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# The effect of surface compliance on the cost and benefit of performing drop-jumps

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# THE EFFECT OF SURFACE COMPLIANCE ON
# THE COST AND BENEFIT OF
# PERFORMING DROP-JUMPS

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ABSTRACT

**The Effect of Surface Compliance on the Cost and Benefit of Performing a Drop-Jumps**

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The purpose of the study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps (DJ). The cost was quantified using peak ground reaction force (GRF) (FPEAK), time to peak GRF (TFPEAK) and loading rate (LR). The benefit was quantified using lower extremity stiffness (K) and amortization phase (AMORT). Ten female subjects performed five DJ trials each on a force plate (C1), turf surface (C2) and aerobics mat (C3). GRF and kinematic data were recorded concurrently at 1000 Hz and 200 Hz, respectively. Dependent variables were analyzed using a repeated measures ANOVA. FPEAK was different between C3 and C2 ($p<0.05$). TFPEAK was different ($p<0.05$) and LR was different ($p<0.05$) across all surfaces. There was no difference in K or AMORT across surfaces ($p>0.05$). It was concluded that surface stiffness plays a role in the costs and benefits of performing a DJ.

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# CHAPTER I

## INTRODUCTION

Plyometric exercise is a method of training, recommended by many coaches and researchers for athletes who wish to perform explosive type activities in competitive sports (Chu, D.A, 1983). Although there are many definitions of plyometrics, the most common definition focuses on describing plyometrics as a quick, powerful movement involving prestretching of the muscle and activating the stretch-shortening cycle to produce a subsequently stronger concentric contraction (Voight & Tippett, 1993). Many studies have shown that plyometrics are effective in improving an athlete's vertical jump performance (Blattner & Noble, 1979; Brown, Mayhew, & Boleach, 1986; Clutch, Wilton, McGown & Bryce, 1983; Holcomb, Lander, Rutland, & Wilson, 1996; Polhemus, 1981; Steben & Steben, 1981).

A common type of plyometric exercise is the drop-jump. A drop-jump is an exercise that involves landing (i.e., drop) from a platform of specified height onto a surface, followed immediately by a jump for maximum height (Komi & Bosco, 1978; Young, Pryor, & Wilson, 1995). It has been reported that the benefit of including drop-jumps in training

programs is improvement in mechanical output of the muscles, triggered by over-load of the muscles during the jump (Bobbert, 1990). This overload stimulus is an important training stimulus. In order to quantify the drop-jump stimulus two variables must be considered: 1) the stretch-shortening cycle, and 2) impact forces due to collision with ground.

Perhaps the most important, yet controversial, component of effective drop-jump training is the stretch-shortening cycle. Although there is no decisive evidence to support or reject the claim of how the stretch-shortening cycle improves force production of the muscles (Ingen Schenau, Bobbert, & Haan, 1997) it is a key variable to consider when investigating the effectiveness of a drop-jump. In most explosive tasks, the stretch-shortening cycle occurs when the concentric phase of an activity is preceded by an eccentric phase (i.e. prestretching) in a short amount of time. According to Schmidtbleicher (1992), the stretch-shortening cycle can be classified as either long (>250ms) or short (<250 ms). The time frame in which the muscle switches from eccentric to concentric contraction is known as the amortization phase (Chu & Plummer, 1984) and is crucial in determining force production during the drop-jump as well as the training stimulus.

Lower extremity stiffness is a variable that can be used to describe prestretching of the muscles. The theory behind lower extremity stiffness is that the neuromuscular skeletal system can be modeled as a simple mass-spring during certain activities (e.g. drop-jumps). Using the mass-

spring model, lower extremity stiffness represents the combined motion of the hip, knee, and ankle joints during a drop-jump. This type of modeling has been used to understand movement strategies, for example. McNitt-Gray, Yokoi and Millward (1994) demonstrated that the knee joint action plays a critical role in lower extremity stiffness as gymnasts performed a two-foot competition-style drop landing onto a stiff versus a soft mat condition. Changes in lower extremity stiffness during drop-jumping may affect the amortization phase. For example, decreasing lower extremity stiffness may result in a longer amortization phase and may be undesirable for certain explosive tasks. Therefore, a key component of the stretch-shortening cycle during drop-jumping is lower extremity stiffness which is related to prestretching of the muscles and the amortization phase.

Despite the benefit of the drop-jump, during the landing phase there is a cost to performing this exercise. For example, Steele and Millburn (1988) reported that after landing in the sport of netball, there is a high risk of injury to the musculoskeletal system due to large ground reaction forces (GRF) and the duration of time that the athlete experiences these forces (See Appendix III for example GRF curve). The magnitude of these forces depend on various factors such as muscular activity, jump technique and material composition of the shoe and surface (Stacoff, Kaelin, & Stuessi, 1988). For example, studies have shown that impact forces and peak vertical forces can be attenuated by

manipulating surface (Ferris & Farley, 1997; Reid, Mercer, Mangus & Dufek, 2000; Steele, & Millburn, 1988). Vertical peak forces have also been shown to decrease as drop-jump height decreases (Bobbert, Huijing, & Schenau, 1987b) and as drop-jump technique changes (Bosco & Komi, 1979; Fowler & Lees, 1998). However, it is not known whether or not manipulating these variables with the goal of reducing impact magnitude and prolonging the period of time the forces are experienced interferes with the drop-jump training stimulus. Since injuries are common in sports that involve drop-jumping as a method of training, it is important to understand how to reduce the cost of drop-jump training. Furthermore, it is important to understand whether or not the stimulus is affected when the cost is reduced. In regards to the costs and benefits of performing drop-jumps, it may be possible to use different surface compliances in order to preserve the variables necessary for effective training while minimizing the effect of large impact ground reaction forces.

## Purpose of the Study

The purpose of this study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps. Specifically, ground reaction forces (GRF), lower extremity stiffness, and the amortization phase were examined for variations in what constitutes effective drop-jump training across different surface compliances.

## Research Questions

Of particular interest in this study was the question: Is the cost of performing a drop-jump reduced (i.e., high impact ground reaction forces) while the benefit is maintained (i.e., lower extremity stiffness and amortization phase) as surface compliance increases?

Specific Research Hypotheses:

1. Magnitude of GRF will decrease as surface compliance increases
2. Time to peak GRF will decrease as surface compliance decreases
3. Loading rate will decrease as surface compliance increases
4. Lower extremity stiffness will increase as surface compliance increases
5. Amortization phase will be affected as surface compliance increases.

In order to explore this question it was necessary to identify the components of drop-jump training, the costs and benefits of this type of training and finally, biomechanical factors associated with changes in surface compliance on an athletic training surface.

## Limitations of the Study

The following limitations apply to the study:

1. Limitations due to the collection of GRF data and kinematic

analysis (video analysis). These limitations include occasional signal noise from the force plate, synchronization of GRF data and kinematic data, imprecise placement of reflective markers between subjects which may affect kinematic analysis.

2. The experimental design limited the validity of the study. External validity was limited due to the number of subjects (ten) tested. Furthermore, the lack of the use of the arms during the jump limits the external validity of the results to plyometric tasks that involve arms.

3. Due to the fact that only vertical ground reaction forces were investigated, this study did not account for the possible contribution of forces in the antero-posterior or medial-lateral direction.

## Assumptions of Study

All subjects were assumed to be novice in the skill of drop-jumping. It was assumed that all subjects were healthy and free from any lower-extremity injury that would limit their ability to perform a drop-jump. It was also assumed that each subject executed the drop-jump with maximal effort and that the time allowed for recovery was adequate in order to minimize the effect of fatigue. All instrumentation was calibrated and assumed to be accurate.

## Definition of Terms

The following definitions were used in the study:

Ground Reaction Force (GRF): The component of the force exerted by the subject on the landing surface perpendicular to the surface.

Touchdown: The instant the subject comes in contact with the surface (usually the feet).

Time to Peak GRF (TFPEAK): Time from touchdown until maximum peak VGRF.

Loading Rate (LR): Relationship between magnitude of impact ground reaction force and time to impact peak ground reaction force.

Lower Extremity Stiffness (K): Description of the lower extremity (hip, ankle and knee joints) as it relates to a mass-spring model. Stiffness of the leg-spring represents the integrated musculoskeletal system during the drop jump.

Plyometric Training: A quick and powerful movement involving a prestretching or countermovement that activates the stretch-shortening cycle to produce a subsequently stronger concentric contraction (Voight & Tippett, 1993).

Drop-Jump: Jumping down from a platform of specified height onto a surface and immediately, upon landing, executing a maximal vertical jump (hands on hips).

Peak Ground Reaction Force (FPEAK): The maximum peak vertical ground reaction force that occurs within 50ms of touchdown.

Stretch-Shortening Cycle: The muscle is stretched while active, resulting in greater force production capability during subsequent

concentric contraction than could be generated during a concentric contraction from a static position (Wathen, 1993).

Amortization Phase (AMORT): The amount of time between undergoing a yielding eccentric contraction (minimum knee angular velocity) and initiating a concentric contraction (maximum knee angular velocity). Calculated using the first central difference method:

$$v_i = (\theta_{i+1} - \theta_{i-1}) / (t_{i+1} - t_{i-1})$$

Center of Mass: The point about which all the mass particles of the body are evenly distributed.

# CHAPTER II

## REVIEW OF LITERATURE

Many researchers have studied drop-jumping in a practical sport setting or in a laboratory setting, where different variables can be manipulated. Since athletes may train on a number of different surfaces, the current study aimed to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps

A review of relevant literature on topics such as the validity of drop-jump training, the components of an effective drop-jump, and the cost of impact ground reaction forces can provide insight in understanding the plyometric training stimulus. Most importantly, a review of the effects of different surface compliances in sports activities will be presented in order to explain biomechanical changes that occur between the athlete and the surface.

### Validity of Drop-Jump Training

Over the past decade coaches have included plyometric training as a part of an athlete's normal training routine in effort to improve the athlete's ability to jump farther, jump higher, throw longer and lower

running times for example.

First described by Verhoshanski (1968), a drop -jump requires the athlete to drop from a height and, upon landing, immediately, perform a jumping movement. He suggested that depth jumps, like other plyometric exercises, increase strength and nerve-reactive ability and that these increases will improve vertical jumping ability. However, there has been inconclusive evidence on whether plyometric training, specifically, drop-jumps, are truly effective in improving an athlete's performance.

A training study by Clutch, Wilton, McGown, and Bryce (1983) investigated the effect of drop-jumps and weight training on leg strength and vertical jump. One of the purposes of their study was to determine whether certain drop-jump routines, when combined with weight training, were better than others. Undergraduate students in beginning weight-training classes trained with three different jumping programs, 1) Maximum vertical jumps 2) 0.3m drop-jumps and 3) 0.75m and 1.10m drop-jumps. In addition to the plyometric training, all subjects lifted weights. Subjects trained for 16 weeks, two times a week and were tested pre and post on 1RM squat, knee extension strength and vertical jump height. The authors reported that for all groups there was an increase in the three performance variables due to training, but there was no significant difference between groups. The researchers concluded

that drop-jumps were effective, but not more effective than a regular jumping routine.

Similar findings were reported by Holcomb, Lander, Rutland, and Wilson (1996). Fifty-one college-aged men were tested on the effectiveness of a modified plyometric program on power and vertical jump performance. Subjects were divided into five different groups: 1) modified plyometric drop-jump program, 2) countermovement jump program, 3) a weight training program, 4) conventional plyometric drop-jump program and 5) control group. The modified plyometric program consisted of isolating and putting emphasis on different lower extremity muscles during the jump. The conventional plyometric program consisted of subjects performing drop jumps from 40cm-60cm over an 8-week period. Maximal vertical jumps were tested pre and post training program and it was concluded that vertical jump height increased for all groups with no significant differences between the different training methods.

Steben and Steben (1981) performed a training study using 160 junior high school students with the intent of determining the validity of the stretch shortening cycle in selected jumping events that qualify as plyometrics. The long jump, high jump and triple jump were tested before and after the training study. Four groups trained under four different conditions: 1) depth-jump, 2) box drills, 3) flexibility-agility exercise and 4) control group. All groups trained five minutes per day,

five days per week for seven weeks. The authors reported that training with any of the plyometric drills increased performance in the long, high and triple jumps. Interestingly, the control group that performed only warm-up activities also showed an increase in performance in the test jumps. The gains seemed to be event specific so that the largest increase in performance in the long, high and triple jump was seen in the groups who trained with the flexibility-agility, depth-jump, and box drills respectively.

Further evidence that validates the effectiveness of drop-jump training is provided by a study by Polhemus (1981). Over a six-week period, 103 college football players were divided into three groups and participated in a training study designed to test the effectiveness of plyometric exercise on athletic ability. Group I was assigned to a conventional weight-training program, Group II performed plyometric drills, including drop-jumps, and trained with weights, and Group III was the same as Group II except that these athletes wore ankle weights and vest weights during plyometric exercise. Vertical jump, standing jump, and 40-yard dash performances were recorded before and after the training study. After six weeks of training, only Group III showed significant gains in all three tests and their scores surpassed those of the other two groups. Specifically, for Group III (weight training and plyometrics) had a gain of 3.20 cm in vertical jump, 12% increase in performance. This gain is comparable to the 3.35-cm gain in vertical

jump height seen in the group that trained with weights and depth-jumps in the study by Clutch et al. (1983). For the standing long jump, Group III improved their jump by 7.91 inches, about 7%. Finally, for the 40-yard dash, Group III improved their time by 0.19 seconds, about 4%. According to Polhemus (1981), plyometric drills with ankle and vest weights provide a stimulus that improved athletic performance in vertical jumping, standing jumping, and the 40-yard dash.

Brown, Mayhew, and Boleach (1986) also investigated the effect of plyometric training on vertical jump height. They tested 26 male high school basketball players who were randomly assigned to a training group and a control group. The training group performed 3 sets of 10 drop-jumps for 3 days/week for 12 weeks. The height of the platform was between 40-50 cm. The control group engaged in regular basketball practice. Similar to the previous studies mentioned, the drop-jump group improved in vertical jump performance by 12.5% while the control group improved by only 5.9%. The authors concluded that, in this study, plyometric training appeared to enhance the coordination of the arms with strength development of the legs.

The effectiveness of drop-jumps compared to isokinetic training on vertical jump performance also validates the effectiveness of drop-jump training (Blattner & Noble, 1979). Forty-eight males were randomly assigned to one of three groups: Group I trained with isokinetic exercises; Group II trained with drop-jumps from a 34-inch box; and

Group III was the control. A pretest and posttest for vertical jump was administered and the results of the study support the hypothesis that drop-jumping and isokinetic training both increased vertical jumping performance. However, similar to Clutch et al. (1983) and Holcomb et al. (1996), neither training method resulted in significantly greater increases compared to each other.

Taken together, it appears that plyometric training, (e.g. drop-jump training), is effective in improving athletic ability, specifically maximum vertical jump performance. Most studies reported improvement in performance, however, when compared to other conventional jump training or weight training methods, drop jumping was not found to be significantly better at improving performance. One possible explanation for the variability in the findings is that the plyometric activity may have been different between the studies. For example some researchers instructed the subject to use arms (Brown et al., 1986), while others modified the plyometric activity altogether (Holcomb, 1996). Another discrepancy may have been the duration of the training program. The duration of the plyometric program in the training studies mentioned ranged from 8 weeks (Blattner & Noble, 1979) to 16 weeks (Clutch et al., 1983). Perhaps the stimulus was the same, but the time to adapt to the stimulus was different. Finally, since different drop-heights were used, gains in vertical jump performance may have varied because of changes in kinematics (i.e., lower extremity stiffness).

Although there is a discrepancy in the literature on the validity of drop-jump training, it has become a popular exercise in the athletic realm. The increase in vertical jump performance may not be more than that of a regular jump routine, but coaches and athletes still incorporate these drills into their practice routine. Due to the inconclusive findings, there is still a need to investigate the stimulus and what constitutes effective drop-jump training.

## Components of an Effective Drop-Jump

A drop-jump is a technique by which an athlete drops from a platform of specified height and immediately upon landing, performs a maximal vertical jump. The benefit of drop jumping can be attributed to increased force production and, in turn, increased performance. The key variables within a drop-jump include the concept of storage and utilization of elastic energy, prestretching of the muscles, the amortization phase, and the stretch-shortening cycle (Bobbert, 1990). All of these concepts are interrelated and must be considered when discussing the drop-jump stimulus.

## Storage and Utilization of Potential Elastic Energy

The basic theory behind plyometric training is that an athlete's improvement is due to the utilization of stored elastic energy of the

muscles. A classic study by Bosco and Komi (1979) tested this concept. A 27-year old volleyball player performed vertical jumps on a force platform under three different prestretch conditions: 1) semi-squatting 2) jump with a counter movement and 3) drop-jump from 20, 40, 60, 80 and 100 cm boxes. Knee, ankle and hip force-velocity and power-velocity curves were derived from ground reaction force data and knee angular velocity. The most important finding was that both average ground reaction forces and calculated mechanical power were enhanced when the vertical jump was performed with a preliminary countermovement (condition 2 and 3). The authors suggested that the increase in performance was due to a combination of the utilization of elastic energy and to the stretch reflex potentiation of the muscle.

Bosco and Komi's (1979) study further validated the work of Cavagna, Dusman, and Margaria (1968). They were among the first researchers to report that a muscle, which contracted immediately after being stretched, produced greater force than a muscle which contracted without a prestretch. Their conclusion was that the greater amount of work done after prestreching was accounted for by stored elastic energy and the force developed by the contractile component of the muscle itself.

Assmussen and Bonde-Petersen (1974) also investigated the concept of storage and utilization of elastic energy in jumping tasks. The purpose of the study was to determine whether muscle could absorb and temporarily store mechanical energy in the form of potential elastic

energy for later re-use. Subjects performed maximal vertical jumps under the same three conditions as Bosco and Komi (1979). The height of the jumps was calculated using flight times and it was found that for the drop-jump, the height of the jump increased compared to the countermovement jump. Similar to the other studies, it was suggested that elastic energy was stored in the muscle and was available to be converted to mechanical energy to produce a greater vertical jump.

## Prestretching of Muscles

The capacity of the muscle's ability to store and utilize elastic energy may depend on many different variables. Cavagna et al., (1968) hypothesized that factors such as speed of prestretch, final muscle length and amount of force developed at the end of the prestretch may be of importance in transforming and reutilizing potential elastic energy. Bosco, Komi and Ito (1981) examined the influence of these variables during countermovement jumps and squat jumps performed by fourteen male power athletes. Significant correlations were found between the utilization of elastic energy and high prestretch speeds, between the utilization of elastic energy and high eccentric force, and between the utilization of elastic energy and short amortization phase.

In more recent studies, the ability of muscle to transform potential elastic energy has been reported to be affected by three main variables: 1)

magnitude of stretch, 2) velocity of stretch and 3) time of stretch (Cavagna et al., 1968; Enoka, 1988).

## Magnitude of Stretch

Magnitude of stretch during a drop-jump is synonymous with the prestretching effect and occurs during the eccentric/landing phase of the jump. The term lower extremity stiffness can also be used to describe magnitude of stretch. Lower extremity stiffness (L.E.S) was a secondary variable that Bosco and Komi analyzed in their 1979 study in which the drop-jumping group was instructed to perform two different drop-jump techniques: 1) undamped (increased L.E.S, minimal knee flexion) and 2) damped (decreased L.E.S, increase in knee flexion). It was reported that knee power values were higher in the undamped condition compared to the damped condition. It was concluded that increasing the range of stretch in the damped condition is likely to decrease the elastic behavior of the muscle (Bosco & Komi, 1979). The authors hypothesized that decreasing lower extremity stiffness during drop-jumping negatively affected short-range stiffness which implies that the muscle performs like a spring when the length change during stretch is very short. Therefore, the authors suggested that part of the storage of elastic energy was dissipated as heat. Consequently, the energy at impact stored as

potential energy could not be utilized in the subsequent contraction (Bosco & Komi, 1979).

## Velocity of Stretch

Velocity of stretch is the second component of the stretch shortening cycle. It has been well documented in the literature that the faster a muscle is eccentrically loaded or lengthened prior to concentric contraction, the greater the resultant concentric force produced (Bobbert, 1990; Edman, Elzinga, & Noble, 1978 Enoka, 1988). Also called potentiation, the enhancement of concentric force produced is increased with the speed of the prestretch. In drop jumps for example, the speed of prestretch of knee extensors and plantar flexors is greater, and the delay between prestretch and concentric action is shorter than during countermovement jumps. Thus a greater potentiation of the contraction of the leg muscles in drop-jumps compared to countermovement jumps may be responsible for the difference in mechanical output during the push-off phase (Enoka, 1988).

In a study performed by Bobbert, Huijing, and Ingen Schenau (1987b), an increased velocity of stretch of the muscles did not significantly increase jump performance. It is unknown why there is a discrepancy in the literature but since there may be an enhancement of mechanical output of the muscles due to an increase in the speed of the prestretch during a drop-jump, researchers have hypothesized that

increasing dropping height would provide the stimulus for the increased velocity of stretch. In Bobbert et al., (1987b), six male students executed drop-jumps with hands on their hips from heights of 20cm, 40cm, and 60cm. Five jumps were taken at each height and during jumping they were filmed and ground reaction force data were recorded. Analysis of the push-off phase indicated no difference in mechanical output of the joints of the lower extremity between the 20 cm and 40 cm drop height. Peak angular velocity of the ankle at landing was observed to increase with dropping height. This increase in angular velocity was accompanied with differences in pre-stretch velocity of the knee extensors and plantar flexors, however, moments and power output about the ankle joints during push-off did not increase.

## Time of Stretch – Amortization Phase

Time is the last of the three components that Enoka (1988) states are important for the stretch-shortening cycle to occur. This time frame is referred to as the amortization phase. This phase can best be described as the amount of time between undergoing a yielding eccentric contraction and initiating a concentric contraction (Chu & Plummer, 1984). As mentioned before, an increase in the velocity of stretch during a drop-jump produces an enhanced subsequent concentric contraction. In a similar manner, increased concentric force production during a

drop-jump is also dependent upon the time frame between the yielding of the eccentric phase and the initiation of the concentric contraction, or, amortization phase (Cavagna, Saibene, & Margaria, 1965). Komi (1984) reported that the greatest amount of tension developed within the muscle during the stretch-shortening cycle occurred during the phase of muscle lengthening just before the concentric contraction. It was concluded that if the duration of the amortization phase increases, then there is likely to be a decrease in muscle tension and therefore a decrease in force production.

It has been hypothesized that the amortization phase is an important component of plyometrics since powerful movements, such as jumping and sprinting, happen in a short time (Chu, 1983). During a jump, for example, potential elastic energy is stored during the eccentric phase of muscle contraction and is partially transformed back to kinetic energy during the concentric contraction. However, the potential elastic energy developed in this process may also be transformed into heat as observed in the study by Bosco and Komi (1979). It has been hypothesized that the loss of potential energy occurs if the eccentric contraction is not immediately followed by a concentric contraction (Bosco and Komi, 1979). Similar to other definitions, Chu (1992) defines this conversion from negative (eccentric), to positive (concentric) work as the amortization phase. Great high jumpers are on the ground for as

little as 0.12 s (Chu, 1992) so the amortization phase must take place within hundredths of a second during this contact period.

## Stretch-Shortening Cycle

Although the stretch shortening cycle is a major component of drop-jumping tasks, it has been a controversial topic of discussion over the past few years. As mentioned before, time available for force development and potentiation of the contractile component are two factors related to the enhancement of maximum work after the landing phase of a drop-jump. It has been argued that for vertical jumps, an increase in force production is due to the release of potential elastic energy which has been transformed into elastic components of the muscle-tendon complex during the prestretch (Asmussen & Bonde-Peterson, 1974; Bosco & Komi, 1979; Bosco et al., 1981). Other authors suggest that non-elastic mechanisms play a role in an increase of force production during the concentric phase of a vertical jump. Still, others reject the idea of the role of elastic energy contributing to the increase in force production and put more emphasis on the involvement of the stretch reflex (Dietz, Schmidtbleicher, & Noth, 1978). The myotatic reflex occurs when the muscle is stretched rapidly and with large amounts of force (Enoka, 1988). Muscle spindles located within the muscle react to sudden stretch by sending signals to the spinal cord, resulting in muscular contraction to resist the sudden stretch (Thomas, 1988). The

stretch reflex may also contribute to the improvement in muscular force generation through the combined effects of voluntary contraction and the involuntary contraction caused by the reflex (Thomas, 1988).

The difference in opinion of the validity of the stretch shortening cycle stem from the idea of storage and reutilization of elastic energy. While researchers such as Bosco and Komi (1979) hypothesize that potential elastic energy can be transformed and re-utilized during a the countermovement phase of a vertical jump, the subsequent enhancement of maximum work during the concentric phase due to this phenomenon is unclear (Ingen Schenau, Bobbert, & Haan, 1997). Arguments against this claim state that the amount of energy stored in series elastic elements at the start of the concentric phase is not determined by the amount of "negative work" performed but solely by the force at the start of push-off. Rather, it seems that the enhancement is largely due to the fact that the muscles can build up force prior to the concentric phase (Ingen Schenau et al., 1997).

There are many components of a drop-jump that must be considered in order to understand the stimulus that this type of training provides. The variables that have been discussed include the concept of storage and utilization of elastic energy, prestretching of the muscles, the amortization phase and stretch-shortening cycle. Not only is athletic performance dependent upon how effectively the athlete incorporates these variables during a drop-jump training session, but also how one

can minimize the chance of injury while obtaining the proper stimulus. Components of an effective drop-jump stimulus do not come without a cost. As in most sports training programs, ground reaction forces due to repetitive impact activities have the potential to cause injury to the musculoskeletal system (Steele & Millburn, 1988).

## Impact Forces and Surface Characteristics in Sport

Steele and Millburn (1988) investigated the effect of synthetic sport surfaces on ground reaction forces (GRF) at landing in a sport called netball. The authors analyzed ground reaction forces during landing from an attacking netball movement pattern performed on 12 different synthetic surfaces (bitumen, concrete, 3 samples of synthetic grass, and 7 samples of rubber surfaces). In standard laboratory shoes, ten subjects performed three landing trials for each of the 12 different surfaces. A Kistler force plate with a sample rate of 333Hz recorded the following variables: 1) Magnitude of maximum peak GRF at impact, 2) Time to maximum peak GRF, 3) Magnitude of initial peak GRF at impact, 4) Time to initial peak GRF, 5) Braking force and 6) Time from onset of impact until the peak braking force. The authors reported that peak vertical GRF values ranged from 3.71 to 3.91 times body weight (BW) for all conditions with no significant differences between surfaces. Time to peak GRF was significantly different between the grass (25.7 ms) compared to the rubber (24.0 ms), bitumen (20.8 ms) and concrete

conditions (24.2 ms), with the longer time to peak GRF occurring on the grass surface. In addition to analyzing peak forces, the authors analyzed the initial peak GRF. This peak occurred between initial contact of the foot and the ground and the maximum peak GRF. Initial peak GRF values were not significantly different between conditions, but time to initial peak GRF was as much as 3.6 ms longer when landing on grass compared to the other surfaces. The authors suggested that the grass surface appeared to provide cushioning, resulting in an increase of the time period over which the force was experienced. The grass surface, however, was not suggested to be the most appropriate surface for minimizing injury since the lowest braking forces were generated when landing on rubber surfaces (3.33 BW) compared to grass (3.46 BW), concrete (3.80 BW), and bitumen (3.51 BW). A high braking force is another variable that has been identified as a major contributing factor to the high incidence of knee and ankle injuries in landing at netball (Steele & Millburn, 1988). Finally, a significant difference in time to peak braking force was reported. There was a shorter time to peak braking force during landing on the grass surface (26.3 ms) compared to the other surfaces (rubber 30.4ms; bitumen 30.0ms; concrete 30.4ms). From these results the authors suggest that the shortened period to peak braking forces may increase the likelihood of injury as in landing on the grass surface.

McNitt-Gray, Yokoi, and Millward (1993) examined landing strategy adjustments made by female gymnast athletes in response to changes in drop height and mat composition. Nine female gymnasts participated in the study and each subject performed drop landings from platforms from heights of 0.69m, 1.25m, and 1.82m on soft and stiff surfaces. A drop landing consisted of stepping out from a platform off a straight leg with the right leg extended slightly forward. Subjects performed the landing by contacting the landing surface with both feet simultaneously and bringing the velocity of the total body center of gravity to zero without taking extra steps. The authors reported differences in peak vertical force, landing phase time, time to peak vertical force and lower extremity kinematics across drop heights. However, only time to vertical impact peak and minimum knee angular position was different between surfaces. The time to impact peak during landing on the stiff mat was 57 ms compared to 64 ms after ground contact for the soft mat. These times are twice as long compared to Steele and Millburn (1988) perhaps because of the difference in landing task. The task in Steele and Millburn (1988) required the subject to run forward from a standard position and then breaking to the side away from a defender, catching a ball, landing on the dominant lower extremity, pivoting, and then throwing the ball to a catcher located 5.6 m away. Steele and Millburn's (1988) landing phase is different from that of McNitt-Gray et al. (1993) because in the latter study, the gymnast landed from three different

heights and there was no horizontal movement prior to landing. Larger degrees of knee flexion were observed for landings on the stiff mat as compared to the soft mat. McNitt-Gray and colleagues (1993) concluded that changes in drop height and mat composition may elicit changes in landing strategies of female gymnasts.

In a follow-up study by McNitt-Gray, Yokoi, and Millward (1994), landing strategies of gymnasts while landing on different surfaces were further investigated. Ten female gymnasts and four male gymnasts participated in the study and performed the a drop landing task from a platform of 69 cm. All subjects performed four trials on each of three surfaces: 1) stiff mat, 2) soft mat, and 3) no mat. The authors reported that time to peak vertical forces decreased as surface stiffness increased. Furthermore, there were significantly lower peak vertical forces (range 0.6 - 1.75 BW), longer landing phase times, and greater knee and hip flexion between the no mat and either mat condition. Max knee flexion was reported to be greater for landings on the stiff mat compared to the soft mat (means not reported). Peak knee flexion velocities were also observed to be greater during landings on the stiff mat compared to those on the soft mat (range of differences 1.0 - 3.1 rad/s). The authors concluded that gymnasts changed their total body stiffness strategy in response to changes in surface condition. The authors also suggested that the presence of a mat may reduce the need for joint flexion and may

alter the vertical ground reaction forces during landing (Mcnitt-Gray et al., 1994).

Stacoff, Kaelin, and Stuessi (1988) investigated the impact of landing after a volleyball block. A Kistler force platform (60x90cm; 500Hz) was placed near the net on a volleyball court such that subjects (n=12) landed on it after performing a game-like volleyball block. The block was executed 10 times and magnitude of the vertical ground reaction force and lower extremity kinematics were analyzed (videocamera 100 Hz). The first impact peak when the forefoot touched down was reported to range between 1000 and 2000 N and the second peak, when the heel touched down, ranged from 1000 to 6500 N. The correlations between the velocity at touchdown and the ground reaction force at the forefoot was low (r=0.15). In contrast to drop-jumping studies (Bobbert, 1990; Edman, et al. 1978; Enoka, 1988) where velocity of stretch may be important in increasing force production, touchdown velocity in this study plays only a minor role in respect to impact loads during landing. Stacoff and colleagues (1988) also that the more the knee was extended at impact, the greater the force of impact of forefoot with the ground. In summary, high impact forces are observed during landing after a volleyball block. Furthermore, lower extremity stiffness at contact may be a more important variable to consider compared to touchdown velocity when examining ground reaction forces. Control of

angle of the knee prior to contact during landing may be a useful strategy to reduce impact loads.

Fowler and Lees (1998) compared the kinetic and kinematic characteristics of plyometric drop-jump and pendulum exercises. Eight male subjects performed 10 maximal effort repetition drop-jumps from a platform of 0.28m and 10 pendulum swings. During a pendulum swing the subject is seated in a swing positioned directly in front of a vertical rebound surface. The subject swings backward and forward in the swing, rebounding against the vertical surface. This training device was designed to minimize the perceived risk of drop-jumping and attempt to mimic the positive effects of this type of training. Ground reaction force data were recorded by a Kistler force plate (500Hz) mounted horizontally on the landing surface for the drop-jumps and vertically on the landing surface in front of the pendulum. There was more range of motion for the ankle and knee during the pendulum exercises (ankle 71 degrees; knee 88 degrees) compared to the drop-jump (ankle 81 degrees; knee 103 degrees). There was also a greater peak vertical ground reaction force during the drop-jump condition (2200 - 2610 N) compared to the pendulum (1770 - 2110 N). Peak loading rate was greatest for the drop-jump condition (33.3 BW/s compared to 24.8 BW /s) for the pendulum. The authors concluded that not only was there a degree of similarity in the movement patterns of the two conditions, but the pendulum exercise

offered a reduced magnitude of peak vertical ground reaction forces compared to the drop-jump condition.

Ricard and Veatch (1990) compared impact forces and loading rates in a high and low impact aerobic dance movement. Five subjects performed five trials of a low impact aerobic knee lift and five trials of a high impact knee lift. A low impact routine consisted of movements where one foot was always in contact with the ground. A high impact routine consisted of movements with various flight phases such as hopping skipping and jumping. An AMTI force plate (1000Hz) was used to record peak impact force, impact impulse, peak loading rate, and mean force curves. Peak impact force was significantly lower in the low impact knee lift (mean 0.98 BW) compared to high impact knee lift (mean 1.98 BW). Loading rate was significantly lower during the low impact knee lift (14.38 BW/s) than the high impact knee lift (42.55 BW/s). Time to peak impact force was significantly longer in the low impact knee lift (160.72 ms) compared to the high impact knee lift (103.68 ms). The authors concluded that, based on differences in loading rates and peak impact forces, low impact front knee lifts impose lower stress on the musculoskeletal system than do high impact knee lifts.

Dixon, Collop, and Batt (2000) investigated surface effects on ground reaction forces and lower extremity kinematics during running. Contrary to the previous studies, the hypothesis of this study was that variations in surface compliance would not influence magnitude or rate

of loading of peak impact force during running, and that adjustments in lower extremity kinematics at initial ground contact would account for the similar impact force. The mechanical impact absorbing properties of three sports surfaces, 1) conventional asphalt, 2) rubber-modified material and 3) synthetic acrylic carpet were tested using a standard impact tester. Six subjects then performed heel-toe running trials on the three different surface compliances. A force plate recorded ground reaction forces at 800 Hz and kinematic data was synchronized using a CODA system (Charnwood Dynamics, Loughborough, UK). Results from the impact testing revealed significant differences in the impact absorbing qualities of the surfaces. The peak g value for the acrylic surface was the lowest and peak g value for the rubber surface was lower compared to the asphalt surface. The authors suggested that peak forces during running should follow the impact characteristics of the surfaces. However, results from subject testing only partially supported this idea. It was reported that only some of the subjects exhibited the same peak vertical force across surfaces, whereas others had a marked change in peak impact forces.

Dixon et al., (2000) reported that average rate of loading of impact was significantly reduced during running on the rubber surface compared with the asphalt surface. There were no differences in kinematic variables for the group, however, individually, there was a varied response in initial joint angles, initial peak joint angles and peak

joint angular velocities. In conclusion, the authors suggested that the mechanism of adaptation during running on different surfaces may vary among runners. The similar peak impact forces across surfaces cannot be explained for all subjects by the sagittal plane kinematic data. Dixon et al., (2000) authors suggested an emphasis on individual subject analyses was needed.

This finding is similar to a drop-jump study by Reid and Mercer (In press) who investigated ground reaction forces during drop-jumping barefoot and with shoes on. Despite performing the plyometric task barefoot, peak forces were not different than wearing shoes (Reid et al., in press). The authors suggested that in a laboratory setting, performing a drop-jump barefoot and with shoes on did not affect the vertical GRF, average GRF or contact time for the group. However, through inspection of the individual data, the authors reported that subjects accommodated to the different surfaces in individual ways.

Sanders and Allen (1993) investigated how changes in kinematics of subjects adapting to a change of surface compliance in a drop-jumping task. It was hypothesized that when skilled jumpers changed from performing drop-jumps on a hard surface to a spring surface, that the pattern of accelerations of the center of gravity would change as a result of enhanced performance. Six subjects volunteered for the two phases of the study. The first phase was a practice phase and consisted of twenty drop-jumps a day for five consecutive days followed by rest after five

days. Then twenty more trials were performed for five consecutive days for a total of 200 jumps. All jumps were performed on the Kistler force plate. The drop-jump was from a height of 40cm and no trials were recorded during the practice phase. The second phase was the test phase and a similar protocol was followed. The first week subjects jumped onto the hard surface and the second week subjects jumped onto a spring surface (62 cm by 62 cm landing platform supported by springs (22.95 kN/m). Authors reported that subjects jumped 0.12 m - 0.41 m higher on the spring surface with practice. In contrast to other studies, peak magnitude of the ground reaction force increased with practice on the spring surface. There was also a trend of increasing rate of loading on the spring surface with increases in length of practice. The authors suggested that the subjects were landing more rigidly with increasing trials. Another interesting finding was that as practice continued for the spring surface, lower extremity kinematics became less similar to the hard surface. In particular, the amount of knee flexion after initial contact on the spring surface was reduced than during the stiff surface. In the case of the hip, subjects changed their strategy almost immediately when switching from the hard surface to the spring surface. Subjects tended to flex less at the hip after initial contact even in the first transfer trial. Overall, subjects gradually made a change in the angular kinematics during drop-jumps performed on the hard surfaces compared to the spring surface. In particular, there was a reduction in flexion of

the ankle, knee, and hip following first contact during the hard surface compared to the spring surface. The authors suggested that the change in kinematics had an effect on producing a faster loading rate of the spring surface and an increase in maximum forces compared to the hard surface.

## Lower Extremity Stiffness

One of the three variables that Enoka (1988) stated is important for an effective drop-jump is the magnitude of stretch, in other words, lower extremity stiffness. Many studies including the previous study by Sanders and Allen (1993) have determined that during running, jumping and hopping, subjects change their lower extremity stiffness strategy as surface compliance changes. Ferris and Farley (1997) explored the interaction of leg stiffness and surface stiffness during human hopping. It was hypothesized that the leg spring stiffness would increase in order to accommodate to the compliant surface, and offsetting the effects of the compliant surface on locomotion. Five subjects hopped on both legs with hands on hips on five different surface compliances placed over a force platform (AMTI, 1000 Hz). With a hopping frequency of 2Hz, significant differences were observed in leg spring stiffness across surfaces. The authors reported that leg stiffness increased from 17.8 kN/m on the most stiff surface to 53.3 kN/m on the least stiff surface. As a result of the change in leg spring stiffness, the total stiffness of the system (lower

extremity and spring surface) and the contact time remained the same across surfaces. However, peak ground reaction forces decreased by 20% as surface stiffness decreased (most stiff, 3.14 BW; least stiff, 3.94 BW).

Ferris, Liang, and Farley (1999) investigated the adjustments made by runners as they take a stride onto a new running surface. The authors hypothesized that, similar to the hopping study, runners would adjust leg stiffness when taking their first step onto a new running surface. Six females volunteered to run on two different surface conditions: 1) soft rubber surface and 2) hard rubber surface. The first two conditions either had the whole length of the track covered in either the hard surface or the soft surface. The next condition had half of the track covered with the soft surface first and then the hard surface last. The final condition was transitioning from hard to soft surfaces. Prior to testing, subjects practiced all conditions. Ground reaction force data were collected for the first and last steps onto the new surface and results showed that runners adjusted leg stiffness appropriately by the first step on the hard surface. The authors reported that subjects also accommodated appropriately when transitioning from the hard surface to the soft surface. The authors also reported that contact time and peak ground reaction forces remained the same between conditions. It was concluded that by changing leg stiffness, each runner was able to make a smooth transition between the two different surface compliances

resulting in no change in peak ground reaction forces or contact time. If runners did not change the kinematics of their running stride when running on a new surface, it would be expected that contact time and ground reaction forces would change instead of remain the same. This would not be desirable if the goal of the task was to run as fast as possible in a given amount of time. Perhaps there is a point in running where the lower extremity stiffness is either too soft or too stiff. In Ferris et al. (1999), if the subject maintained the same lower extremity stiffness when running on a new, harder surface, there may be the possibility of injury to the musculoskeletal system or lack of ability to complete the task. In this case the lower extremity may be too stiff and the forces of the ankle, hip and knee joints may be too excessive.

## Summary

Four areas of research were reviewed to provide background information on the cost:benefit ratio of drop-jumping. Specifically, the validity of drop-jump training, components of an effective drop-jump, impact ground reaction forces in sport and surface characteristics in sport were discussed.

Several researchers, for example, Blattner and Noble, 1979; Brown et al., 1986, and Polhemus, 1981, have tested the validity of drop-jump training and have concluded that drop-jumping improves vertical jump

performance compared to a program involving no jump training. In turn, improved vertical jump ability may improve athletic performance overall.

The components of an effective drop-jump include the concept of storage and utilization of elastic energy, prestretching of the muscles, the stretch-shortening cycle and the amortization phase. In more recent studies the variables magnitude of stretch, velocity of stretch and time have been the focus of this type of training. These variables play a big role in the benefit and effectiveness of drop-jumping.

Ground reaction forces due to landing in sports activities have been hypothesized to be a causitive factor in injury to the musculoskeletal system during repetitive impact tasks (Steele and Millburn, 1988) such as drop-jump training.

Finally, changes in surface compliance have been shown to effect not only ground reaction forces, but lower extremity stiffness in activities such as hopping, running, jumping and landing. While certain surface compliances may be beneficial in reducing the risk of injury, the changes in lower extremity kinematics may lead to an ineffective training stimulus.

# CHAPTER III

# PROCEDURES

The purpose of the study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps. Specifically, ground reaction force variables, lower extremity stiffness, and the amortization phase were examined for variations in what constitutes effective drop-jump training across different surface compliances.

## Population

Ten female subjects (age: 23.3±3.5 years; height: 1.68±0.04meters; mass: 62.4±9.7 kg) from the University of Nevada, Las Vegas participated as volunteers in this study (Appendix II). All subjects had experience with drop-jump tasks and were free from any history of lower extremity joint problems or surgeries that would prevent them from completing a drop-jump activity. Subjects signed an informed consent form (Appendix I) approved by the Human Subjects Review Committee at the University of Nevada, Las Vegas.

## Instrumentation

Vertical ground reaction force data were measured and recorded (1000Hz) during the landing and push-off phase of the drop-jump using a force platform (Kistler; 9581B). Digitized coordinates of the hip, knee, and ankle were recorded at 200Hz using an automated digitizing system (MotionAnalysis, VP320). The two systems were synchronized using a timing light.

## Force Platform

One Kistler force platform model 9581B (Amherst, NY) was used in this study. The surface of the force plate was flush with the surface of the laboratory floor. The dimensions of the force plate were 40 cm x 60 cm. The force plate was set to begin sampling with a pretrigger value of 10%. Anterior/posterior, medial/lateral and vertical GRF values were sampled, however, only vertical GRF values plotted against time were analyzed. The total sampling period was 2 seconds. A synchronization switch was triggered upon contact, sending a square-wave to the force plate data collection system simultaneously with triggering an LED light to go on. Laboratory software (Bioware version 4.0) was used to collect force plate data.

## Motion Analysis

In addition to the GRF data, digitized records of specified anatomical landmarks were obtained using an autodigitizer (MotionAnalysis). This auto digitizing system recorded the X,Y coordinates of the greater trochanter, head of the fibula, lateral malleolus, and 5$^{th}$ metatarsal from a sagittal plane of view for every trial. LED's were placed on all five anatomical landmarks so the camera could track the exact movement. The kinematic data were sampled at a rate of 200 Hz. The camera distance was set up so that all of five joints remained in the field of view for the whole jump trial (20 feet from subject). The f-stop of the lens was set to the smallest diameter. All data was recorded and processed using custom software.

## Surfaces

Three surfaces were used as independent variables: 1) force platform 2) turf surface and 3) aerobics mat. The last two surfaces were cut to the same dimensions as the force plate (40 x 60 cm) and placed on top of the platform. The increase in height of the force platform due to the added material was accounted for by subsequently increasing the height of the platform the subjects dropped from. Subjects jumped down so that one landed on the force plate and the other foot landed right next to the force plate. A separate piece of the like surfaces was placed next

to the force plate so that both feet landed on the same surface even though the force plate only recorded one foot.

## Experimental Protocol

Subjects were asked to report to the Biomechanics Laboratory on two different days. Height and weight were recorded prior to any testing. In general, subjects were asked to perform drop-jumps onto three different surface compliances. The first day of testing was a training day. After a warm-up and demonstration by the investigator of the technique for a drop jump, the subject practiced drop-jumps from a platform of 40 cm onto the force platform. Subjects wore standard running shoes during practice as well as during testing to minimize possible effects due to shoe type between surface compliances. As many as 20 drop-jumps were performed onto the force plate during the training day. The practice session lasted about 10-15 minutes and sufficient rest was allowed between drop-jumps for recovery.

The second day was a test day. Before data collection, the force platform and motion analysis system was calibrated, synchronized and tested to ensure of proper functioning. The order of the surfaces was counterbalanced among subjects. After a 5-minute, self selected warm-up routine, subjects performed the same style of drop-jump that were practiced on day one. During the landing phase of the drop-jump, the subject was instructed to land with one foot on the force plate and one

foot off of the force plate with both feet hitting the ground simultaneously. With both hands on their hips, the subject held their left leg off of the 40 cm platform and dropped down onto the surface. The subject then performed a countermovement jump and jumped for maximal vertical height and landed back on the surface (Appendix VI). The subject was then instructed to remain on the force plate until a cue from the researcher indicated that sampling was complete. All trials were monitored visually by the researcher to ensure that the subject targeted the force plate accurately. Five to eight drop-jump trials on each surface were executed for a total of 15 - 24 jumps. Only five acceptable trials were analyzed for statistical testing. Trials were performed with hands on hips to minimize any effect due to arm assistance and sufficient rest was allowed for recovery. Testing lasted about 30 - 45 minutes. At least 24 hours, and no more than 3 days separated the training and testing days.

## Data Reduction

### Ground Reaction Force Data

GRF data were scaled relative to body weight (BW) and plotted using Bioware Software. A force threshold of 20N was chosen to represent initial contact time. Data were processed using custom laboratory software (Matlab). Three variables from each trial were recorded and averaged per subject – condition combination. The

variables include 1) peak GRF (FPEAK) 2) time to peak GRF (TFPEAK) and 3) loading rate (LR). Loading rate was calculated as the ratio of peak ground reaction force and time to peak ground reaction force.

## Kinematic Data

Laboratory software (QuickBasic 4.5) was used to process the digitized X,Y coordinates of the hip, knee, ankle, and 5$^{th}$ metatarsal. A 4$^{th}$ order zero lag Butterworth Filter smoothing routine was performed. Lower extremity stiffness was calculated using the equation k=F/x where F is the GRF corresponding with the minimum hip position (x) and k represents LES. The displacement data were obtained from the MotionAnalysis digitized record and the force data (F) were obtained from the GRF curve.

The amortization phase was determined by calculating knee angular position from the digitized data . Knee angular position was defined as the relative angle between the thigh and leg segments. From knee angular position (anatomical position = 0 degrees), knee angular velocity was calculated using the 1$^{st}$ central difference technique:

$$v_i = (\theta_{i+1} - \theta_{i-1}) / (t_{i+1} - t_{i-1})$$

The amortization phase was defined as the amount of time between undergoing a yielding eccentric contraction and initiating a concentric contraction. From the knee angular velocity plot, the yielding of

eccentric contraction and initiation of concentric contraction were identified (Figure 1 & 2).

## Statistical Analysis

The statistical analysis consisted of computing a within-subjects repeated measures analysis of variance (ANOVA) across surface conditions on each of five dependent variables (three GRF variables including FPEAK, TFPEAK and LR; and two kinematic variables including K and AMORT. Planned comparisons were performed following the analysis of variance.

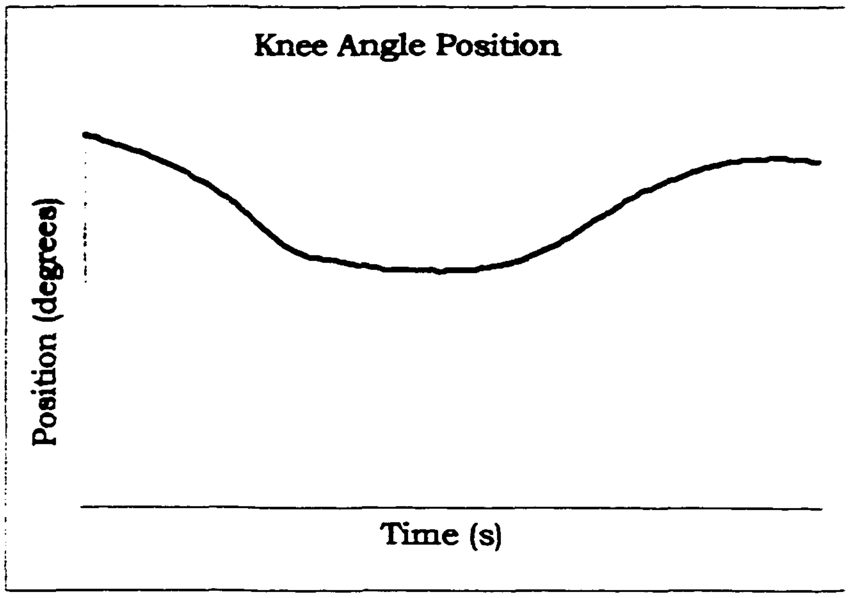



Figure 1. Example of knee angle position during landing phase of drop-jump

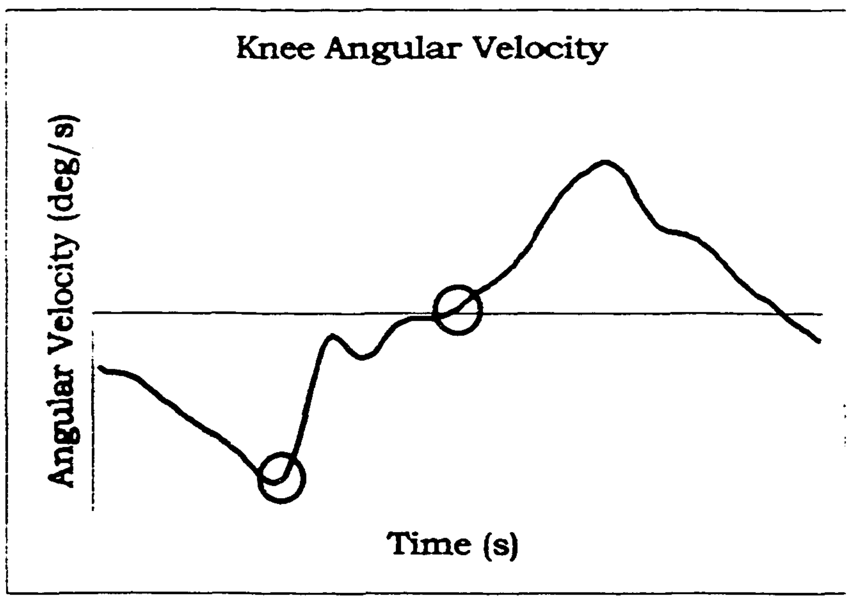



Figure 2. Knee angular velocity calculated from knee angle position using the 1st Central Difference method.

## CHAPTER IV

## RESULTS

The purpose of this study was to investigate the effect of surface compliance on the cost and benefit of performing drop jumps. Specifically, ground reaction forces (GRF) lower extremity stiffness, and the amortization phase were examined for variations in what constitutes effective drop-jump training across different surface compliances.

Of particular interest in this study was the question: Is the cost of performing a drop-jump reduced (i.e., high impact ground reaction forces) while the benefit maintained (i.e., lower extremity stiffness and amortization phase as surface compliance increases?

There was a significant difference in FPEAK between conditions, $F(2,18) = 6.170$, $p = 0.009$: Table 2. (See Table 1 for definition of abbreviations). Follow up testing indicated that only C2 FPEAK was significantly greater than C3 ($p<0.05$). There was a significant difference in TFPEAK between conditions, $F(2,18) = 32.630$, $p = 0.001$: Table 3. Planned comparisons revealed that C1 TFPEAK was significantly longer than C2 ($p<0.05$) and shorter compared to C3 ($p<0.05$). Furthermore, TFPEAK was significantly lower during C2 than C3 ($p<0.05$). There was a

significant difference in LR between conditions, $F(2,18) = 11.240$, $p = 0.001$: Table 4. Follow up tests indicated that C2 LR was greater than C1 and C3 ($p<0.05$) and C1 LR was greater than C3 ($p<0.05$). K was not different between conditions, $F(2,18) = 0.775$, $p = 0.402$: Table 5. Finally, AMORT was not different between conditions, $F(2,18) = 1.849$, $p = 0.186$: Table 6 (See Appendix VI for ANOVA tables).

Table 1. Abbreviations Used in the Study

| Abbreviation | : | Definition |
|---|---|---|
| FPEAK | : | Peak ground reaction force |
| TFPEAK | : | Time to peak ground reaction force |
| LR | : | Loading rate |
| K | : | Lower extremity stiffness |
| AMORT | : | Amortization phase |
| C1 | : | Force plate condition (stiff) |
| C2 | : | Turf surface |
| C3 | : | Mat surface |

Table 2. Mean and Standard Deviation Values of Peak Ground Reaction Forces (FPEAK).[a,b]

| SUBJECT | C1 | (STDEV)[c] | C2 | (STDEV)[c] | C3 | (STDEV)[c] |
|---|---|---|---|---|---|---|
| 1 | 4.05 | 0.39 | 4.79 | 0.25 | 3.87 | 0.53 |
| 2 | 4.05 | 0.73 | 4.90 | 0.43 | 4.59 | 0.39 |
| 3 | 3.45 | 0.39 | 3.64 | 0.43 | 3.57 | 0.26 |
| 4 | 4.23 | 0.36 | 3.83 | 0.68 | 3.56 | 0.93 |
| 5 | 4.62 | 0.69 | 4.84 | 0.43 | 5.18 | 0.87 |
| 6 | 3.98 | 0.86 | 4.96 | 0.83 | 3.55 | 0.18 |
| 7 | 4.01 | 0.83 | 3.35 | 0.50 | 2.95 | 0.39 |
| 8 | 3.92 | 0.38 | 4.35 | 0.38 | 3.13 | 0.29 |
| 9 | 3.47 | 0.34 | 4.25 | 0.31 | 3.54 | 0.08 |
| 10 | 5.14 | 0.96 | 5.89 | 0.92 | 4.00 | 0.70 |
| MEAN | 4.09 | | 4.48 | | 3.79 | |
| STDEV[d] | 0.50 | | 0.75 | | 0.66 | |

Legend. [a] All units normalized to body weight
[b] C1 = force plate; C2 = turf; C3 = mat
[c] between-subject standard deviation
[d] within-subject standard deviation

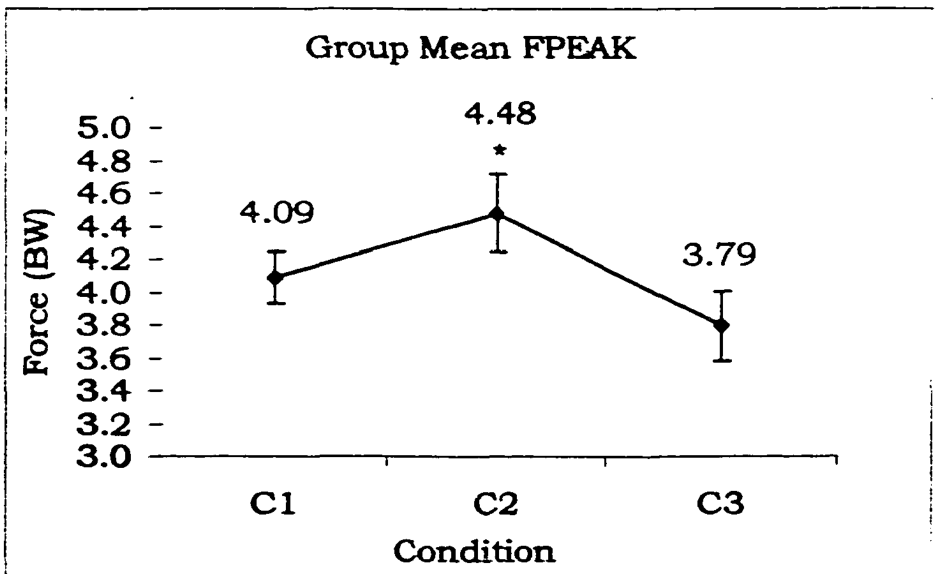



Figure 3. FPEAK Group means and standard error across subjects where each subject completed five drop-jump trials.

Legend. * Denotes C2 > C3 ($p<0.05$)
C1 = force plate, C2 = turf, C3 = mat

**Table 3. Mean and Standard Deviation Values of Time to Peak Ground Reaction Forces (TFPEAK)[a,b]**

| SUBJECT | C1 | (STDEV)[c] | C2 | (STDEV)[c] | C3 | (STDEV)[c] |
|---|---|---|---|---|---|---|
| 1 | 0.070 | 0.003 | 0.061 | 0.003 | 0.075 | 0.001 |
| 2 | 0.049 | 0.008 | 0.045 | 0.003 | 0.060 | 0.002 |
| 3 | 0.050 | 0.001 | 0.046 | 0.003 | 0.062 | 0.002 |
| 4 | 0.046 | 0.003 | 0.046 | 0.001 | 0.064 | 0.004 |
| 5 | 0.063 | 0.023 | 0.049 | 0.005 | 0.063 | 0.002 |
| 6 | 0.057 | 0.006 | 0.049 | 0.003 | 0.061 | 0.007 |
| 7 | 0.049 | 0.004 | 0.052 | 0.002 | 0.056 | 0.002 |
| 8 | 0.049 | 0.005 | 0.045 | 0.005 | 0.062 | 0.004 |
| 9 | 0.060 | 0.007 | 0.050 | 0.001 | 0.068 | 0.006 |
| 10 | 0.038 | 0.008 | 0.031 | 0.006 | 0.061 | 0.025 |
| MEAN | 0.053 | | 0.047 | | 0.063 | |
| STDEV[d] | 0.009 | | 0.007 | | 0.005 | |

Legend. [a] Units reported in seconds
[b] C1 = force plate; C2 = turf; C3 = mat
[c] between-subject standard deviation
[d] within-subject standard deviation

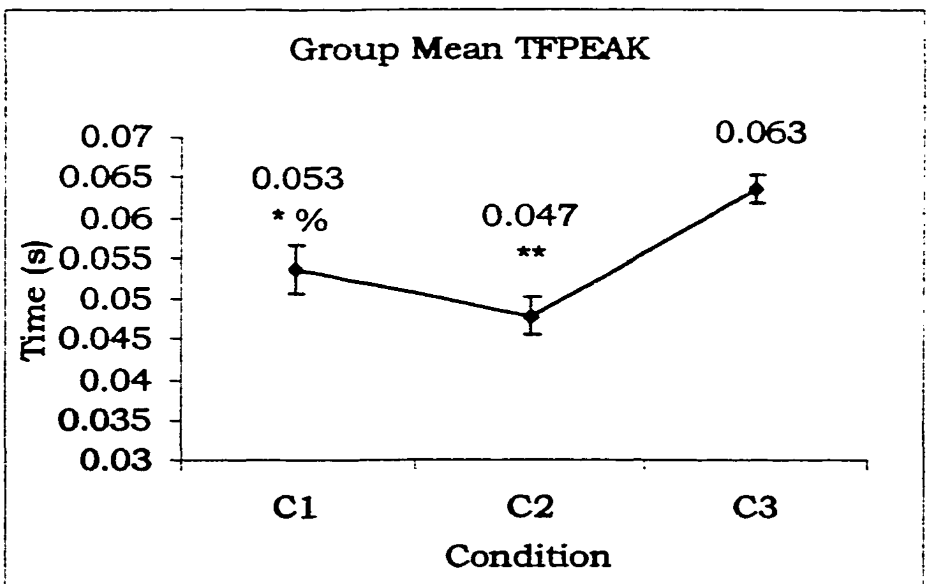



Figure 4. TFPEAK group means and standard error across subjects where each subject completed five drop-jump trials.

Legend. * Denotes C1 > C2 ($p<0.05$)
% Denotes C1 < C3 ($p<0.05$)
** Denotes C2 < C3 ($p<0.05$)
C1 = force plate, C2 = turf, C3 = mat

Table 4. Mean and Standard Deviation Values for Loading Rate (LR)[a,b]

| SUBJECT | C1 | (STDEV)[c] | C2 | (STDEV)[c] | C3 | (STDEV)[c] |
|---|---|---|---|---|---|---|
| 1 | 57.2 | 6.5 | 78.6 | 7.1 | 51.0 | 7.1 |
| 2 | 84.2 | 24.4 | 107.4 | 10.6 | 75.9 | 5.7 |
| 3 | 69.0 | 8.5 | 79.9 | 15.5 | 57.4 | 5.3 |
| 4 | 90.2 | 6.7 | 82.9 | 18.4 | 55.5 | 15.9 |
| 5 | 81.0 | 29.4 | 99.3 | 18.3 | 82.6 | 15.4 |
| 6 | 71.3 | 21.4 | 102.4 | 23.7 | 59.0 | 10.1 |
| 7 | 82.2 | 23.0 | 63.8 | 12.2 | 52.8 | 7.9 |
| 8 | 79.5 | 10.6 | 95.9 | 15.9 | 50.5 | 7.2 |
| 9 | 58.5 | 10.0 | 84.5 | 7.5 | 51.9 | 4.8 |
| 10 | 142.6 | 51.4 | 196.8 | 60.9 | 74.9 | 33.6 |
| MEAN | 81.6 | | 99.2 | | 61.2 | |
| STDEV[d] | 24.0 | | 36.7 | | 12.0 | |

Legend. [a] Units reported in body weights/second
[b] C1 = force plate; C2 = turf; C3 = mat
[c] between-subject standard deviation
[d] within-subject standard deviation

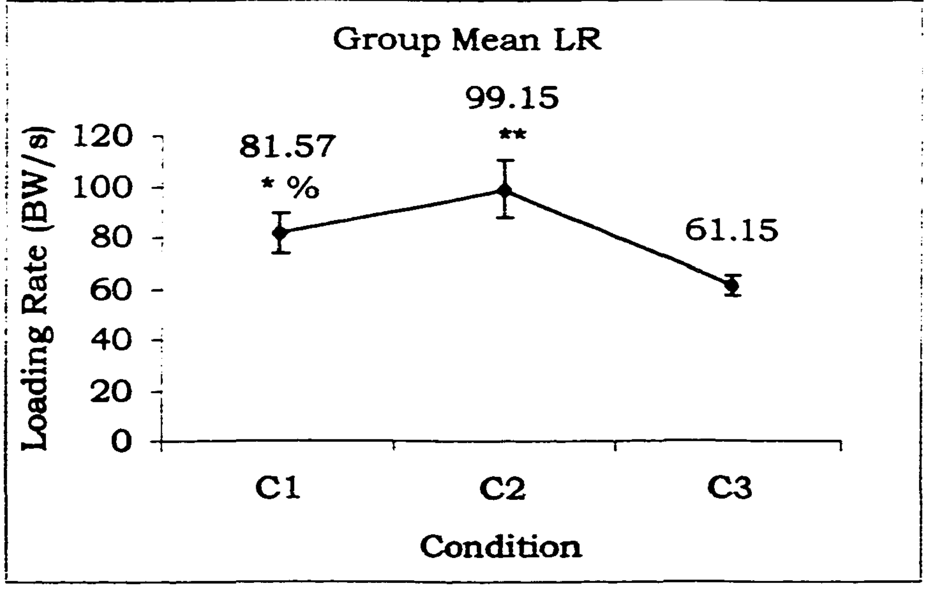



Figure 5. LR group means and standard error across subjects where each subject completed five drop-jump trials.

Legend. * Denotes C1 < C2 ($p<0.05$)
% Denotes C1 > C3 ($p<0.05$)
** Denotes C2 > C3 ($p<0.05$)
C1 = force plate, C2 = turf, C3 = mat

Table 5. Mean and Standard Deviation Values for Lower Extremity Stiffness (K)[a,b]

| SUBJECT | C1 | (STDEV)[c] | C2 | (STDEV)[c] | C3 | (STDEV)[c] |
|---|---|---|---|---|---|---|
| 1 | 0.063 | 0.003 | 0.060 | 0.006 | 0.055 | 0.004 |
| 2 | 0.106 | 0.007 | 0.121 | 0.021 | 0.106 | 0.008 |
| 3 | 0.081 | 0.006 | 0.089 | 0.009 | 0.092 | 0.009 |
| 4 | 0.066 | 0.003 | 0.068 | 0.004 | 0.077 | 0.009 |
| 5 | 0.142 | 0.014 | 0.136 | 0.015 | 0.146 | 0.020 |
| 6 | 0.081 | 0.014 | 0.073 | 0.006 | 0.092 | 0.006 |
| 7 | 0.059 | 0.006 | 0.056 | 0.005 | 0.052 | 0.004 |
| 8 | 0.066 | 0.005 | 0.064 | 0.006 | 0.065 | 0.004 |
| 9 | 0.061 | 0.005 | 0.063 | 0.008 | 0.062 | 0.003 |
| 10 | 0.077 | 0.008 | 0.098 | 0.011 | 0.116 | 0.021 |
| MEAN | 0.080 | | 0.083 | | 0.087 | |
| STDEV[d] | 0.026 | | 0.028 | | 0.030 | |

Legend. [a] Units reported in body weight/cm
[b] C1 = force plate; C2 = turf; C3 = mat
[c] between-subject standard deviation
[d] within-subject standard deviation

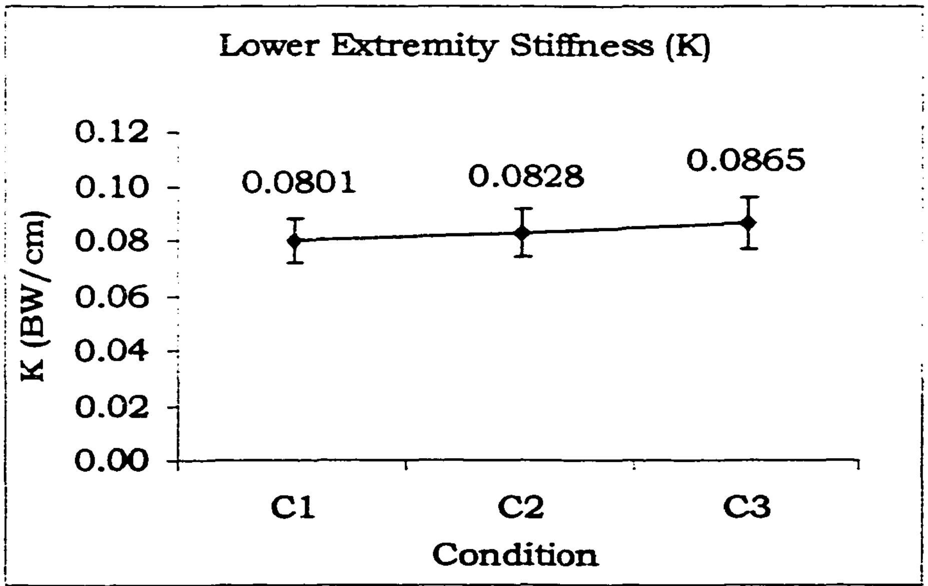



Figure 6. K group means and standard error across subjects where each subject completed five drop-jump trials.

Legend. C1 = force plate, C2 = turf, C3 = mat
No significant differences.

Table 6. Mean and Standard Deviation Values for Amortization Phase (AMORT)[a,b]

| SUBJECT | C1 | (STDEV)[c] | C2 | (STDEV)[c] | C3 | (STDEV)[c] |
|---|---|---|---|---|---|---|
| 1 | 0.246 | 0.035 | 0.223 | 0.039 | 0.203 | 0.022 |
| 2 | 0.123 | 0.008 | 0.088 | 0.020 | 0.097 | 0.021 |
| 3 | 0.181 | 0.016 | 0.178 | 0.004 | 0.170 | 0.007 |
| 4 | 0.235 | 0.013 | 0.199 | 0.013 | 0.185 | 0.012 |
| 5 | 0.073 | 0.016 | 0.091 | 0.007 | 0.071 | 0.007 |
| 6 | 0.173 | 0.021 | 0.185 | 0.011 | 0.165 | 0.005 |
| 7 | 0.195 | 0.012 | 0.193 | 0.009 | 0.230 | 0.009 |
| 8 | 0.175 | 0.030 | 0.188 | 0.019 | 0.200 | 0.017 |
| 9 | 0.271 | 0.025 | 0.225 | 0.019 | 0.274 | 0.015 |
| 10 | 0.223 | 0.028 | 0.174 | 0.014 | 0.154 | 0.027 |
| MEAN | 0.190 | | 0.174 | | 0.175 | |
| STDEV[d] | 0.059 | | 0.048 | | 0.059 | |

Legend. [a] Units reported in seconds
[b] C1 = force plate; C2 = turf; C3 = mat
[c] between-subject standard deviation
[d] within-subject standard deviation

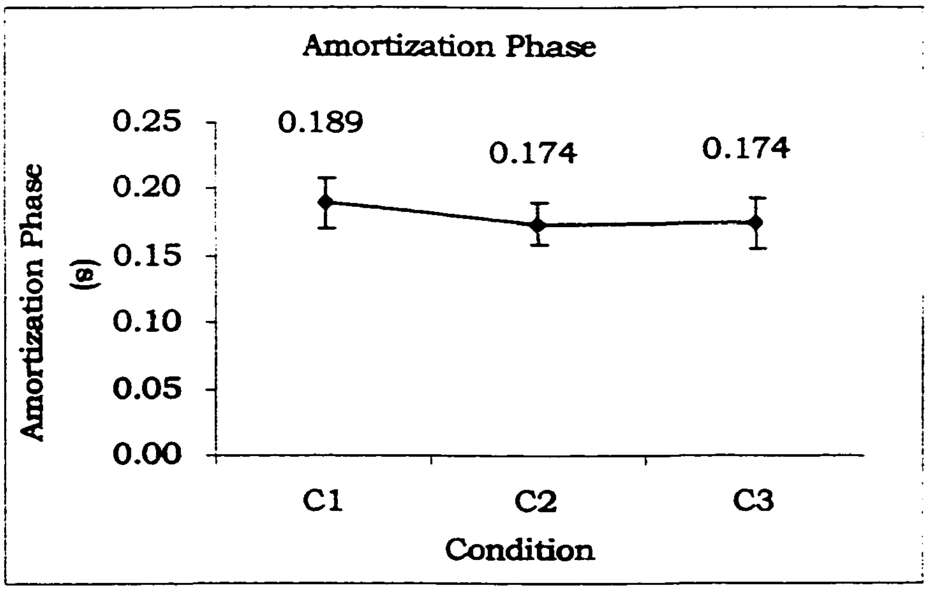



Figure 7. AMORT group means and standard error across subjects where each subject completed five drop-jump trials.
Legend. C1 = force plate, C2 = turf, C3 = mat
No significant differences

# CHAPTER V

## DISCUSSION AND SUMMARY

Drop-jumping is a plyometric task that athletes perform in order to develop the explosive and reactive ability of the muscles. The benefit of this type of task is a training stimulus. The training stimulus is related to force production (Bobbert, 1990; Ingen Schenau et al. 1997; Thomas, 1988) and dependent upon certain variables such as lower extremity stiffness and amortization phase (Duda, 1988; Reid et al., 2000; Voight & Tippett, 1988). In a practice setting, drop-jumps are performed on a variety of surfaces such as concrete, grass, turf or a rubber track surface. Previous research on the interaction between the foot and the surface during various tasks such as jumping, landing and running, has indicated that the cost, or injury to the muculoskeletal system, may be reduced by minimizing large ground reaction forces by means of manipulating surface compliance (Ferris & Farley, 1997; McNitt-Gray et. al, 1994; Reid, et al., 2000; Steele & Millburn, 1997). However, it is not presently known if the positive training stimulus exists concurrently with reduced impact forces during drop-jumps on compliant surfaces.

The purpose of the study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps. Specifically, GRF variables represented the cost whereas lower extremity stiffness and the amortization phase represented the benefit of this type of training.

## Discussion of Results

Five variables were collected for analysis in this study: FPEAK, TFPEAK, LR, K, and AMORT. Repeated measures ANOVAs were conducted for each variable using the group mean values across three conditions. It was concluded that for the cost of drop-jumping in this study, FPEAK was different ($p<0.05$), TFPEAK was different ($p<0.001$) and LR was different ($p<0.001$) between the force plate (referred to as 'stiff' condition from this point forward), turf and mat conditions. Additionally, for the variables that constituted the benefit of drop-jump training, there was no significant difference in K ($p>0.05$), and no significant difference in AMORT ($p>0.05$) between the force plate, turf and mat conditions.

## Magnitude of Peak Ground Reaction Forces

Peak GRF values in the current study were similar to a drop-jump study performed by Fowler and Lees (1998). In their study, when

comparing conventional drop-jumps to a modified pendulum swing drop-jump, peak GRF during the conventional drop-jump were recorded at about 2.75 BW. This value is slightly lower than the current study (4.09 - 4.48 BW), but the subjects in their study dropped from a slightly lower height of 0.28 m compared to 0.40 m in the current study.

Peak GRF values recorded in a drop-jump study by Bobbert et al, (1987a) were in line with the current study. Group mean values in Bobbert et al. (1987a) for subjects performing drop-jumps from a 0.20 m platform were 3.15 BW. The peak GRF observed in the current study were slightly higher (4.09 - 4.48 BW) than that reported by Bobbert and colleagues (1987a). This difference is explained by the higher drop height used in the current study (0.40 m) compared to Bobbert et al. (1987) (0.20 m).

In a follow up study by Bobbert et al. (1987b), peak GRF values of subjects performing a drop-jump from 0.40m (4.18 BW) was right in line with the current study (4.09 BW). Furthermore, Bobbert et al. (1987b) had subjects jump directly onto a force plate. For the current study, peak GRF values for force plate condition reached 4.09 BW, a difference of 0.08 BW between the two studies.

In previous research (Reid et al., in press), while performing drop-jumps barefoot and with shoes on from a 30 cm platform, peak GRF were 2.20 BW - 2.49 BW. This is similar compared to the present study with the exception that the drop height in Reid et al. (in press) was 0.10 m

lower than the current study (0.40 m). Based on the comparison with other published literature, the values of peak GRF accurately reflect the maximum GRF expected for this type of task.

Using an impact tester the stiffness of the surfaces were tested in this study. After dropping a missile mass of 8.50 kg from a height of 20 mm onto the turf and mat surfaces, the observed surface stiffness values were 38892 N/m for the turf compared to 18038 N/m for the mat surface. The impact tester was not capable of measuring the stiffness of a very stiff surface – such as the force plate. It would be expected that the stiffness of the stiff surface would be quite higher than either of the other two surfaces simply because there would be very little deformation of the stiff surface upon impact. The drop test results demonstrated that there was a clear mechanical difference in the impact absorbing quality of the two surfaces. The turf surface was stiffer than the mat surface and an increase in forces during drop-jumps on the turf compared to the soft is conceivable. It seems logical that the impact absorbing qualities of the turf surface compared to the force plate would be different as well. The subjects in this study did not follow the mechanical model. That is, impact forces should have increased during drop-jumps on the stiff surface.

Considering that the force plate was the "stiff" surface, the turf was the "medium" surface and the mat was the "soft" surface, the hypothesis was rejected. It was hypothesized that peak GRF would decrease as

surface compliance increased. The peak GRF were greater for the turf surface (mean = 4.48 BW) compared to the mat (mean = 3.79 BW) ($p<0.05$). However, there was no difference between the turf or mat surface compared to the stiff condition ($p>0.05$).

Similar findings were reported by McNitt-Gray et al. (1994) who observed greater peak GRF when gymnasts landed onto a stiff mat compared to a soft mat or no mat at all. The means for peak GRF for the current study (3.79 BW - 4.48 BW) were similar to the means for McNitt-Gray, et al (1994) (3.93 BW - 6.96 BW). In addition, the difference in peak GRF values between surfaces for the current study (0.30 BW - 0.69 BW) are in line with those of McNitt Gray, et al (1994) (0.6 BW - 1.75 BW) where a majority of differences in peak GRF between surfaces were around 0.25 BW.

In a hopping study, Ferris and Farley (1997) recorded peak GRF values across a number of surface compliances ranging from 3.94 BW on the most stiff surface to 3.14 BW on the least stiff surface, or about a 20% decrease between the stiffest and most compliant surfaces. Peak forces in the current study decreased by 30% for the turf surface (medium) compared to the mat surface (soft).

In a landing study by Steele and Millburn (1988), there was no difference in peak GRF values as subjects performed a netball landing task on a variety of different surfaces. The range of forces across 12 different surface compliances (3.71 BW - 3.91 BW) was similar to the

current study (3.79 BW - 4.48 BW). An explanation for the lack of difference in peak GRF across surfaces in Steele and Millburn's study (1988) compared to the current study which observed a surface effect in peak GRF could be that the two tasks, drop-jumping and landing in netball, differed more than in the previous mentioned studies.

Since peak GRF was attenuated as subjects performed drop-jumps on the mat surface compared to the turf surface, it is likely that the cost of drop-jump training is reduced and there is less chance that injury will occur to the musculoskeletal system due to impact. An idea is that perhaps the change in forces may be a result of changes in individual segment accelerations since the mass of the subject remained the same.

It is reasonable to suspect peak forces are not changed between the turf and stiff condition because the subject's mass does not change nor does the subject's impact velocity since drop height was the same across the three conditions. Perhaps the turf surface and stiff surface were more similar than the turf surface compared to the mat surface. An explanation for the lack of difference in peak GRF between the stiff surface and mat surface could be that subjects accommodated their strategy by means of shifting joint moments about four joints (hip, knee, ankle and 5$^{th}$ metatarsal) before landing onto each surface therefore maintaining the same GRF magnitude.

## Time to Peak Ground Reaction Forces

Time to peak GRF values represent the time from the onset of ground contact until the maximum peak ground reaction force. Studies that have investigated the time to peak force values during running have reported values occurring within 20 – 30 ms following initial contact with the ground (Cavanaugh & Lafortune, 1980). Steele and Millburn (1987) have reported the mean time to peak GRF during a netball landing activity with netball shoes on to be 32 ms compared to landing barefoot (18 ms). The difference in the time period was said to be a result of the additional dampening of impact forces provided by the shoes that, in turn increased the time to peak GRF. Time to peak GRF in the present study ranged from 47 ms to 63 ms across surfaces. This is a difference of 16 ms which is greater than the difference seen across surface compliances in Steele and Millburn's (1987) study (7 ms).

It is not known why there is a difference in time to peak GRF surfaces between studies. The difference may be related to the task, since Steele and Millburn (1988) studied a task that required subjects to run forward from a standard position breaking to the side away from a defender, catching a ball, landing on the dominant lower extremity, pivoting, and then throwing the ball. In the current study, the task required subjects to drop from a platform of 0.40 m land on both feet then immediately perform a maximal vertical jump.

Another explanation for differences between studies is the number of peaks that are classified and analyzed as impact peaks. Steele and Millburn (1988) identified two impact peaks. The first was an initial impact peak defined as the magnitude of initial peak GRF at impact which usually occurred between 15 and 17 ms of ground contact. The second peak Steele and Millburn (1988) identified was maximum peak GRF defined as the magnitude of the maximum peak GRF at impact usually occurring between 20 and 27 ms. Fowler and Lees (1998) identified three force peaks including 1) passive impact occurring within 50 ms 2) eccentric resistance occurring within 150 ms and 3) concentric drive off occurring within 230 ms. The difference is that Fowler and Lees (1998), compared to the current study, defined the peaks as occurring during impact or during midstance of a drop-jump. In the current study, the greatest impact peak GRF was analyzed due to the fact that the initial impact peak occurring within 10 ms - 20 ms was not always observed for all subjects for all conditions. Since it has been suggested that impact peaks are related to musculoskeletal injury (Steele & Milburn, 1988), the lack of an observed initial impact peak was an important observation for the mat condition. In this study the occurrence initial impact peaks were observed 96% of the time for the stiff surface, 88% of the time for the turf surface and 4% of the time for the mat surface. The observation of attenuation of initial impact peak is

evidence that the softer mat surface compared to the turf surface reduces the cost of performing drop-jumps.

It has been suggested that a longer time to peak force is beneficial in reducing the chance of injury in netball (Steele & Millburn, 1988). If the time period over which subjects experience large GRF is extended, then the shock of landing might be attenuated. When comparing time to peak GRF values in the present study, the values in all three conditions were different from each other ($p<0.05$). The fastest time to peak occurred when subjects jumped on the turf surface (47 ms). The next fastest time to peak was observed on the stiff condition (53 ms) and the slowest time to peak was observed on the mat surface (63 ms) (Appendix V). It seems reasonable that the turf surface is considered to be more compliant than the stiffest surface in the current study. Therefore, a faster time to peak GRF would be expected for stiff compared to the turf surface – but the opposite was observed. A possible explanation for this could be that subjects thought the turf surface would cushion their landing more than the stiff surface condition but perhaps the two surfaces were much more alike than the subjects expected. Since the shortest time to peak ground reaction forces were observed on the turf surface, it may be plausible that the cost of performing drop-jumps on the turf surface is no different, or even worse, compared to the stiff surface.

Time to peak ground reaction force values recorded in the landing study (Mcnitt-Gray et al, 1994) were similar to those in the present study for two of the three surfaces. McNitt-Gray et al (1994) recorded time to peak force values of about 60 ms for the soft mat condition and about 45 ms for the no mat condition (means not reported). In the current study, times to peak force were 63 ms for the mat surface and 53 ms for the force plate (hard) condition. Despite these similarities, again, the "medium" surface in both studies yielded very different time to peak force values compared to the other two surface conditions. In McNitt-Gray et al (1994), there was an increase in time to peak ground reaction forces as surface stiffness decreased. In the present study, this was only true for the hard surface compared to the soft surface.

## Loading Rate

Loading rate is a variable that describes the magnitude or how fast a force is increasing or decreasing. It has been hypothesized that loading rate is associated with the development of movement related injuries (Nigg, 2000). In the present study, it was hypothesized that loading rate would decrease as surface compliance increased therefore reducing one of the variables constituting the cost of drop-jump training. The hypothesis was rejected. In the current study as surface compliance increased from the turf to the mat surface, loading rate was decreased

(turf LR = 99.15 BW/s; mat LR = 61.15 BW/s) ($p<0.05$). This is in line with the hypothesis of the current study. As surface compliance increased from the stiff surface to the mat surface, loading rate decreased (stiff LR = 81.57 BW/s; mat LR = 61.15 BW/s) ($p<0.05$). This also is in line with the hypothesis of the current study. However, as surface compliance increased from the stiff surface compared to the turf surface, loading rate did not decrease (stiff LR = 81.57 BW/s; turf LR = 99.15 BW/s) ($p>0.05$).

The highest loading rate was observed on the turf surface (99.15 BW/s) ($p<0.05$) compared to the mat and stiff condition respectively (61.15 BW/s; 81.57 BW/s) ($p<0.05$). Since it has been hypothesized that loading rate is associated with overuse type injuries (Nigg, 2000) the turf surface may potentially increase the chance for injury compared to the stiff condition. An explanation could be that subjects may have thought that the turf surface would cushion the landing phase of the drop-jump, but perhaps the stiffness properties of the turf surface were more similar to the stiff condition than they thought.

In another drop-jump study (Fowler and Lees, 1998), loading rates of a drop-jump performed from a 0.20 m platform yielded smaller values compared to the current study. Fowler and Lees (1998) reported loading rates of about 33.3 BW/s whereas in the present drop-jump study, loading rates ranged from 61.15 to 99.15 BW/s. The difference in

loading rate may be a result of the higher platform used in the present study.

Loading rates observed during running also change as surface compliance changes (Dixon et al., 2000). In Dixon and colleague's (2000) study, group analysis indicated that there was a significant reduction in loading rate for a rubber-modified surface (47.7 BW/s) compared to the conventional asphalt surface (51.4 BW/s). Although the values are higher compared to the present study, perhaps due to the difference in task, the same surface effect was observed as in the current study. There was a significant reduction in loading rate for subjects performing drop-jumps on the mat surface compared to the stiff surface.

An explanation for the differences in loading rate may be related to both magnitude of peak GRF and time to peak GRF. Since loading rate is the relationship between peak force and the time to peak force, and the fastest loading rate was observed for the turf surface compared to the mat surface, it makes sense that the larger group mean peak GRF and the shortest time to peak were observed for the turf compared to the mat surface. Loading rate is different between surfaces because of the difference in peak GRF and time to peak GRF between surfaces. Since loading rates are different across surfaces ($p<0.05$) with mean loading rates for the mat being the lowest ($p<0.05$) and most beneficial, the cost of drop-jumping is reduced for this condition. Furthermore, since peak GRF values for the mat are lower than the turf condition ($p<0.05$) the

cost of drop-jumping is reduced. Finally, since time to peak GRF is greater for the mat condition compared to the turf condition or stiff condition ($p<0.05$) the cost of drop-jumping is reduced. In contrast, there does not seem to be a reduced cost of performing drop-jumps on the turf surface compared to the stiff surface since peak forces and loading rate were not different between turf and stiff surfaces. Perhaps the reason for this is because subjects may have accommodated their strategy and jeopardized the benefit of the training stimulus.

## Lower Extremity Stiffness

One of the chosen variables to represent the benefit of drop-jump training is lower extremity stiffness (LES). Magnitude of LES observed in this study did not change as surface stiffness changed ($p>0.05$). The magnitude of LES in the current study is closely related to the magnitudes observed during running (Ferris & Farley, 1999). Ferris and Farley (1999) measured changes in LES as subjects ran onto surfaces with different stiffness characteristics. The range of LES in their study was 7.1 kN/m to 10.7 kN/m. Group means for LES in the present study were about 5.0 kN/m. In contrast to the present study, subjects changed the LES as they transitioned from running onto a different surface compliance (Ferris and Farley, 1999). For example, when subjects transitioned from a soft surface onto a hard surface, there was a

decrease in LES by 29%. It was concluded that by rapidly adjusting leg stiffness, each runner made a smooth transition between surfaces so that the path of the center of mass would be unaffected. As subjects in the current study performed drop-jumps on a variety of surface compliances, there was no observed change in LES. An explanation for the difference in results between Ferris and Farley's (1999) study and the present study is that maybe a drop-jump is more demanding than running. The hypothesis for LES was that as surface compliance increased, LES would increase. The hypothesis for this study was rejected. However, it is important to note that the since LES did not change, the associated benefit of drop-jumping was preserved as surface stiffness changed.

In a hopping study (Ferris & Farley, 1997), lower extremity stiffness values were considerably higher than those in the present study. Subjects hopping on a variety of surface compliances changed their lower extremity stiffness from 53.3 kN/m on the most compliant surface to 17.8 kN/m on the most stiff surface. Although the values are higher compared to the present study, there was still a trend for subjects to increase lower extremity stiffness as the surface became more compliant. The higher values reported in Ferris and Farley (1997) may be accounted for by the fact that there was less deformation of the lower extremity while hopping compared to subjects drop-jumping in the current study. The most stiff surface in Ferris and Farley (1997) was

35000 kN/m and the least stiff was 26.1 kN/m). Comparing these values, the surface stiffnesses of the surfaces that subjects performed drop-jumps on in the current study were: turf = 38892 N/m, mat (least stiff) = 18038 N/m and a stiff surface similar to that used in Ferris and Farley (1997).

McNitt-Gray et al. (1994) reported that gymnasts performing a double-back somersault landing onto surfaces with different stiffness characteristics increased LES as surface stiffness decreased. This was not apparent in the current study. In contrast to one of their previous landing studies McNitt-Gray and colleagues (1994), reported that for gymnasts landing onto different mats, there was a subsequent increase in peak vertical forces as surface stiffness increased. This cannot be concluded in the present study because of the difference in tasks. Since GRF variables were recorded during the impact phase of the drop-jump and LES was calculated during midstance of the drop-jump, the lack in change of LES cannot explain the difference is peak GRF.

Komi and Bosco (1979) stated that increasing the range of stretch of the lower extremity during a countermovement jump is likely to decrease the elastic behavior of the muscle. It seems logical that by decreasing the elastic behavior of the muscle, force production may be reduced. This may interfere with the drop-jump stimulus. Since LES was not different across surfaces, the associated benefit of drop-jump training does not seem to be affected for the surfaces tested in this study.

## Amortization Phase

The amortization phase is a relatively new variable for describing the components of a drop-jump. One of the benefits of drop-jumping stems from achieving a relatively short amortization phase (Chu, 1992) which is closely related to ground contact time.

The method previously used to calculate amortization phase was to measure the flattened portion of knee angle position plot. Since the concept of amortization is to quantify the time period that the muscle starts to resist eccentric action and starts concentric action, this study focused on identifying the amortization phase as it relates to knee angular velocity. This study is the first to use this idea. Often times the amortization phase is thought of as part of ground contact time. Chu (1992) reported that great jumpers and sprinters relying on the speed and strength capabilities of the muscles do not spend that much time on the ground so a short amortization phase is advantageous. The amortization phase, or conversion from eccentric to concentric action typically takes place within hundredths of a second. Chu (1992) also stated that great high jumpers are on the ground for a mere 0.12 seconds. If amortization phase is related to ground contact time then the values for amortization phase in the present study were not too far off from 0.12 seconds. Across surfaces the group mean time period the amortization phase for subjects performing drop-jumps was 0.174 s - 0.189 s.

Young, Pryor and Wilson (1995) recorded contact time for drop-jumps performed from three different heights. When subjects were instructed to perform the drop-jump for maximum height, mean contact times ranged from 0.409 s - 0.421 s, also similar to the values recorded in the present study (contact time = 0.508 s - 0.515 s). The percentage of contact time represented by amortization phase was about 34% - 37%.

It was hypothesized that changes in amortization phase would be observed as surface compliance changed. The hypothesis was rejected. There was no difference in amortization phase as subjects performed drop-jumps on different surface compliances so the benefit associated with this variable was maintained.

## Summary

The purpose of the study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps. The cost of drop-jumping appears to be reduced from the mat compared to the turf surface by observing the differences in peak GRF, time to peak GRF and loading rate. The benefit of drop-jumping does not seem to be affected by surface stiffness used in this study. Evidence supporting this conclusion is the lack of difference in LES and amortization phase across stiffnesses.

Since the GRF variables were different for the mat compared to the turf surface, and subjects did not change their jump strategy by

changing LES during the jump, a different method of accommodation may have been present. It may be that subjects have two or more strategies for accommodating to different surfaces. The first strategy could be that if the peak GRF do not change at impact as surface compliance changes and the subject does not change LES, perhaps the surface absorbed the impact energy. If peak GRF values do change and LES changes as well, this may be another strategy used by the subject. The, results from this study indicate that subjects may choose to keep LES constant across surface compliances during midstance while peak GRF at impact remain the same (i.e., stiff surface compared to turf surface), or keep LES at midstance constant while GRF variables at impact change (i.e., turf compared to mat surface). It may be very important to distinguish what happens to these variables when a drop-jump is divided into the impact phase and stance phase.

According to Bosco and Komi (1979) increasing the range of stretch of the lower extremity is likely to decrease the elastic behavior of the muscle. Since there was no change in LES as surface compliance increased, the benefit of drop-jumping represented by LES seems to be maintained across the surfaces tested.

Amortization phase was not different across surface compliances. Cavagna, Saibene and Margaria (1965) reported that the benefit of increased concentric force production during a drop-jump is dependent upon the time frame between the yielding of the eccentric phase and the

initiation of the concentric contraction. Komi (1984) also points out the importance of the amortization phase by stating that if this time frame is increased, then there is likely to be a decrease in muscle tension and therefore a decrease in force production. In the present study, this time frame was not jeopardized as surface compliance changed.

In conclusion, the cost of drop-jump training was reduced and the benefit preserved as subjects performed drop-jumps on a mat surface compared to a turf or force plate condition. In contrast, the cost of performing drop-jumps on the turf compared to stiff surface was not different but the benefit was the same. Since the cost of drop-jump training is not different in the turf condition compared to the force plate condition, subjects may not have chosen to accommodate their jump strategy at impact. As a result they opted to tolerate the higher ground reaction forces compared to the mat condition. In the long run this strategy may result in overuse injuries to the musculoskeletal system.

In light of these findings, coaches may benefit from instructing their athletes to perform drop-jumps on a mat surface as well as a stiffer surface throughout the season. Based on the results from this study, performing drop-jumps on a softer surface would reduce the risk of injury as well as give the athlete the proper drop-jump stimulus. Since athletes often compete on surfaces stiffer than a mat, drop-jump training on a stiffer surface during part of the season would be recommended. Based on the results in this study, athletes can still achieve the same

benefit of drop-jumping on a stiff surface compared to a softer surface, but the athlete would be exposed to the high forces that would also be seen in a competition setting.

Based on the results in this study, since the benefit, represented by lower extremity stiffness and amortization phase, was not jeopardized, and the cost, represented by high ground reaction forces seen at impact was attenuated, athletes may get the proper drop-jump stimulus on different surface compliances and reduce the chance of injury due to overuse. However, caution must be made that athletes do not train on soft surfaces all of the time because in a competition setting, surfaces are not always soft. According to Wolff's Law, the ability of the bone to adapt by changing size, shape, and structure depends on the mechanical stresses on the bone. This is important to the recommendations made in the study because if the bone does not experience the stresses that are apparent in a competition setting, the chance of injury to the musculoskeletal system may be increased.

## Recommendations for Further Study

An attempt was made to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps. The surfaces used were similar to what would be seen in a practical athletic setting. Previous research investigating the affect of impact forces on different surface compliances often use one surface whose stiffness level

can be manipulated by changing the mechanics of the surface. This may account for the difference in ground reaction force variables observed between the force plate and turf surface. Future research should include an evaluation of other surfaces used in the sports arena.

In Dixon et al. (2000), factors that have been previously identified as influencing the magnitude of impact force include: impact velocity, contact area between the impacting surface and the foot, joint angles at initial impact, motion of the segment centers of masses preactivation of the muscles and surface stiffness. Although ground reaction forces were recorded in the present study, it only reports the total ground reaction force for the subject's total body center of mass. Further inspection of the center of masses and moments of each segment during the impact phase of a drop-jump completed on different surface compliances (i.e., head-arms-trunk, thigh, shank, and foot) could give insight as to which segment is responsible for the change in peak ground reaction forces.

Future research should aim to examine peak GRF and lower extremity stiffness both during the impact phase and during the stance phase of the drop-jump. In this study LES was calculated from the stance phase of the jump but GRF variables were calculated during the impact phase of the jump. Since the two phases are very different, relationships cannot me made between the two variables.

If the cost of drop-jump training is reduced and the benefit is maintained as a person jumps on a mat compared to a turf or force plate

surface, as in the present study, implications for a long-term training study is warranted. It is unknown if performance would be affected if athletes completed a preseason drop-jump training regimen on a mat compared to a stiff surface. Furthermore, the incidence of injury may be affected in the long run as well.

## APPENDIX I

## SUBJECT INFORMED CONSENT FORM

University of Nevada, Las Vegas

Department of Kinesiology

Informed Consent

**PROJECT TITLE: THE EFFECT OF SURFACE COMPLIANCE ON THE COST AND BENEFIT OF PERFORMING DROP-JUMPS**

**Information:**

Welcome to the Biomechanics Laboratory. My name is Michele Reid from the UNLV Department of Kinesiology. You are invited to participate in a research study that will examine the different joint angles and forces your body produces while jumping on different types of surfaces. The purpose of this study was to investigate the effect of surface compliance on the cost and benefit of performing drop-jumps.

**Procedure:**

Your weight will be taken prior to the testing and this informed consent will be signed. You will be asked to report to the Biomechanics Laboratory on two different days. The first day will be a training day. After a demonstration of how a drop jump is performed, you will be asked to practice drop jumps from a platform of 40 cm onto the four different surfaces provided. Standard running shoes will be provided for you. As many as 15 jumps will be performed over a force plate. The practice session will last about 10-15 minutes and sufficient rest will be allowed for recovery. You are aware that you should have some skill in executing a basic jumping and landing activity.

The second day will be a test day. After warming up for 5 minutes, you will be asked to perform the same style of drop jumps that were practiced on day one. Five trials on each surface will be executed for a total of 20 jumps. All trials will be performed with hands on hips and sufficient rest will be allowed for recovery. Testing will last about 30 minutes. Each day will be separated by at least 24 hours.

Small lights will be placed on you hip, knee and ankle joint as well as your little toe so that a video camera can record the movement of your lower extremity. Spandex shorts must be worn so loose clothing does not get in the way of the lights.

**Benefits of Participation:**

By participating you will be contributing to the body of human performance literature. The anticipated benefits of the study will be to determine whether drop-jumps can be performed on a softer surface while reducing the risk of injury. Your data is an important part of the investigation and hopefully you will receive satisfaction from participating in a research project.

**Risks:**

The potential risks in this study are minimal. As in any jumping activity there is always the possibility of lower extremity joint or muscle injury. There is also the risk of participants slipping during the landing phase and injuring themselves. Investigators will be sure to demonstrate the proper jumping technique. Participants should note that in case of injury, UNLV will not be responsible for any healthcare needed.

**Contact:**

If you have any questions about the study or if you experience adverse effects as a result of participation in this study, you may contact the researcher Michele Reid at 895-1582. For questions regarding the rights of the research subjects, you may contact the UNLV Office for the Protection of Research Subjects at 895-2794.

**Participation:**

Your participation in this study is voluntary. You may refuse to participate in this study or in any part of this study and you may withdraw at any time without prejudice to your relations with the University. You are encouraged to ask questions about this study prior to the beginning or at any time during the study. You will be given a copy of this form.

**Confidentiality:**

All information gathered in this study will be kept completely confidential. Consent forms will be stored in a locked file cabinet in the Sports Injury Research Center (SIRC 102) for at least three years. No reference will be made in written or oral materials, which could link you to this study.

**Consent:**

I have read the above information and agree to participate in this study.

____________________________ __________________

Signature of Participant Date

____________________________ __________________

Signature of Researcher Date

# APPENDIX II

## SUBJECT INFORMATION

Table 7. Subject Information.

| Subject | Age | Height (m) | Body Weight (N) | Mass (kg) |
|---|---|---|---|---|
| 1 | 24 | 1:67 | 563 | 57.5 |
| 2 | 21 | 1.75 | 606 | 61.9 |
| 3 | 23 | 1.63 | 575 | 58.7 |
| 4 | 21 | 1.65 | 684 | 69.9 |
| 5 | 22 | 1.65 | 590 | 60.3 |
| 6 | 22 | 1.65 | 534 | 54.5 |
| 7 | 19 | 1.67 | 542 | 55.4 |
| 8 | 30 | 1.67 | 646 | 66.0 |
| 9 | 29 | 1.73 | 844 | 86.2 |
| 10 | 22 | 1.70 | 528 | 53.9 |
| MEAN | 23.3 | 1.68 | 611.2 | 62.4 |
| STDEV | 3.53 | 0.04 | 95.74 | 9.78 |

APPENDIX III

# EXAMPLE GROUND REACTION FORCE CURVE

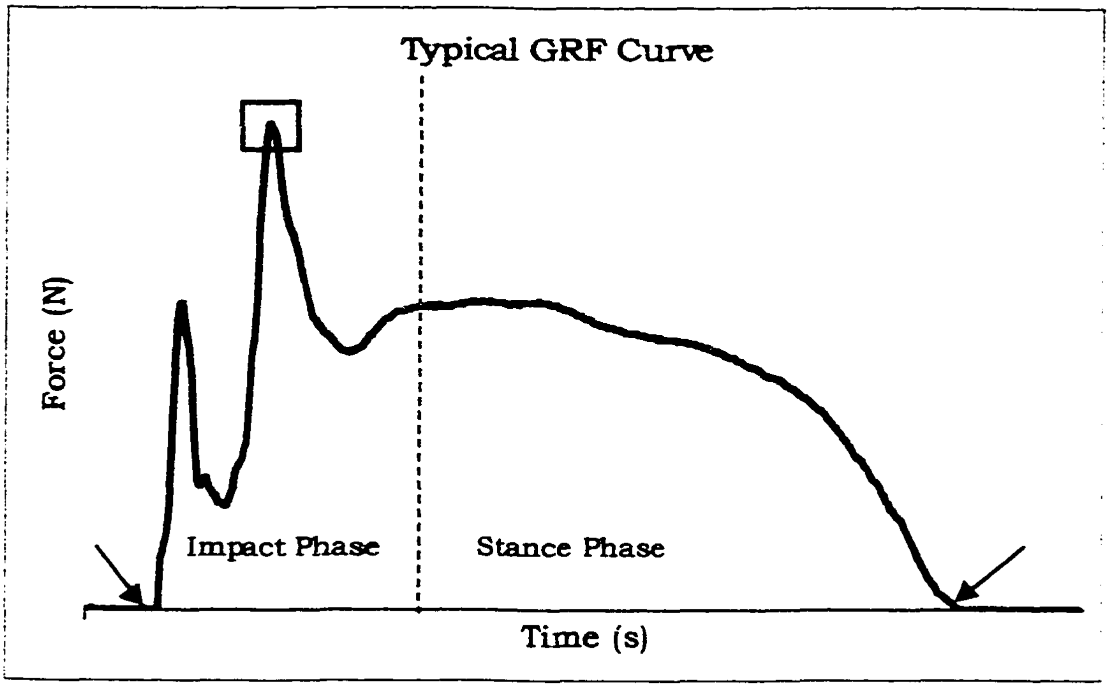



Figure 8. Example of typical GRF curve during a drop-jump

Legend. Arrows indicate ground contact and toe-off, respectively
Square indicates peak GRF
Impact Phase = GRF occurring within 50 ms of contact
Stance Phase = GRF occurring from 50 ms until toe off

## APPENDIX IV

## ENSEMBLE GROUND REACTION FORCE CURVES

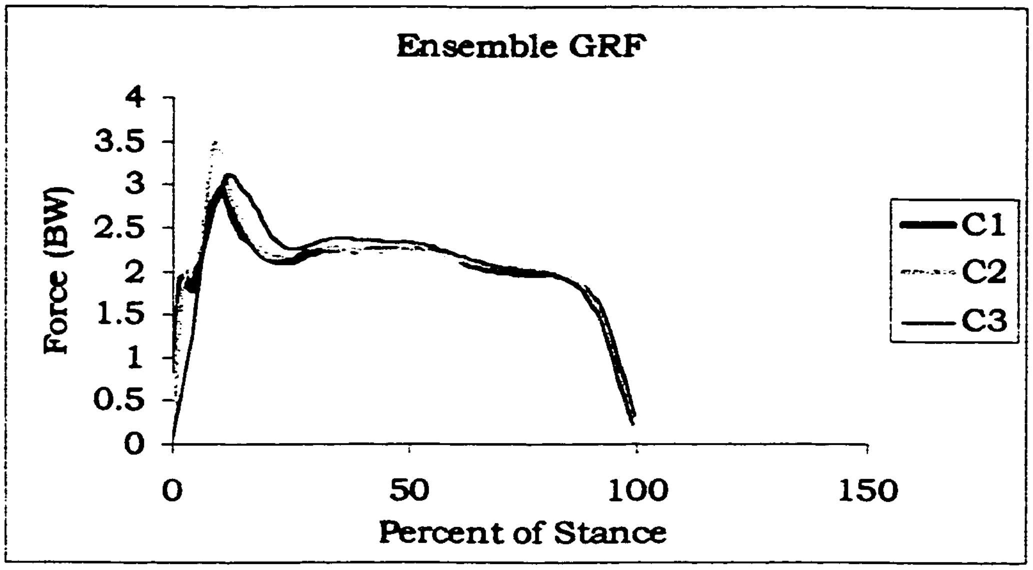



Figure 9. Ensemble GRF curve for means of all subjects across three conditions

Legend. C1 = force plate; C2 = turf; C3 = mat

# APPENDIX V

## ANOVA TABLES

Table 8. Summary of repeated measures ANOVA results between conditions for FPEAK

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| FPEAK | 2.375 | 2 | 1.188 | 6.17 | 0.009 |
| Error | 3.465 | 18 | 0.192 | | |

Table 9. Summary of repeated measures ANOVA results between conditions for TFPEAK

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| TFPEAK | 1.26E-03 | 2 | 6.31E-04 | 32.63 | 0.001 |
| Error | 3.48E-04 | 18 | 1.93E-05 | | |

Table 10. Summary of repeated measures ANOVA results between conditions for LR

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| LR | 7235.51 | 2 | 3617.75 | 12.045 | 0 |
| Error | 5406.50 | 18 | 300.36 | | |

Table 11. Summary of repeated measures ANOVA results between conditions for K

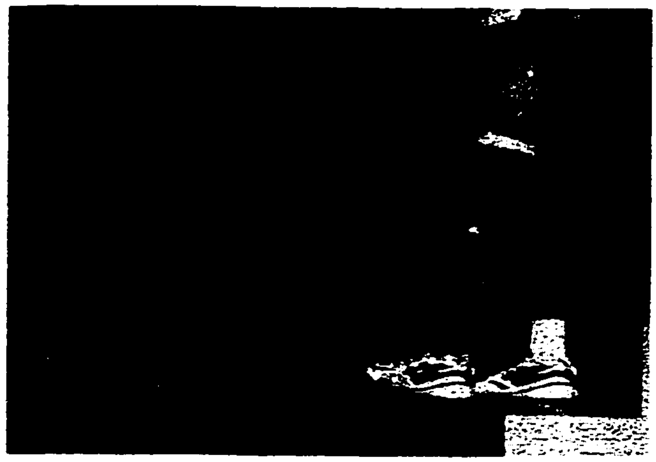
| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| K | 0.0002 | 2 | 0.00010 | 1.548 | 0.24 |
| Error | 0.0012 | 18 | 0.00007 | | |

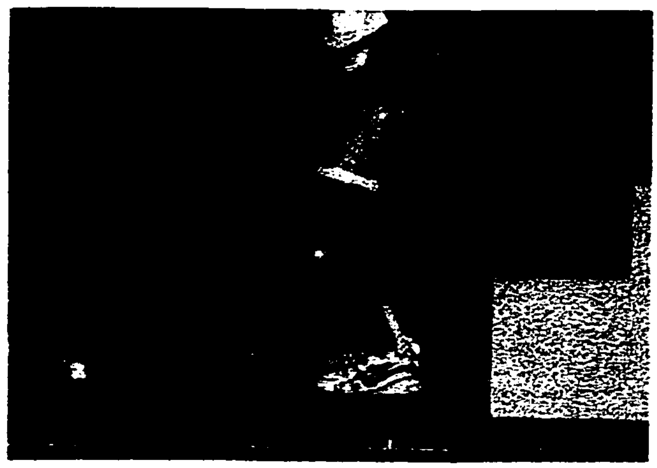
Table 12. Summary of repeated measures ANOVA results between conditions for AMORT

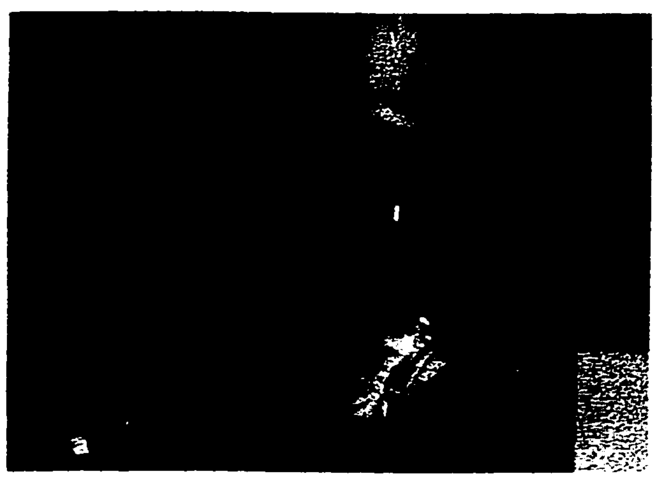
| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| AMORT | 0.0015 | 2 | 0.00074 | 1.849 | 0.186 |
| Error | 0.0072 | 18 | 0.00040 | | |

## APPENDIX VI

## PICTURE OF DROP-JUMP TASK







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**Thesis Title: The Effect of Surface Compliance on the Cost and Benefit of Performing Drop-Jumps.**

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