physical Education Curriculum

IA= instructional activities, FDA= Fitness Development Activity, LFA= Lesson Focus Activities, GA= Game Activity, HAC= High as Can, Hop= single leg take-off and landing on same leg, Leap= hopping from one leg to the other, Jump= take off and landing using two feet.

<table>
<thead>
<tr>
<th>Activity (up to 4th Grade)</th>
<th>Week</th>
<th>Level</th>
<th>Lesson Type</th>
<th>Jump Type</th>
<th>Duration</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity Drills</td>
<td>31 and pg. 200</td>
<td>2</td>
<td>FDA</td>
<td>Hop</td>
<td>25 seconds</td>
<td>Self Selected</td>
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<tr>
<td>Crossing the River</td>
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<td>Fitness Challenges- Run &amp; leap, skip</td>
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<td>Run &amp; Leap</td>
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<td>Leap the Brook (could have lateral)</td>
<td>4</td>
<td>1</td>
<td>GA</td>
<td>Leap</td>
<td>Unknown</td>
<td>Self Selected</td>
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<tr>
<td>Flexibility Jackpot Fitness</td>
<td>21, 22</td>
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<td>Hurdles-continuous</td>
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<td>Hurdle</td>
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<td>FDA</td>
<td>hop-step-jump (sand)</td>
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<td>Partner Leaping</td>
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<td>3-5 minutes</td>
<td>Over person</td>
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<td>High Jump</td>
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<td>1</td>
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<td>Hop</td>
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## Two-Leg Forward Landings

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<th>Lesson Type</th>
<th>Jump Type</th>
<th>Duration</th>
<th>Height</th>
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<td>Jump</td>
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<td>(could have lateral)</td>
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<td>Leap the Brook</td>
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<td>GA</td>
<td>Jump</td>
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<td>Self</td>
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<td>Long Jump</td>
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<td></td>
<td>(sand)</td>
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<td>LFA</td>
<td>Jump:</td>
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<td>Self</td>
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<tr>
<td>(continuous)</td>
<td></td>
<td></td>
<td></td>
<td>some</td>
<td></td>
<td>Selected</td>
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<tr>
<td></td>
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<td></td>
<td>continuous</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>down</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>back</td>
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<td>Balance Beams</td>
<td>33(L)</td>
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<td>1&amp;2</td>
<td>LFA</td>
<td>Swing and Jump</td>
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<td>Variety</td>
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<td>Hexagon Hustle</td>
<td>4, 5</td>
<td>2</td>
<td>FDA</td>
<td>Jump</td>
<td>1 minute</td>
<td>Self/HAC</td>
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<td>Jump</td>
<td>1 minute</td>
<td>Self/HAC</td>
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<td>13, 15, 16,</td>
<td>2</td>
<td>FDA</td>
<td>Jump from box then roll</td>
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<td>21, 22</td>
<td>2</td>
<td>FDA</td>
<td>Jump Rope</td>
<td>30 seconds</td>
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<tr>
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<td>2</td>
<td>FDA</td>
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<td>25 seconds</td>
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<td>LFA</td>
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<td>15 minutes</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Fundamental Skills Using Jumping Boxes</td>
<td>25</td>
<td>1</td>
<td>LFA</td>
<td>Jump</td>
<td>30 min</td>
<td>Box height</td>
</tr>
<tr>
<td>Magic Number Challenges</td>
<td>Level 1 (10) Level 2(6)</td>
<td>1&amp;2</td>
<td>IA</td>
<td>could have jumping</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
</tbody>
</table>
### One-Leg Vertical Landings

<table>
<thead>
<tr>
<th>Activity (up to 4th Grade)</th>
<th>Week</th>
<th>Level</th>
<th>Lesson Type</th>
<th>Jump Type</th>
<th>Duration</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magic Number Challenges</td>
<td>Level 1 (10) &lt;br&gt; Level 2(6)</td>
<td>1&amp;2</td>
<td>FDA</td>
<td>Hop</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Mini-Challenge Course</td>
<td>10, 15, 16,</td>
<td>1</td>
<td>FDA</td>
<td>Hop in hoops</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Drill Sergeant</td>
<td>16</td>
<td>1</td>
<td>IA</td>
<td>March/Jump 2 and freeze</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Four Corners Fitness</td>
<td>2, 17, 29</td>
<td>1</td>
<td>FDA</td>
<td>Hop</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Four Corners Fitness</td>
<td>2, 17, 29</td>
<td>1</td>
<td>FDA</td>
<td>Galloping</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
<tr>
<td>*Fundamental Skills Using Benches</td>
<td>Level 1(20) &lt;br&gt; Level 2(20)</td>
<td>1&amp;2</td>
<td>LFA</td>
<td>Variety</td>
<td>Unknown</td>
<td>Bench Height</td>
</tr>
<tr>
<td>Fundamental Skills Using Jumping Boxes</td>
<td>25</td>
<td>1</td>
<td>LFA</td>
<td>Leap</td>
<td>Unknown</td>
<td>box height</td>
</tr>
<tr>
<td>Fundamental Skills Using Jumping Boxes</td>
<td>25</td>
<td>1</td>
<td>LFA</td>
<td>Hop</td>
<td>Unknown</td>
<td>box height</td>
</tr>
<tr>
<td>Gymnastics Skills (could have lateral)</td>
<td>Level 1(7, 28) &lt;br&gt; Level 2(7, 15, 23)</td>
<td>1&amp;2</td>
<td>LFA</td>
<td>Jump (pogo stick)</td>
<td>minimal</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Activity Using Hoops</td>
<td>2</td>
<td>1</td>
<td>LFA</td>
<td>Hop</td>
<td>Few Minutes</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Movement Skills (Transfering Weight)</td>
<td>30</td>
<td>1</td>
<td>LFA</td>
<td>Jump</td>
<td>5 minutes</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Locomotor Movements &amp; Freeze</td>
<td>33</td>
<td>1</td>
<td>IA</td>
<td>Hop</td>
<td>5 minutes</td>
<td>Self Selected</td>
</tr>
<tr>
<td>Challenge Course</td>
<td>13, 15, 16,</td>
<td>2</td>
<td>FDA</td>
<td>Hop</td>
<td>Unknown</td>
<td>Self Selected</td>
</tr>
</tbody>
</table>
## Participant Information and Health History Questionnaire

<table>
<thead>
<tr>
<th>CHILD'S NAME (Last, First)</th>
<th>TODAY'S DATE</th>
<th>VISIT#</th>
<th>ID#</th>
</tr>
</thead>
</table>

**OREGON STATE UNIVERSITY BONE RESEARCH LABORATORY**

Participant Information

Boy ___  Girl ___

Date of Birth: __________________________

Parent/Guardian __________________________ Home phone __________________________

Address, Street __________________________ Work phone/cell __________________________

City, State __________________________ E-mail __________________________

Person to contact in case of emergency __________________________ Phone number __________________________

<table>
<thead>
<tr>
<th>Physician name</th>
<th>Physician phone number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Which describes your ethnic category?
Not Hispanic or Latino

Hispanic or Latino: A person of Cuban, Mexican, Puerto Rican, South or Central American, or other Spanish culture or origin, regardless of race. The term, “Spanish origin,” can be used in addition to “Hispanic or Latino.”

Decline to respond

Which describes your racial categories (check all that apply):

- White: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.
- Asian: A person having origins in any of the original peoples of the Far East, Southern Asia, or the Indian subcontinent including, for example, Cambodia, China, India, Japan, Korea, Malaysia, Pakistan, the Philippine Islands, Thailand, and Vietnam.
- Black or African American: A person having origins in any of the black racial groups of Africa. Terms such as “Haitian” or “Negro” can be used in addition to “Black or African American.”
- Native Hawaiian or Other Pacific Islander: A person having origins in any of the original peoples of Hawaii, Guam, Samoa, or other Pacific Islands.
- American Indian or Alaska Native: A person having origins in any of the original peoples of North, Central, or South America and maintains tribal affiliation or community.
- Decline to respond
OREGON STATE UNIVERSITY BIOMECHANICS LABORATORY
Health History Questionnaire

Health History
Do you or have you ever had?

<table>
<thead>
<tr>
<th>Condition</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cancer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diabetes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Disease of arteries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epilepsy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart trouble</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High blood pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High cholesterol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High or low thyroid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lactase deficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lung disease</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Musculoskeletal injury</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rheumatic fever</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other illness/disease</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

If yes to any of the above, please explain: ____________________________________________________________

PRESENT SYMPTOMS
Have you recently had?

<table>
<thead>
<tr>
<th>Symptom</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back pain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chest pain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coughing blood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cough on exertion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart palpitations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Painful, stiff or swollen joint</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shortness of breath</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other illness/disease</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Medications: Are you taking medications? YES or NO

Please list your present medications and dosages:

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

OVER
Injuries: Have you had any injuries that restricted your activities? YES or NO (e.g., broken bone, torn ligament, tendonitis, pulled muscle, concussion, etc.)

If yes, please give us the following information about these injuries (starting with the most recent injuries):

1. Date of injury__________________________
   Type of injury (e.g., sports related, car accident)______________________________________
   Injury description (e.g., left tibia fracture, dislocated right shoulder, left ACL tear)_____
   ______________________________________
   ______________________________________
   Treatment, yes or no?___________If so, course of treatment and duration
   (e.g., casted for two months)_____________________________________________________
   ______________________________________

2. Date of injury__________________________
   Type of injury (e.g., sports related, car accident)______________________________________
   Injury description (e.g., left tibia fracture, dislocated right shoulder, left ACL tear)_____
   ______________________________________
   ______________________________________
   Treatment, yes or no?___________If so, course of treatment and duration
   (e.g., casted for two months)_____________________________________________________
   ______________________________________
Appendix C

INFORMED CONSENT DOCUMENT

Project Title: Effect of Jumping on Growing Bones: Forces During Different Landings

Principal Investigator: Michael Pavol, Ph.D., Dept of Exercise and Sport Science
Research Staff: Brad Black, Jeremy Bauer, Brian Higginson, Matt Johnson

PURPOSE

This is a research study. The purpose of this research study is to determine how large the forces at the hip are during landings from different types of jumps, as compared to the forces during landing from a drop of 24". The OSU Bone Research Laboratory has demonstrated that, over time, children performing drop landings from a 24" height develop stronger bones at the hip than children not performing the drop landings. Our goal is now to determine whether landing from other types of jumps produces forces large enough to cause children to develop stronger bones. If so, these other types of jumps could be included in physical education classes to help in developing stronger bones in children and, potentially, delay the onset of osteoporosis later in life. The purpose of this consent form is to give you the information you will need to help you decide whether your child should be in the study or not. Please read the form carefully. You may ask any questions about the research, what your child will be asked to do, the possible risks and benefits, your child’s rights as a volunteer, and anything else about the research or this form that is not clear. When all of your questions have been answered, you can decide if you want your child to be in this study or not. This process is called “informed consent”. You will be given a copy of this form for your records.

The researchers are inviting your child to participate in this research study because: (a) your child is healthy and fully able to perform a variety of repeated jumping activities, (b) your child is of the same age as those who developed stronger bones from drop landings in previous studies, and (c) your child did not perform drop landings during physical education class in our previous studies. Approximately 20 children will participate in this study.

PROCEDURES

If you agree to allow your child to participate, your child’s involvement will last for approximately 1.5 - 2 hours in a single session on a single day.

The following procedures are involved in this study.

- **Health History Questionnaire:** You will assist your child in recording his or her health history on a questionnaire that will take approximately 5-10 minutes to complete. The questionnaire will provide current information on your child’s health.

- **Force and Motion Measures During Jumping Activities:** Your child will wear athletic shoes, Lycra shorts, and a tank top shirt. He or she will begin with a 2-3 minute warm-up of light walking, skipping, and hopping. Next, 34 small, reflective Styrofoam balls will be taped to your child’s skin and clothes for our cameras to see. Loose clothes may be pinned or taped to keep from hiding the balls. Long hair may be placed in a ponytail.
Your child’s height will be measured and he or she will be briefly filmed while standing still. He or she will then perform 13 different types of jumps. One type involves jumping down from a 24” box and landing on both feet. In the other types, your child will start out standing on the floor and will either jump upward as high as he or she can, jump forward a specific distance, or jump sideways a specific distance. He or she will land on either one foot or both feet, and will perform either one or two of the same jumps in a row. These different jump directions, number of feet used in landing, and number of jumps in a row can be combined 12 ways, giving 12 different types of jumps that your child will perform. Your child will perform 5 trials of each type of jump, for a total of 65 trials, plus 1-3 practice jumps of each type. In each trial, our cameras will film the motion of the reflective markers taped to your child, and force plates will measure the forces between the feet and the ground. Your child will be allowed to rest between trials. After all of the jumping is finished, your child will cool down with 2-3 minutes of walking.

- **Anthropometric Measures:** Finally, your child will have his or her weight and selected body dimensions measured. These dimensions include: his or her foot length, ankle width, knee width, pelvis-to-waist height, and arm width at the shoulder.

**RISKS**

The possible risks associated with participating in this research project are as follows. There is a slight chance that an injury such as a muscle strain (pulled muscle) or a sprained ankle will occur during the jumping activities, or that your child might fall and incur an injury while landing. There is also a slight chance that muscle soreness will result from the repeated jumping and landing. However, the different jumping activities being performed in the current project are based on, and very similar to, the types of jumps regularly performed during physical education class in elementary school. The portion of the testing session spent on jumping activities will also be comparable in duration to a physical education class, about 30-40 minutes including brief rest periods between trials. The distances of the jumps are well within the capabilities of most children and your child will be able to request and take breaks whenever he or she wants to. To further minimize the potential for injury and muscle soreness, brief sets of warm-up and cool-down exercises have been included. Also, to reduce the chances of accidental injury, the testing area will be free of any obstacles within an 8-foot radius. Trained personnel will closely monitor all exercises performed in the Biomechanics Laboratory during testing.

**BENEFITS**

There may be no personal benefit to your child for participating in this study. However, the researchers anticipate that, in the future, society may benefit from this study through the development of exercise prescriptions and physical education programs for developing strong bones in children and delaying the onset of osteoporosis later in life.

**COSTS AND COMPENSATION**

You and your child will not have any costs for participating in this research project. As compensation for participating in this research, your child will receive a Dairy Queen gift
certificate, redeemable for a free DQ Sandwich, Dilly Bar, or Kid’s Cone or for $0.39 off a Blizzard Treat. Your child will also receive a pen and magnet from the Bone Research Laboratory. If your child does not complete the testing, he or she will not receive the Dairy Queen gift certificate but will still receive the pen and magnet.

CONFIDENTIALITY

Records of participation in this research project will be kept confidential to the extent permitted by law. However, federal government regulatory agencies and the Oregon State University Institutional Review Board (a committee that reviews and approves research studies involving human subjects) may inspect and copy records pertaining to this research. It is possible that these records could contain information that personally identifies your child. To preserve your child’s confidentiality, all recordings will be identified only by an assigned subject code, and not by name. Only the investigators will have knowledge of your child’s name and code number. In addition, the system that will be used to record your child’s movements has special cameras that record only the positions of the reflective markers that are taped to a person. No identifiable video images of your child will be recorded or saved. Any documents that include your child’s name will be stored in a locked filing cabinet in the Biomechanics Laboratory, and will be accessible only to the research staff. In the event of any report or publication from this study, your child’s identity will not be disclosed. Results will be reported in a summarized manner in such a way that your child cannot be identified.

VISUAL RECORDING

By initialing in the space provided, you verify that you have been told that visual recordings will be generated during the course of this study. The recordings are being made in order for us to estimate how much force the hip is being exposed to during the jumping activities. As indicated above, all recordings will be identified only by an assigned subject code and only the reflective markers that were attached to your child will appear in the images; your child will not be visible. The recordings will be stored on a computer, on CD’s, and/or on computer disks in the Oregon State University Biomechanics Laboratory. They will be accessible only to those working in the laboratory and will be kept no longer than 10 years.

__________________________ Parent/Guardian’s initials

RESEARCH RELATED INJURY

In the event of research related injury, compensation and medical treatment is not provided by Oregon State University.

VOLUNTARY PARTICIPATION

Taking part in this research study is voluntary. You may choose not to have your child take part at all. If you agree to allow your child to participate in this study, and your child also agrees to participate, either you or your child may stop your child’s participation at any time. You are also free to skip any questions in your child’s health history questionnaire that you would prefer not to answer. If you decide not to allow your child to take part, or if your child stops participating at any time, your or your child’s decision will not result in any penalty or
loss of benefits to which you or your child may otherwise be entitled. Any data collected from your child will be saved and may be included in the study results, even if your child withdraws partway through the study. Should your child withdraw from the study for other than medical reasons before completing the testing, he or she will not receive the Dairy Queen gift certificate for participation but will still receive the Bone Research Laboratory pen and magnet.

QUESTIONS

Questions are encouraged. If you have any questions about this research project, please contact: Brad Black by e-mail at blackbr@onid.orst.edu or by phone at (541) 737-5933 or Dr. Mike Pavol at Mike.Pavol@oregonstate.edu or (541) 737-5928. If you have questions about your rights as a participant, please contact the Oregon State University Institutional Review Board (IRB) Human Protections Administrator, at (541) 737-3437 or by e-mail at IRB@oregonstate.edu or by mail at 312 Kerr Administration Building, Corvallis, OR 97331-2140.

Your signature indicates that this research study has been explained to you, that your questions have been answered, and that you agree for your child to take part in this study. You will receive a copy of this form.

Participant's Name (printed):
________________________________________

(Signature of Parent/Guardian or Legally Authorized Representative) (Date)

There is a chance you may be contacted in the future for your child to participate in an additional study related to this project. If you would prefer not to be contacted, please let the researcher know, at any time.

INVESTIGATOR STATEMENT

I have discussed the above points with the participant or, where appropriate, with the participant's legally authorized representative, using a translator when necessary. It is my opinion that the participant understands the risks, benefits, and procedures involved with participation in this research study.

(Signature of Investigator) (Date)
Appendix D

ASSENT DOCUMENT

Project Title: Effect of Jumping on Growing Bones: Forces During Different Landings

Principal Investigator: Dr. Michael Pavol, Dept. of Exercise & Sport Science
Research Staff: Brad Black, Jeremy Bauer, Brian Higginson, Matt Johnson

We are doing a research study. A research study is a special way to find out about something. We are trying to find out how big the forces in the bones of your hip are when you do different kinds of jumps. This form is about the study, so you can learn about the study and decide if you want to be in the study or not. You can ask any questions. After all of your questions have been answered, you can decide if you want to be in this study or not.

If you decide that you want to be in this study, we will ask you to do several things:

Tell us about your health: We will ask you (with help if you need it) to write down how healthy you are and if you’ve been hurt lately.

Warm-up: We will ask you to do a few minutes of walking, skipping, and hopping to get your muscles ready to jump.

Jumping: We will ask you to do 13 different kinds of jumps for us. In one kind of jump, we will ask you to jump off a box that is 2 feet high and land on the ground. The rest of the time, you will jump off the ground:
- Sometimes you will jump up as high as you can, sometimes you will jump forward, and sometimes you will jump sideways.
- Sometimes we will ask you to land on one foot and sometimes we will ask you to land on both feet.
- Sometimes you will do one jump, then stop, and sometimes you will do two jumps in a row, then stop.
  We will ask you to do each of the 13 kinds of jumps 5 times. That adds up to 65 jumps overall. We will show you how to do each kind of jump and where we want you to land. We will ask you to practice each new jump a few times before you do it for real. You will be able to rest whenever you want.

Before you start, we will ask you to put on some tight-fitting clothes and we will tape 34 shiny little balls to your skin and your clothes. These will help our video cameras measure how your body moves while you jump and land. We are also going to measure how hard your feet hit the ground when you land.
**Body Measurements:** We will measure how tall you are when you stand up straight, how long your foot is, how wide your ankles and knees are, how high your waist is, how wide your arms are, and how much you weigh.

We will ask you to come to the Biomechanics Laboratory just one time for this study.

We want to tell you about some things that might happen to you if you are in this study. You might get hurt or sore from the jumping exercises. You might also get hurt if you fall as you are landing. Other children doing jumps and tests like these in school and at Oregon State University have not gotten hurt.

If you decide to be in this study, we might find out some things that will help other children grow stronger bones, and might help old people not get hurt if they fall.

When we are done with the study, we will write a report about what we found out. We won’t use your name in the report.

You don’t have to be in this study. It’s up to you. If you say okay now, but you want to stop later, that’s okay too. All you have to do is tell us.

If you want to be in this study, please sign your name.

I, ______________________________________, want to be in this research study.

(Print your name here)

___________________________________________ (Date)

___________________________________________ (Sign your name here)
Appendix E

Jump Protocol Instructions

1. **2-Foot Vertical Discontinuous**: High as can jump from two feet, landing with two feet and stopping.

2. **2-Foot Vertical Continuous**: High as can jump from two feet, landing with two feet, immediately followed by an identical jump and land.

3. **2-Foot Forward Discontinuous**: Jump forward from two feet a distance of 80% of subject height, landing with two feet and stopping.

4. **2-Foot Forward Continuous**: Jump forward from two feet a distance of 80% of subject height, landing with two feet, immediately followed by the exact jump forward the same distance.

5. **2-Foot Sideways Discontinuous**: Jump sideways from two feet a distance of 65% of subject height, landing with two feet and stopping.

6. **2-Foot Sideways Continuous**: Jump sideways from two feet a distance of 65% of subject height, landing with two feet, immediately followed by the same jump in the opposite direction.

7. **1-Foot Vertical Discontinuous**: High as can hop from dominant/preferred leg, landing on same foot and stopping.

8. **1-Foot Vertical Continuous**: High as can hop from dominant/preferred leg, landing on same foot, immediately followed by the same jump.

9. **1-Foot Forward Discontinuous**: Hop forward from dominant/preferred leg a distance of 80% of subject height, landing with same foot and stopping.

10. **1-Foot Forward Continuous**: Hop forward from dominant/preferred leg a distance of 80% of subject height, landing with same foot, immediately followed by another forward Hop with the same foot and landing with the same foot.

11. **1-Foot Sideways Discontinuous**: Hop sideways from dominant/preferred leg a distance of 65% of subject height, hopping to the outside, landing with same foot and stopping.

12. **1-Foot Sideways Continuous**: Hop sideways from dominant/preferred leg a distance of 65% of subject height, hopping to the outside, landing with same foot, immediately followed by another hop from same foot to the inside in the opposite direction.
13. **Drop landing**: step onto two force plates (one foot each plate) from a height of 61 cm. After each landing, participants will return to the 61-cm height by first stepping onto a 30-cm high box, then to the 61-cm high box.