

THE EFFECT OF DOWNHILL RUNNING  
ON IMPACT SHOCK AND ASYMMETRY

by

Megan Leigh Killian

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Approved for the Department of Health and Human Development

Craig Stewart, Ed.D.

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## ABSTRACT

Biomechanical studies are important for the prevention and treatment of injuries. Of special interest is running locomotion and its effect on impact shock. Impact shock magnitudes are often 2-3 times greater at the tibia during running compared to walking and have been reported to increase with decreasing grade conditions. The primary goal of this study was to determine the effect of downhill running on impact shock and asymmetry over varying grades. The secondary and tertiary goals of this study were to determine if there was significant symmetry difference between lower-limb preference groups and between training groups, respectively. Seventeen subjects (10 female, 7 male) were sampled from two populations with different types of downhill training (trained versus untrained) experience. The procedures included two visits, the first of treadmill familiarization and preference testing and the second for impact shock data collections. The data collection visit included a self-directed warm-up on the treadmill followed by a 16-minute running session that included four different running grade conditions (0%, -3%, -6% and -9%). Four samples of 5 consecutive tibial impact shock magnitudes (TIS) of each limb were collected at each running grade condition using piezoelectric accelerometers. Symmetry indices (SI) were calculated using TIS for left and right limbs from a previously established equation. The results indicate that measured SI was not significantly influenced by decreasing running grade conditions for all subjects. Also, there were no significant differences between preference groups across running grade conditions. A trend suggested differences between training groups across grade conditions, and analysis of covariance for stride length and step frequency indicated a significant difference between downhill trained and untrained subjects ( $p \leq 0.038$ ). Post-hoc analysis indicated a significant difference in left and right step length for downhill trained runners across grade conditions ( $p < 0.05$ ). It is possible that a learned unilateral forward stepping technique is present for those who frequently incorporate steep downhill running in their training. Further research is needed to determine ways of reducing SI for preventative measures, as well as determining possible longitudinal affects of asymmetry.

## CHAPTER ONE

## INTRODUCTION

Development of Problem

Biomechanical studies are important for the prevention and treatment of injuries. Of special interest is running locomotion and its effect on impact shock. Impact shock can be measured by quantifying ground reaction forces and transient accelerations at the tibia during heel striking (Mizrahi, Verbitsky, & Isakov, 2000a). Impact shock magnitudes at the tibia recorded during the stance phase of running are often two to three times that of impact shock values measured during walking (Keller, Weisberger, Ray, Hasan, & Shiavi, 1996). Increases in impact shock magnitude, frequency and dissipation through the body have been linked to an increased likelihood of degenerative diseases, stress fractures and other overuse injuries (Guanche & Sikka, 2005; Hamill, Derrick, & Holt, 1995; Simon, Radin, Paul, & Rose, 1972).

It has also been observed that vertical impact force is greater during downhill running compared to level running, due to the greater vertical displacement of the body associated with ground contact while running downhill (Yokozawa, Fujii, & Ae, 2005). An increase in vertical impact force implies an increased likelihood of injury when running downhill (Gottschall & Kram, 2005). The acceleration of impact (impact shock) is an important characteristic to measure in relation to highly-repetitive impact loading. If the body does not properly dissipate the impact shock encountered during walking and running, degenerative changes in the joint and articular cartilage are likely to occur.

Furthermore, muscular damage and mechanical stress have been found to increase during downhill running compared to level running (Mizrahi et al., 2000a).

Natural variations in one's own gait, such as asymmetry, have been suggested to heighten risks of injury (Subotnick, 1981). Such asymmetry can be quantified and used to evaluate causation of injury and subsequent prescription of rehabilitation protocol, but has also been observed in healthy gait (Maupus, Paysant, Datie, Martinet, & Andre, 2002).

### Impact Shock

Impact shock can be defined as the magnitude that a body decelerates over a very small period of time. Impact shock is often represented as a factor of gravitational acceleration,  $g$ , in meters per second squared ( $9.81 \text{ m/s}^2$ ). Impact shock magnitudes have been used to evaluate gait parameters such as asymmetry (Chavet, Lafortune, & Gray, 1997; Zifchock, Davis, & Hamill, 2006).

### Asymmetry

Gait symmetry is defined when both limbs behave identically (Sadeghi, Allard, Prince, & Labelle, 2000). Gait symmetry is often assumed for simplicity of data collections and analyses to reduce the evaluation of both limbs (Maupus et al., 2002). However, asymmetry has been frequently reported for both pathological and able-bodied gait (Sadeghi et al., 2000). Lower-limb asymmetry has been quantified for gait variables using the following equation as proposed by Robinson, Herzog, & Nigg (1987):

$$SI = \frac{(XR - XL)}{0.5(XR + XL)} \times 100\% \quad [1]$$

where SI represents the symmetry index, and XR and XL are the gait variables for the right and left limb, respectively. An SI value of zero (0) indicates perfect gait symmetry within the measured parameters.

Asymmetry in gait has been measured by previous researchers in many ways. Maupus et al. (2002) measured angular changes of the knees using electrogoniometry. Perttunen, Anttila, Södergård, Merikanto, & Komi (2004) used force platforms as well as plantar pressure monitors and electromyography to determine asymmetry for people with limb length discrepancies. Sadeghi, Allard & Duhaime (1997) measured muscle powers and related mechanical energies using inverse dynamics to determine whether asymmetry existed during able-bodied gait. For all three of these studies, it was concluded that asymmetry between limbs existed in non-pathological, normal gait.

Many sports, such as competitive running, require symmetrical movements for high levels of performance. Energy costs are known to increase as asymmetry increases (Genthon & Rougier, 2005; Mattes, Martin, & Royer, 2000). Furthermore, lower-limb asymmetry during running has been associated with the onset and recurrence of injury. Zifchock et al. (2006) found that natural levels of kinetic asymmetry vary widely, and it is unclear whether asymmetry causes injury or vice versa. Their study, however, concluded that individuals with previous stress fractures have a greater peak impact shock. Stress fractures have been suggested to arise from many different factors such as overloading and increased impact shock (Beck, 1998; Kim & Voloshin, 1992).

## Downhill Running

It is unlikely in most mountainous regions that runners pursue routes that are without climbs or downhill terrain (Mizrahi et al., 2000b; Yokozawa et al., 2005). Different surfaces offer different kinetic responses during running (Kim & Voloshin, 1992). Unfortunately, research exploring the effects of downhill running on kinetic characteristics is somewhat limited.

Highly repetitive impact loading may result in degenerative changes to the hip, knee and ankle joints (Simon et al., 1972; Radin, Paul, & Rose, 1972; Collins & Whittle, 1989). Therefore, it is important to study the mechanics of downhill running which can amplify the magnitude of vertical shock values. Impact force and loading rate are expected to be larger during downhill running compared to level running due to the greater potential energy of the body's center of mass caused by decline grade (Yokozawa et al., 2005).

### Statement of Purpose

Researchers have reported an inverse relationship between impact shock magnitude and decline terrain grade. The purpose of this study was to determine the relationship between impact shock magnitude and lower-limb symmetry while running on varying downhill grades.

### Primary Hypothesis

It was hypothesized that lower-limb asymmetry will increase with greater decline grade running due to an amplification of inter-limb differences in impact shock caused by downhill running.

$$H_{01}: \mu_1 = \mu_2 = \mu_3 = \mu_4$$

$$H_{a1}: \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$$

The notations  $\mu_1$ ,  $\mu_2$ ,  $\mu_3$  and  $\mu_4$  represent the population means of SI at level, - 3%, - 6% and - 9% grade conditions, respectively.

### Secondary Hypothesis

It was also hypothesized that SI values will be different between lower limb right and non-right preferred running populations.

$$H_{02}: \mu_1 = \mu_2$$

$$H_{a2}: \mu_1 \neq \mu_2$$

The notations  $\mu_1$  and  $\mu_2$  represent the population means of symmetry index for right preferred and non-right preferred running groups, respectively.

### Tertiary Hypothesis

It was also hypothesized that SI values will be different between experienced and inexperienced downhill running populations.

$$H_{02}: \mu_1 = \mu_2$$

$$H_{a2}: \mu_1 \neq \mu_2$$

The notations  $\mu_1$  and  $\mu_2$  represent the population means of symmetry index for experienced and inexperienced downhill running groups, respectively.

### Assumptions

It was assumed that all subjects were healthy at the onset of this study, and that they are injury-free and aerobically fit. It was assumed that the subjects used in this study represent an avid running population.

### Limitations

A decreased generalizability of the study findings to the general population could result due to the exclusive subject selection; specifically, the exclusion of those with less than 20 miles per week training volume. Younger (under 18) and older (over 60) runners were excluded and the results of this study may not be applicable to such populations.

### Operational Definitions

The following definitions were adopted for the purposes of this study:

*Accelerometry*: measurement of impact shock magnitude using piezo-electric quartz accelerometers attached to the anterior-medial tibia.

*Impact shock*: the sudden deceleration of a mass caused by collision

*Asymmetry*: imbalance; inequality; a non-proportionate relationship between kinetic measurements of opposite limbs

$$\text{Symmetry Index (SI): } SI = \frac{(XR - XL)}{0.5(XR + XL)} \times 100\% , \text{ where XR is the kinetic}$$

measurement of the right limb, and XL is the kinetic measurement of the left limb.

*Attenuation*: The dissipation of heel-strike induced impact shock by means of soft tissues, bones and joints.

*Limb dominance*: The central nervous system (CNS) phenomenon of default use and superior performance of one side of the body compared to the other.

*Limb preference*: a subjective, preplanned choice of limb

## CHAPTER TWO

## LITERATURE REVIEW

Introduction

Individuals involved in high-impact sports, particularly running, often have training disruptions caused by lower extremity injuries. Stress fracture injury rates have been reported to be as high as 72% for the running population (Mizrahi et al., 2000a). Joint and cartilage degeneration is thought to occur because of long-term highly repetitive lower limb loading demands (Radin et al., 1972; Simon et al., 1972). Tibial stress fractures and medial tibial stress syndrome are injuries that cause immediate suspension of training, and are suspected to be directly related to impact shock (Beck, 1998; Mizrahi, et al., 2000a). Consequently, reduced activity involving impact shock is the most common and effective recommendation for the healing of such injuries (Beck, 1998). Such reductions in training can be detrimental for those whose psychological and financial well-being depends on their performance; including professional athletes, military recruits and even recreational runners. Therefore, it is of utmost importance to develop mechanisms of prevention to reduce the likelihood of injury. In order to do so, the mechanisms of injury must first be determined.

Instrumentation

Sensors provide an easy and beneficial means of collecting measurements for use in biomechanical gait analysis. These measurements, represented as electronic voltage

signals, can be filtered to reduce the effect of noise and transformed to reveal information specific to walking and running gait.

Strain gauge force platforms have been used to measure ground reaction forces along the vertical, anterior/posterior, and medial/lateral axes (Hamill, Bates, & Knutzen, 1984; Herzog, Nigg, Read, & Olsson, 1989). Very small changes in the resistance of a strain gauge, caused by deformation of the length of the gauge wire ( $\Delta\text{length}/\text{original length}$ ), changes the voltage output of the device. This voltage change is read and interpreted as a force measurement by use of an analog-to-digital converter.

Accelerometers have been used to measure deceleration of body segments as well as dissipation of shock waves through the body (Derrick, Hamill, & Caldwell, 1998; Mercer, Devita, Derrick, & Bates, 2003; Zifchock et al., 2006). Piezoelectric accelerometers consist of a crystal that produces a voltage charge when compressed or distorted. The use of accelerometry has been a common method for measuring impact shock. The ease of use and portability of such devices are very valuable to the study of impact biomechanics. Measured as factors of gravitational acceleration ( $g$ ;  $9.81\text{m/s}^2$ ), normal impact shock values during running can range between 5-14  $g$ 's (Flynn, Holmes & Andrews, 2004).

### Impact Shock

The sudden deceleration of the foot at heel strike transmits a strong shockwave through the body. The magnitude of this impact shock at the tibia increases as stride length increases (Mercer et al., 2003) and is usually 2-3 times greater during running compared to walking (Nilsson & Thorstensson, 1989). During running and walking,

shock is dissipated by bones and muscles before reaching the head to protect the brain and maintain consistent environmental perception for the vestibular and visual systems (Hamill et al., 1995). When comparing previously injured and injury-free runners, Hreljac, Marshall, & Hume (2000) found that the injury-free runners demonstrated significantly lower values of impact shock as well as vertical loading rates compared to previously injured runners.

Kinematic alterations have been noted to affect kinetic responses during running, especially impact shock. Mercer, Bezodis, Russell, Purdy & DeLion (2005) demonstrated that preferred stride length increases as velocity increases. Increases in preferred stride length and velocity have been related to increases in impact force and attenuation. However, Mercer et al (2005) found that impact force and attenuation tends to stay the same when stride length remains constant over varying velocities. Their findings suggest that stride length is a strong factor in determining impact magnitudes and attenuations.

### Symmetry and Asymmetry

Asymmetry, or bilateral variation, of gait is also an important criterion to consider when evaluating running biomechanics. Gait symmetry is often thought to be critical for many bipedal sports and activities. However, functional gait asymmetry may exist naturally, without a higher likelihood of injury (Herzog et al., 1989; Maupus et al., 2002; Zifchock et al., 2006). Unfortunately, studies rarely contain longitudinal components and it is difficult to conclude if asymmetry causes injury or vice versa (Zifchock et al., 2006).

Lower-limb symmetry occurs when both limbs behave identically with respect to a specific gait parameter, and previous researchers have suggested using the term when

no statistically significant differences are seen between bilateral parametric measurements (Sadeghi et al., 2000). Functional gait symmetry has been observed in several studies. While studying bilateral kinematics, Hannah, Morrison, & Chapman (1984) found that, for able-bodied subjects, joint motion symmetry was present during walking between left and right hips in all three planes of motion as well as the knees in the sagittal plane. Analysis of ground reaction forces (GRF) revealed symmetry during healthy walking and running (Hamill et al., 1984). Herzog et al. (1989) also evaluated ground reaction forces in relation to symmetry. Although no perfect intra-individual gait symmetry was found, the average symmetry index (SI) for vertical GRF and stance time of all subjects deviated less than 4% from zero. The right and left leg were not determined to be used preferentially for gait variables associated with vertical GRF. Therefore, Herzog et al.'s (1989) sample average SI was calculated to be zero.

Although previous research suggests the presence of functional gait symmetry, there is more research that reports functional gait asymmetry. Previous studies have reported that normal asymmetry ranges between SI values of 3 to 54% (Zifchock et al., 2006). Pilot data from our group suggests the existence of asymmetry in measures of impact shock for individual subjects range between SI = 18-42% (Killian, Nagashima & Hahn, 2006). Angular asymmetry of the knees has been observed in healthy subjects (Maupus et al., 2002). Ounpuu & Winters (1989) suggested that intra-individual analysis of electromyography (EMG) was able to reveal bilateral differences. In their study, the pooling of subjects and averaging of kinetic measurements suggested bilateral symmetry for nearly all lower-limb muscles. However, nine of the ten subjects also provided individual evidence of gait asymmetry. Although Chavet et al. (1997) suggested mean

bilateral symmetry in measurements of external impact loading for a group of subjects, their findings also revealed asymmetry in individual subjects. Thus, analysis of individual results rather than pooled results may be more beneficial when evaluating bilateral gait characteristics.

Structural inequalities of the lower limbs, such as limb length and muscle strength differences, often result in gait asymmetry. It has been suggested that running on cambered roads may lead to uneven loading of the lower limbs (O'Connor & Hamill, 2002). Such imbalance may result in unilateral injuries. Functional leg length inequalities can occur because of the shortening or relaxation of soft tissue from compensatory changes of the lower limb (Neely, 1998). Natural limb length discrepancies associated with growth are often present among children and young adults (Perttunen et al., 2004; Sutherland, 1997). Gait variables affected by limb-length inequalities, such as step frequency and stride length, change often until gait maturation occurs (Sutherland, 1997). Knutson (2005) studied natural incidences of limb-length inequalities for adults for several different populations, determining that 99% of the population has some extent of leg-length inequalities. Another study reported that one in every 1,000 people has a limb length difference of 2 cm or more (Kaufman, Miller, & Sutherland, 1996), which may increase the risks of pain and injury (Knutson, 2005).

Kinematic measurements have also been used to evaluate gait asymmetry. One study used larger versus smaller gait measurements in the SI equation, rather than left/right measurements, for patients with Chronic Fatigue Syndrome (Saggini, Pizzigallo, Vecchiet, Macellari, & Giacomozzi, 1998). Toe-out angle and stride width revealed the greatest asymmetry and were noted to be highly associated with balance. Holder-Powell

& Rutherford (2000) discussed a relationship between unilateral balance and its decrease following injury. Balance measurements were suggested to be useful in the assessment of injury and recovery. They further concluded that maintenance of symmetrical lower limb muscular strength provides better balance.

From this review, it is apparent that kinematic, kinetic, structural and neurological measurements provide evidence that natural variations in gait are present in healthy individuals. Reports of laterality in kinetic measurements raises the question as to whether limb preference has an effect on the onset of injury.

### Limb Preference

A few studies investigated the relationship between neurological function and symmetry (Golomer & Mbongo, 2004; Hebbal & Mysorekar, 2003; Lenoir, Van Overschelde, De Rycke, & Musch, 2005). Laterality is defined as a preference to use one side more than the other, and has been linked to externally imposed tasks, the vestibular system, and intrinsic preferences (Lenoir et al., 2005). Lower-limb dominance, detected with tests of preferred foot such as run/walk leading and ball-kicking, has been studied using kinematic and kinetic relationships. Golomer & Mbongo (2004) used motion analysis and force platforms to measure variations of movements and center of pressure, respectively. They found that balance on one foot could depend on footedness rather than hemispheric visual asymmetry. They also suggested that differences between right- and left-footers' uni-podal postures could result from differences in equilibrium perception and action (eg. left-footers' posture controlled by re-equilibration and independent of supporting foot; right-footers' posture controlled by a rightward sway regardless of

supporting foot). Using electromyography (EMG), Ounpuu & Winter (1989) found a relationship between plantar flexor EMG and limb dominance. Differences between dominant and non-dominant limb EMG indicate asymmetry during healthy gait. However, this study was limited by small sample size. Neurological demands for mobility and stability are assumed to be equivalent for lower limbs during bilateral movement (Previc, 1991). However, for most bilateral tasks, neurological demands are placed on the task of mobility (Sadeghi et al., 2000). Therefore, the dominant limb is often associated with the limb primarily involved with mobility (i.e. kicking a ball). More specific to this study, it has been suggested that local asymmetry in the lower limbs can be attributed to the propulsive and supportive characteristics of the lower limbs (Chavet et al., 1997; Sadeghi et al., 1997; Smak, Neptune, & Hull, 1999).

It is estimated that less than 10% of the human population is left-handed (Hebbal & Mysorekar, 2003). Asymmetry may be revealed by handedness and footedness, however the two are not perfectly related. Previous research suggests that while right handedness and right footedness are strongly linked, left footedness is not as dependent on left handedness (Peters & Durdning, 1979; Hebbal and Mysorekar, 2003).

The literature has often used limb dominance and preference interchangeably. However, the two have somewhat different definitions. Therefore, we must adequately define the following terms: lateral dominance, preference/laterality, and asymmetry. Lateral dominance is defined as the central nervous system (CNS) phenomenon of default use and superior performance of one side of the body compared to the other (Coren & Porac, 1978; Harris, 1958). Dominance is associated with the notion of the brain being functionally asymmetric (Sadeghi et al., 2000). Sutherland, Olshen, Cooper, and Woo

(1980) reported that a large majority of individuals with left-sided cerebral dominance were right-footed. A scale has been established to measure lateral dominance in which five parameters of the lower limb are used (Dusewicz and Kershner, 1969). However, some of the parameters measured can be described as preferential and not inherent. Preference, also known as laterality, is defined as a subjective, preplanned choice of limb use (Touwen, 1972), such as the first foot used when climbing stairs, or the hand used to carry a bag or hold a coffee cup. Asymmetry, as defined previously, is similar to imbalance and inequality, and can be expressed as a non-proportionate relationship between bilateral gait parameters. Sadeghi et al. (2000) have suggested that dominance should be used in gait research in reference to the automatic reactionary response to an action. However, the limb used for repetitive kicking of a ball or leading natural gait should be defined as preferred rather than dominant because of possibly unknown CNS contributions.

Functional asymmetry has been noted for able-bodied gait (Maupus et al., 2002; Ounpuu & Winter, 1989; Sadeghi et al., 1997; Sadeghi, Sadeghi, Allard, Labelle & Duhaime, 2001). When analyzing symmetry with respect to laterality, the preferred limb often has a different magnitude of kinetic measurement than the non-preferred limb. Functional differences have been observed for subjects concerning footedness (Sadeghi et al., 2001). Their study concluded that, for right-footed subjects, the left limb's main task was control (power-absorption bursts) and the right limb's main task was propulsion. Gumustekin et al. (2004) found that bone mineral density was consistently greater in the left hip for right-dominant subjects than the right hip, thus supporting the categorization

of fine motor control for the dominant limb and strength and power for the non-dominant limb (Sainburg, 2002).

Several researchers have studied associations between injury and limb dominance with mixed results (Murphy, Connolly & Beynnon, 2003). Beynnon, Renstrom, Alosa, Baumhauer & Vacek (2001) found no difference in the incidence of ankle injury between left and right dominant subjects, which supports other research (Surve, Schwellnus, Noakes & Lombard, 1994). However, some researchers have found that lower extremity injuries to the dominant limb are prevalent in sports such as soccer and Australian football (Ekstrand & Gillquist, 1983; Orchard, 2001).

Balance has also been studied concerning dominant and non-dominant lower-limb injuries (Holder-Powell & Rutherford, 2000), where dominance was defined as the fine-motor limb (i.e. kicking a ball). It was found that balance was greatly reduced for individuals sustaining dominant limb injuries compared to those who experience non-dominant limb injuries. The injuries sustained by the subjects in Holder-Powell's study were typical running injuries involving repetitive loading, such as fractures and degenerative joint problems.

Limb dominance has been observed as the cause of several gait variations including leading (preferred) leg, fine-motor control and balance. Favoritism of one limb to the other is suggested to be derived from dominance and asymmetry (Hebbal & Mysorekar, 2003), but can also be exacerbated by injury. Recent studies have both supported (Gumustekin et al., 2004; McManus & Wysocki, 2005) and refuted (Sadeghi et al., 2000) the notion that limb dominance is a factor for unilateral injury.

During running, unilateral preference may be accentuated by varying terrain and training history. For example, preference of leading and propulsion may be accentuated to a greater extent with multiple obstacle clearance, such as roots and logs on trails, or steep uphill and downhill terrain.

### Downhill Running

Many distance runners use hill training as a means of improving aerobic fitness, stamina and strength (Tulloh, 1998). Vertical impact force has been reported to be 14% higher during downhill running compared to level running (Dick & Cavanagh, 1987) and 22% lower during uphill running (Gottschall & Kram, 2005). It has been suggested that downhill running amplifies magnitudes of vertical ground reaction forces and impact shock due to increased potential energy, stride lengthening and increased velocity (Gottschall & Kram, 2005; Mizrahi, Verbitsky, & Isakov, 2001; Yokozawa, et al., 2005). Logically, adaptations are required within an altered running environment in order to improve performance and avoid injury (Derrick, 2004).

Impact shock transmission along the body has been reported to cause bone injury and joint degeneration (Mizrahi, Verbitsky, & Isakov, 2000b). A greater attenuation of impact shock between the shank and the sacrum was reported for downhill running compared to level running. Such attenuation is thought to be associated with an increase in muscle damage. This, in turn, may reduce dissipation and future attenuation of shock by the muscle tissue. Although downhill running does not promote the development of metabolic fatigue, fatigued running has been shown to increase tibial impact shock

(Mizrahi, Verbitsky, Isakov, & Daily, 2000c). However, natural gait alterations are likely to occur in order to compensate for impact shock demands.

A reduction in synergistic muscle control has been suggested to cause a decrease in shock attenuation during metabolic fatigued running (Mizrahi, Voloshin, Russek, Verbitsky & Isakov, 1997). Local fatigue of the quadriceps muscle has been previously suggested to cause increases in impact shock transmission during downhill running (Mizrahi, et al., 2001). However, Flynn et al. (2004) found that localized fatigue of the gastrocnemius and tibialis anterior muscles resulted in a decrease in peak tibial accelerations. It was suggested that an increase in localized muscular fatigue, indicated by a decrease in maximum voluntary contraction by means of EMG, is associated with decreased muscle stiffness. Such reduction in rigidity resulted in greater attenuation of force and reduced peak accelerations.

Derrick (2004) reviewed previous research to evaluate impact shock in relation to knee contact angle, impact accelerations and forces, and different adaptations that may occur during environmental changes. Two suggested reasons for adapting to an altered environment are avoidance of injury and increase in performance. Unusual environmental conditions often lead to incremental changes in knee flexion. Peak impact acceleration of the leg and attenuation increase in response to unusual environmental conditions, such as decreased running grade and uneven terrain, but such increases do not always lead to an increase in vertical ground reaction forces. Increasing knee flexion is often a metabolic cost, and so such changes in kinematics are related to injury prevention mechanisms rather than performance enhancement.

Yokozawa et al.'s (2005) study showed a trend of increasing impact shock for downhill running compared to level running when stride length and speed were maintained. However, the trend, which implied that runners responded to increased vertical displacement by means of kinematic changes, was not consistently linear. Subjects increased their hip extension which allowed their foot to contact the ground earlier, perhaps to reduce impact velocity. Knee angle alterations were also noted and determined to be advantageous for the absorption of shock after heel strike. It was suggested that gait adaptations allow runners to avoid excessive impact load (Yokozawa, et al., 2005).

Chu and Caldwell (2004) observed different strategies for experienced male runners while running on a treadmill at level and downhill grades. Two apparent groups of runners existed within their findings, suggesting different strategies for individual's shock attenuation and control of upper-body center of mass. Half of the subjects in their study decreased shock attenuation by increasing extension of body position, and the other half decreased heelstrike velocities and implemented a more flexed heelstrike posture, allowing them to maintain their attenuation. Such adaptations suggest variations in impact shock and attenuation mechanisms within running population. Specific running types (eg. ultramarathon trail runners, 5-kilometer road-specific racers, etc.) could result in more consistent representations of adaptations.

### Summary

Many different gait parameters can be measured in order to better understand biomechanical influences on pain and injury. Of these, impact shock has been easily

measured and analyzed. Accelerometry can effectively measure shock and attenuation, which have been noted to have detrimental effects on bones and joints (Derrick, et al., 1998; Hamill, et al., 1995; Mercer, Bates, Dufek, & Hreljac, 2003; Mercer, Devita, et al., 2003; Mizrahi, et al., 2000a, b, & c; Radin, et al., 1972; Simon, et al., 1972; Zifchock, et al., 2006). Long distance runs and races that include varying grade can be detrimental to a runner's bones, muscles and joints if precautions are not taken.

The study of gait asymmetry has often revealed that natural variations are present in healthy individuals (Chavet, et al., 1997; Ounpuu & Winter, 1989; Sadeghi, et al., 1997; Sadeghi, et al., 2000). It is important to understand the influence of impact shock on asymmetry to improve prevention of injuries and treatments related to running.

## CHAPTER THREE

## METHODOLOGY

Subjects

Seventeen subjects (10 females and 7 males) from the community of Bozeman, Montana volunteered to participate in this study. The age of the subjects ranged from 22 to 63 (mean  $\pm$  SD: 35  $\pm$  14.1), mean body mass was 64  $\pm$  9.99 kg, and mean height was 172.8  $\pm$  7.6 cm. Subjects were categorized as either right or non-right lower limb preferred, as determined from responses to unilateral activities, outlined in Appendix A, Table 3.1. Activities determining lower-limb preference included kicking a ball, stepping up stairs, forward starting limb when running, preference for rolling a ball with the forefoot and preference for picking up a small object with the forefoot. Non-right preference referred to the performance of three or more unilateral activities with both or primarily left lower limb.

Subjects were also categorized according to their training experience based on each subjects' response to a simple activity questionnaire and previous racing qualifications (Appendix B, Table 3.1). The 'trained' category referred to those subjects with downhill running experience, and included subjects who had previously completed endurance trail races such as the Bridger Ridge Run, Old Gabe 25/50K or Devil's Backbone. The 'untrained' category referred to those subjects who did not intentionally incorporate downhill running training in their training. Subjects were excluded if they did not run twenty or more miles per week, if they had lower limb muscular or joint

injury or pain at the time of collection or if they had raced in the previous seven days prior to the date of collection.

Table 3.1. Subject demographics of limb preference and training categories.

| Category          | Classification      | N  | Height (cm)  | Weight (kg)  |
|-------------------|---------------------|----|--------------|--------------|
| <b>Preference</b> | <i>Right</i>        | 6  | 171.52 (7.4) | 61.15 (9.3)  |
|                   | <i>Non-Right</i>    | 11 | 173.84 (8.8) | 66.33 (11.3) |
| <b>Training</b>   | <i>Downhill</i>     | 9  | 175.64 (9.0) | 66.82 (12.7) |
|                   | <i>Non-downhill</i> | 8  | 170.06 (6.3) | 61.89 (7.6)  |
| <b>Total</b>      |                     | 17 | 173.02 (8.1) | 64.5 (10.6)  |

Mean (standard deviation)

### Informed Consent and Questionnaire

Subjects provided informed consent as required by Montana State University's Institutional Review Board. A questionnaire was completed by all subjects prior to data collections to ensure qualifications and provide demographic information about the subjects (Appendix C).

### Data Collection

Subjects were fully rested and had not run previously on the day when data was collected. The accelerometry protocol was separated into two parts following no less than two days post-treadmill familiarization. A downhill-capable treadmill (Trackmaster, Newton, KS) located in the Movement Science Laboratory (MSL) at Montana State University was used. Grade variations were level (0%), -3%, -6% and -9% grade. This grade selection has been used previously in other research by Yokozawa et al. (2005).

Prior to data collections, subjects were required to perform a familiarization session on the treadmill. Following a brief jogging warm-up on the treadmill (time

determined by the subject), subjects performed speed selection, which required self-selection of a natural running pace at each of the four grades (decline running speed within +/-5% level grade running speed). “Natural” was defined as a comfortable, steady pace that can be maintained for approximately forty minutes of running. During pilot data collections, the selected speeds for 0%, -3%, -6% and -9% grades were 2.27, 2.29, 2.35 & 2.38 m/s on average, respectively (Killian et al., 2006). Each subject’s speed was allowed to vary minimally between grades to prevent shortening of stride lengths from level to negative grades. Previous researchers reported that when allowed to select their preferred running velocity for level and varying grades, subjects had no significant differences in stride length between grades (Yokozawa, Fujii, & Ae, 2005). If speed were to remain the same for each subject regardless of treadmill grade, it would be more likely that subjects would alter their postural orientation at heelstrike (Chu & Caldwell, 2004). Altering stride length has been reported to directly affect impact loading rate and shock despite maintaining a constant velocity (Derrick, Hamill, & Caldwell, 1998; Mercer, Devita, Derrick, & Bates, 2003). A flow chart is presented in Figure 3.1 to represent the reasoning behind self-selection of speed at each grade. Pilot data have revealed no significant differences ( $p=0.38$ ) in normalized stride lengths for subjects over varying grades (Killian et al., 2006). Subjects ran at each grade for approximately five minutes to ensure comfortable speed/grade combinations.

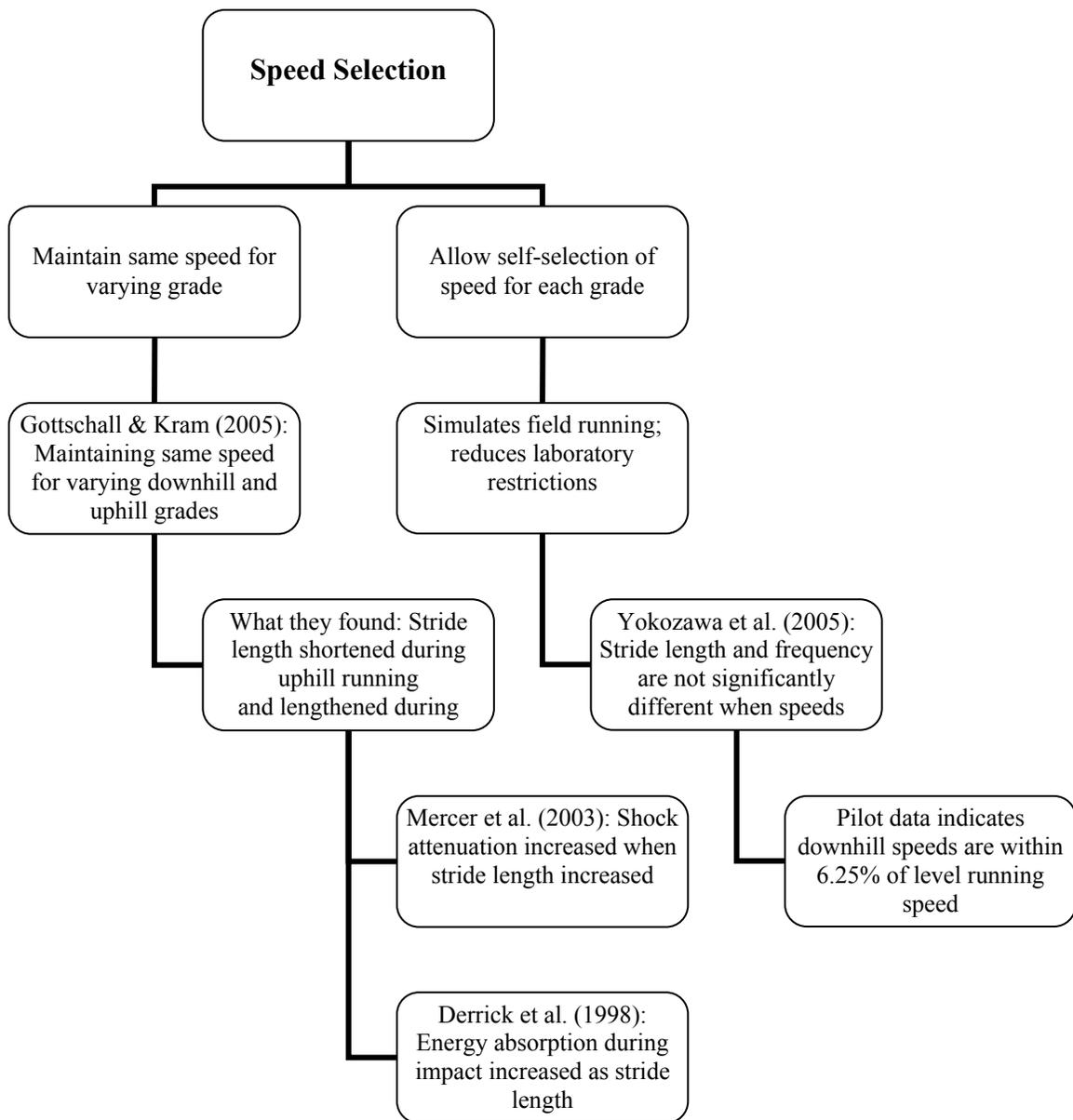


Figure 3.1. Flow chart explanation of the reasoning for self-selection of speed.

Instrumentation

All subjects were provided with a pair of Brooks™ Radius cushion trainer shoe to wear during data collections. Tibial accelerations were measured using lightweight (1.7gram) uniaxial piezoelectric accelerometers (PCB Piezotronics, Depew, NY) attached to the anteromedial aspect of the left and right tibias. These sites were chosen to reduce effects of soft tissue oscillation during impact (Hamill, Derrick, & Holt, 1995). Each accelerometer was mounted to a small piece of plastic backing using double-sided tape (Lake & Lafortune, 1998). The accelerometer mounts were then attached to the shin using flexible wrap tape tightened to the subject's comfort tolerance with the axis of the accelerometer parallel to the long axis of the tibia (Figure 3.2). Connection wire were attached posteriorly at the mid-thigh and sacrum of each subject using flexible wrap tape to reduce electronic noise caused by excessive wire movement. The output signal was

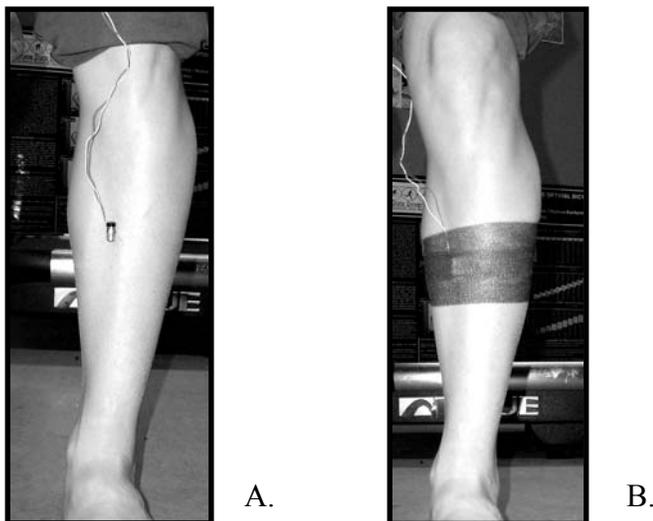


Figure 3.2. A) Orientation of accelerometer attached to anteromedial tibia using plastic backing and two-sided tape; B.) post-wrapping using flexible wrap tape.

converted to electrical current by means of a corresponding coupler.

### Impact Shock Data Collections

Impact shock data at level and decline grades were measured following speed selection. Subjects ran for four minutes at each grade during impact shock collections. A four-minute period allowed each subject to run consistently without fatigue at the grade and matched predetermined running speed, as well as allowed enough time for investigators to collect at least four impact shock samples. A counterbalanced technique was used to determine grade order for each subject. Subjects performed each graded running period continuously without rest between grade changes. Subjects were not informed of when impact shock data sampling occurred in order to prevent possible gait alterations.

During each four-minute period, samples were collected on approximately 20 sec intervals after the subject had run at speed/grade for one minute. Each sample included five full strides, a full stride being defined as a heel strike to the next consecutive heel strike of the same limb (Figure 3.3). At least 4 samples were taken at each running condition, and were immediately followed by the next running condition (Figure 3.4).

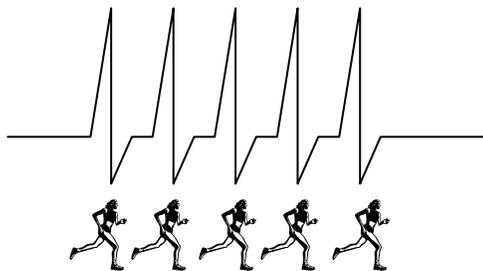


Figure 3.3. Representation of impact shock peaks.

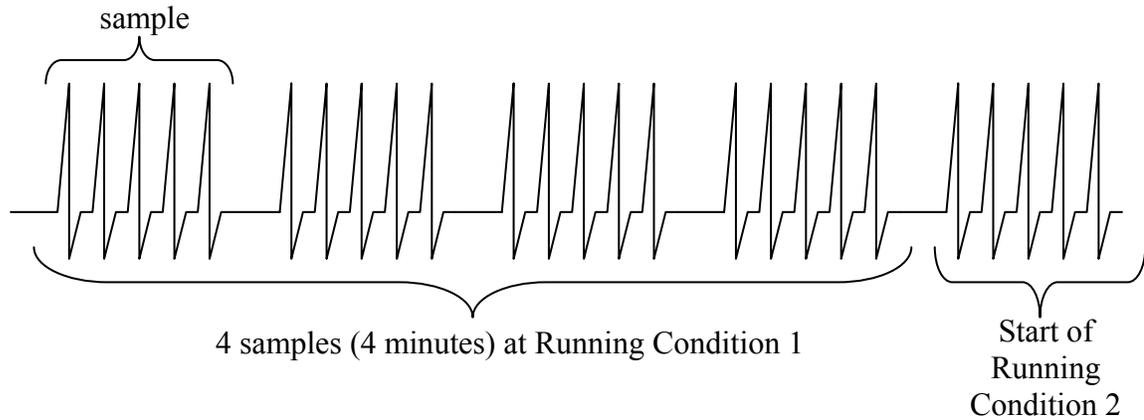


Figure 3.4. Representation of impact shock collections.

Stride length was calculated by taking the product of the belt speed in meters/second and time between left limb impact shock peaks. Step frequency was calculated in steps/minute using time between left limb impact shock peaks, assuming low variability in frequency during grade and speed matched conditions.

Accelerometry data was collected using Vicon Workstation software (ViconPeak, Lake Forest, CA) and analyzed using a custom Matlab program (V.7.1, The Mathworks, Natick, MA). Consecutive impact shock peaks of both left and right tibias for all four grades were analyzed. Such peaks represent the sudden deceleration of the shank at heel strike. Gait symmetry was assessed using the SI equation [eq. 1]:

$$SI = \frac{(XR - XL)}{0.5(XR + XL)} \times 100\%$$

where SI represents the symmetry index, and XR and XL are the gait variables for the right and left limb, respectively. An SI value of zero (0) indicates perfect gait symmetry within the measured parameters.

Data Analysis

The dependent variables of this study were the impact shock magnitudes of right and left limbs during running and the SI relationship for four different running conditions. The independent variable was the grade steepness during running. A single-factor analysis of variance (ANOVA) was used to test for significant differences in treadmill speed, stride length and stride frequency over running conditions. A two-factor ANOVA with repeated measures of grade was performed to test for significant differences in SI values between running conditions and between groups (mixed limb preference versus right limb preference). A two-factor ANOVA was also performed to test for significance in SI differences between running conditions and between training groups (Table 3.2).

Table 3.2. Statistical analyses of impact shock data.

| <b>Statistics</b>   | <b>Categorical variable</b> | <b>Factors</b>                 | <b>Repeated Measures</b> | <b><math>\alpha</math></b> | <b>Conclusion (if <math>p &lt; \alpha</math>)</b>                  |
|---|-----------------------------|--------------------------------|--------------------------|----------------------------|--|
| <b>One-way ANOVA</b>  | Speed                       | Grade                          | ----                     | 0.05                       | Speed changes with change of grade                                 |
| <b>One-way ANOVA</b>  | Stride length               | Grade                          | ----                     | 0.05                       | Stride length changes with change of grade                         |
| <b>One-way ANOVA</b>  | Stride frequency            | Grade                          | ----                     | 0.05                       | Stride frequency changes with change of grade                      |
| <b>One-way ANOVA</b>  | Symmetry Indices            | Grade                          | ----                     | 0.05                       | SI changes with change of grade                                    |
| <b>2-Factor ANOVA w/ Repeated Measures (Within Subjects)</b>  | Symmetry Indices            | Limb pref                      | Grade                    | 0.05                       | Limb preference has an affect on asymmetry during downhill running |
| <b>2-Factor ANOVA w/ Repeated Measures (Between Subjects)</b> | Symmetry Indices            | Limb pref                      | Grade                    | 0.05                       | Limb preference has an affect on asymmetry during downhill running |
| <b>2-Factor ANOVA w/ Repeated Measures (Within Subjects)</b>  | Symmetry Indices            | Trained and untrained subjects | Grade                    | 0.05                       | Training has an affect on asymmetry during downhill running        |
| <b>2-Factor ANOVA w/ Repeated Measures (Between Subjects)</b> | Symmetry Indices            | Trained and untrained subjects | Grade                    | 0.05                       | Training has an affect on asymmetry during downhill running        |
| <b>ANCOVA</b>   | Symmetry Indices            | Pref groups: Stride length     | Grade                    | 0.05                       | Preference has an affect on asymmetry during downhill running      |
| <b>ANCOVA</b>   | Symmetry Indices            | Pref groups: Step freq         | Grade                    | 0.05                       | Preference has an affect on asymmetry during downhill running      |
| <b>ANCOVA</b>   | Symmetry Indices            | Training groups: Stride length | Grade                    | 0.05                       | Training has an affect on asymmetry during downhill running        |
| <b>ANCOVA</b>   | Symmetry Indices            | Training groups: Step freq     | Grade                    | 0.05                       | Training has an affect on asymmetry during downhill running        |

## CHAPTER FOUR

## RESULTS

Subject Characteristics

Seventeen subjects (10 females and 7 males) from the community of Bozeman, Montana volunteered to participate in this study. The age of the subjects ranged from 22 to 63 (mean +/- SD: 35 +/- 14.1 years), mean body mass was 64 +/- 9.99 kg, and mean height was 172.8 +/- 7.6 cm. All subjects reported compliance with the inclusion and exclusion criteria of this study.

Subjects were allowed to select their preferred running speed at each running condition. However, gait speed for each running condition was restricted to vary no more than 5% from level running speed. No significant differences in speed or step frequency were detected over running conditions (Table 4.1). However, significant differences were found over running for stride length ( $p=0.017$ ).

Table 4.1. Descriptive temporal-distance parameters for the sample.

|                           | 0%           | - 3%         | - 6%         | - 9%        | p-value |
|---------------------------|--------------|--------------|--------------|-------------|---------|
| Speed (m/s)               | 2.6 (0.3)    | 2.63 (0.3)   | 2.7 (0.36)   | 2.7 (0.36)  | 0.129   |
| Step frequency (step/min) | 169.8 (10.4) | 168.3 (10.4) | 166.0 (10.3) | 165.4 (9.2) | 0.051   |
| Stride length (m)         | 1.84 (0.3)   | 1.9 (0.3)    | 1.9 (0.3)    | 2.0 (0.3)   | 0.017*  |

Mean (standard deviation)

\* denotes significance ( $\alpha = 0.05$ )

Impact Shock Magnitudes

Impact shock magnitudes were found to be inversely related to running conditions; as grade decreased, the magnitude of impact shock increased. An example of a subject's tibial impact shock measurement for one step length is represented in Figure

4.1. The peak represents the magnitude of shock transmission recorded on the antero-medial aspect of the tibia at heel-strike. Average peak tibial impact shock magnitudes (TIS, reported in g's, or multiples of gravity) for left and right limbs of all subjects are shown in Figure 4.2 and Table 4.2. There were significant effects of grade for TIS in both left and right limbs ( $p < 0.001$ ). There was no significant difference between left and right TIS for the sample.

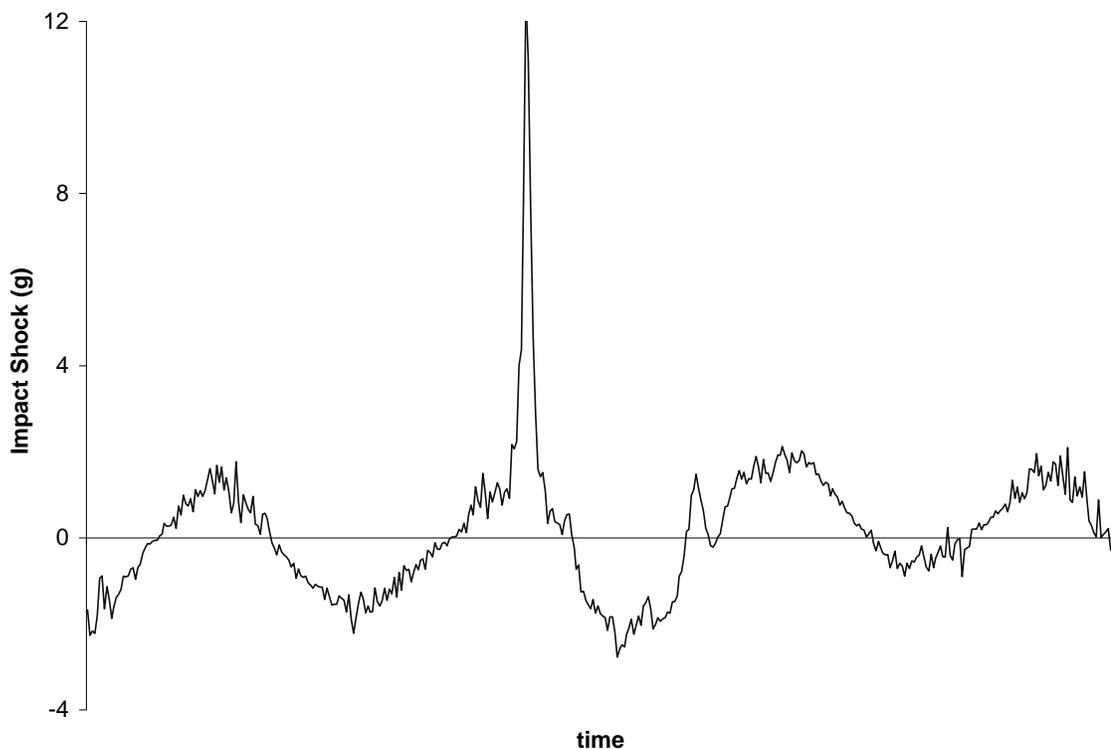


Figure 4.1. Example TIS peak for one subject.

Table 4.2. Measured TIS for all subjects.

|     |              | 0%          | -3%         | -6%         | -9%         | Grade<br>Effect (p) |
|-----|--------------|-------------|-------------|-------------|-------------|---------------------|
| TIS | <i>Left</i>  | 3.95 (0.98) | 4.23 (1.10) | 4.71 (1.34) | 4.94 (1.54) | <0.001*             |
| (g) | <i>Right</i> | 4.16 (1.18) | 4.54 (1.10) | 4.77 (1.12) | 4.86 (1.27) | <0.001*             |

g = gravitational acceleration,  $9.81\text{m/s}^2$ ; Mean (standard deviation)

\* denotes significant ( $\alpha=0.05$ )

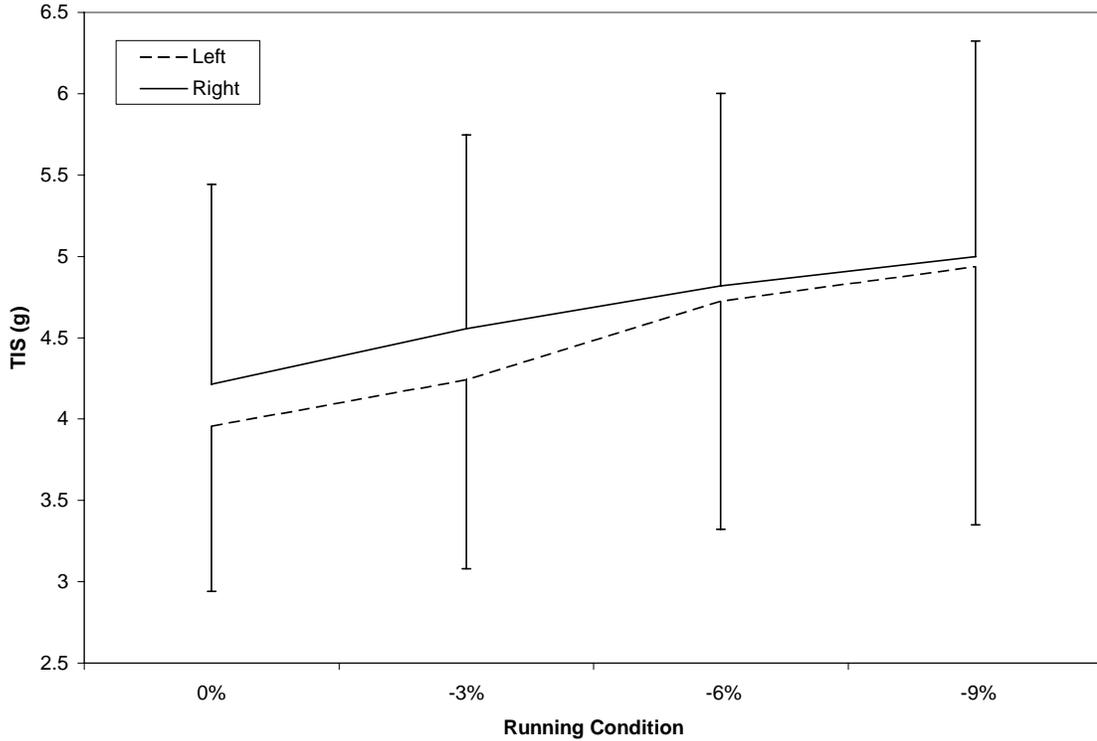


Figure 4.2. Tibial Impact Shock across running conditions for left and right limbs of all subjects.

Downhill trained runners on average tended to have lower relative TIS than downhill untrained runners across running conditions, however these differences were not determined to be significant. This relationship is presented in Figure 4.3. It includes a standardized magnitude of right and left TIS for all running conditions with respect to the left TIS magnitude of the level condition for each subject.

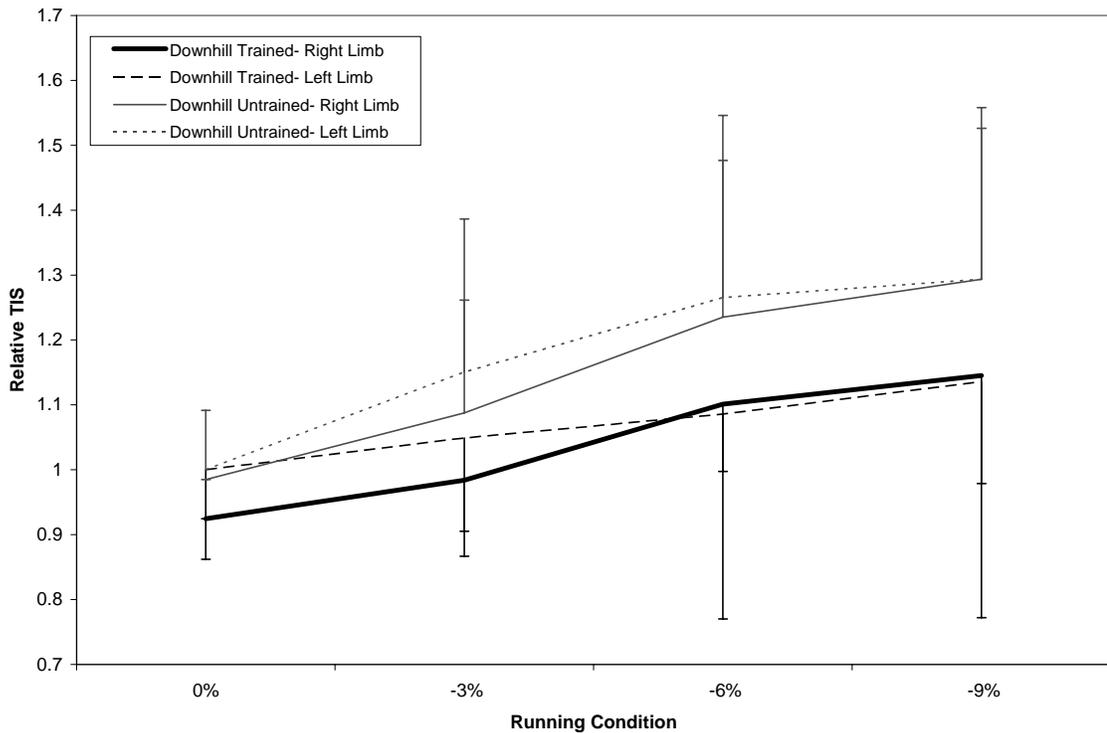


Figure 4.3. Relative TIS across running conditions for left and right limbs of training groups. All values are relative to the left limb TIS value of the level condition.

### Symmetry Indices

Symmetry indices (SI) were calculated for all subjects using a previously established equation (Robinson et al., 1987). SI values differing from zero indicated TIS asymmetry between limbs. All values were absolute and unitless, removing unilateral bias. There was not a significant effect of grade for SI when all subjects were combined. Furthermore, there was no effect of grade when stride length or step frequency were entered as covariates (Table 4.3).

Table 4.3. Average SI for all subjects.

|              | n  | 0%         | -3%        | -6%        | -9%         | p-value |  |
|--------------|----|------------|------------|------------|-------------|---------|--|
| All subjects | 17 | 11.5 (6.4) | 13.0 (9.4) | 17.0 (9.2) | 15.8 (11.5) | 0.333   |  |

SI values are unitless and absolute; Mean (standard deviation)

T

here was no significant difference in SI between right and non-right preferred groups. Nor was there a significant effect of grade on SI when categorizing subjects by lower-limb preference (Table 4.4). Figure 4.4 demonstrates the level of SI over grade for all right and non-right preferred subjects. Furthermore, no significant differences were determined between SI for right and non-right preferred subjects when stride length or step frequency were entered as covariates.

Table 4.4. Average SI for right and non-right preferred subjects.

|           | n  | 0%         | -3%         | -6%         | -9%         | p-value |       |
|-----------|----|------------|-------------|-------------|-------------|---------|-------|
| Right     | 6  | 10.3 (4.8) | 13.1 (10.3) | 14.6 (6.1)  | 10.2 (7.9)  | Group   | Grade |
| Non-right | 11 | 12.7 (7.1) | 13.3 (9.0)  | 18.8 (10.3) | 18.9 (11.8) |         |       |

SI values are unitless and absolute; Mean (standard deviation)

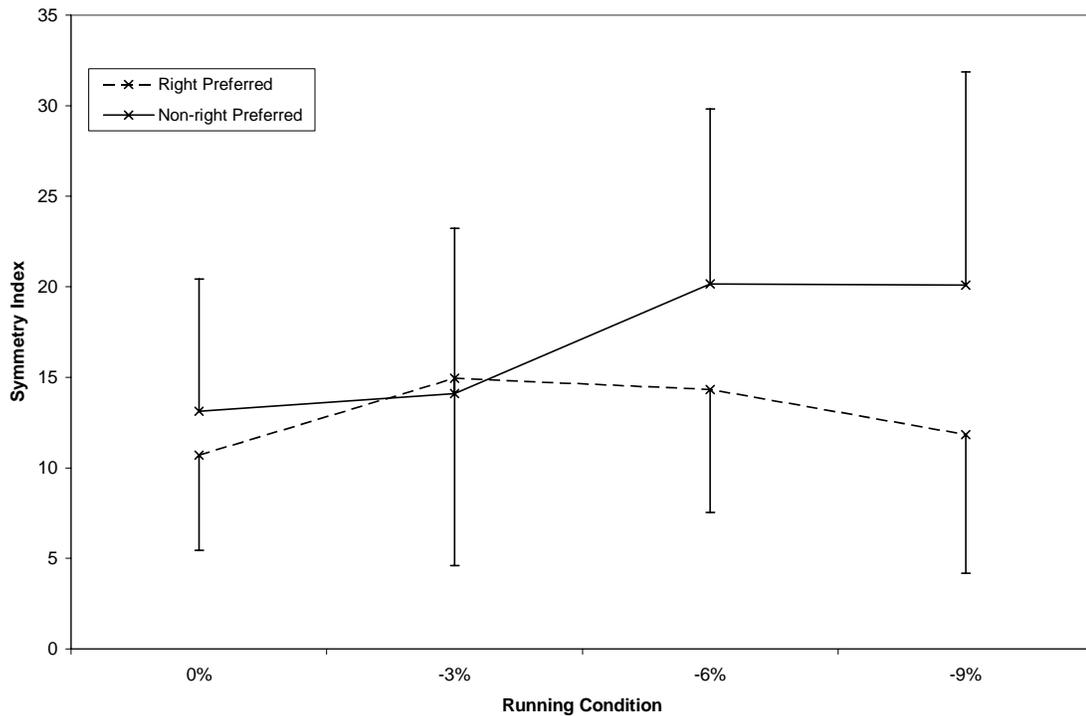


Figure 4.4. Symmetry Index across grades for lower-limb preference groups.

Average SI based on training categories are provided in Figure 4.5 and Table 4.5.

There was not a significant effect of grade on SI when categorizing subjects by training.

There were no significant differences in SI between downhill trained and downhill untrained groups, however a trend indicating differences was apparent ( $p=0.088$ ). When stride length was entered as a covariate, a significant difference in SI values between training groups was observed ( $p=0.034$ ). When step frequency was entered as a covariate, a significant difference in SI values between training groups was also observed ( $p=0.038$ ).

Table 4.5. Average SI for trained and untrained subjects.

|           | n | 0%         | -3%         | -6%        | -9%         | p-value |       |
|-----------|---|------------|-------------|------------|-------------|---------|-------|
| Trained   | 9 | 14.7 (7.7) | 15.6 (10.1) | 18.5 (9.6) | 19.3 (13.6) | Group   | Grade |
| Untrained | 8 | 8.6 (1.2)  | 10.7 (7.6)  | 15.9 (7.6) | 12.0 (6.5)  | 0.088 † | 0.171 |

SI values are unitless and absolute; Mean (standard deviation)

† when stride length or step frequency were entered as covariates,  $p \leq 0.038$

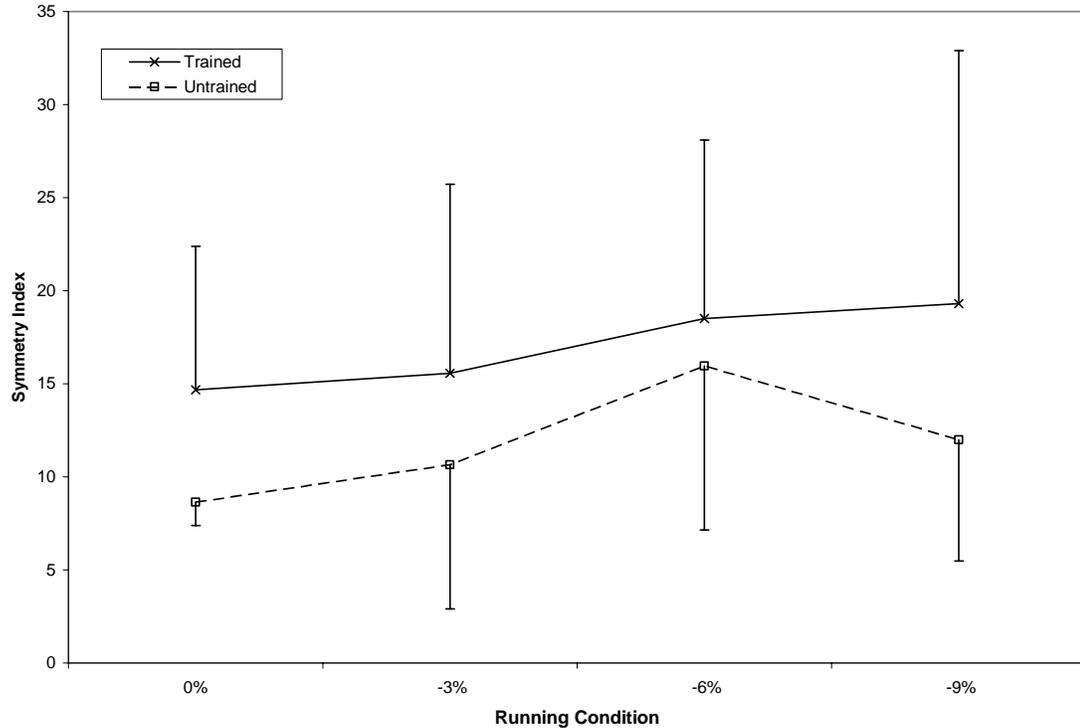


Figure 4.5. Symmetry Index across grades for training groups.

A post-hoc analysis was performed to determine if step length differences were a contributing factor to asymmetry for trained and untrained subjects. Step length was measured for consecutive left-to-right and right-to-left steps using TIS data. It was assumed that step length began at heel strike of the limb of interest, and was completed at heel strike (indicated by TIS peak) of the contra-lateral limb. Paired t-tests were performed on all subjects' step length comparisons, as well as by training groups. Trained

subjects' left and right step lengths were significantly different ( $p < 0.001$ ). However, step length was not significantly different in the untrained group when comparing left step length to right step length (Table 4.6, Figure 4.6). To account for to a possible side effect, the step length data from the untrained group were further sorted for comparisons of larger to smaller step length. If a subject had one side with a noticeably greater step length than the other (no more than one out of five samples being different), all conditions for that particular subject were adjusted for comparisons of larger to smaller step lengths. Only two sets of data from the six untrained subjects fit this description, however the difference between larger and smaller step length was significant ( $p=0.01$ ). When trained subjects' step length were modified for larger to smaller step length comparisons, the differences remained significant, with no change in p-value ( $p<0.001$ ).

Table 4.6. Step-length comparison for trained and untrained subjects.

|                                     | 0%          | -3%         | -6%         | -9%         |
|-------------------------------------|-------------|-------------|-------------|-------------|
| <b>Untrained</b> <i>Speed (m/s)</i> | 2.72 (0.45) | 2.76 (0.48) | 2.81 (0.51) | 2.86 (0.52) |
| <i>Left step length (m)</i>         | 0.96 (0.14) | 0.99 (0.17) | 1.02 (0.16) | 1.04 (0.16) |
| <i>Right step length (m)</i>        | 0.98 (0.21) | 1.01 (0.19) | 1.03 (0.22) | 1.04 (0.21) |
| <b>Trained</b> <i>Speed (m/s)</i>   | 2.56 (0.23) | 2.56 (0.25) | 2.61 (0.25) | 2.69 (0.24) |
| <i>Left step length (m)†</i>        | 0.91 (0.09) | 0.93 (0.09) | 0.97 (0.09) | 0.99 (0.11) |
| <i>Right step length (m)†</i>       | 0.93 (0.11) | 0.95 (0.11) | 0.99 (0.12) | 1.00 (0.13) |

† indicates significant difference between left and right step lengths

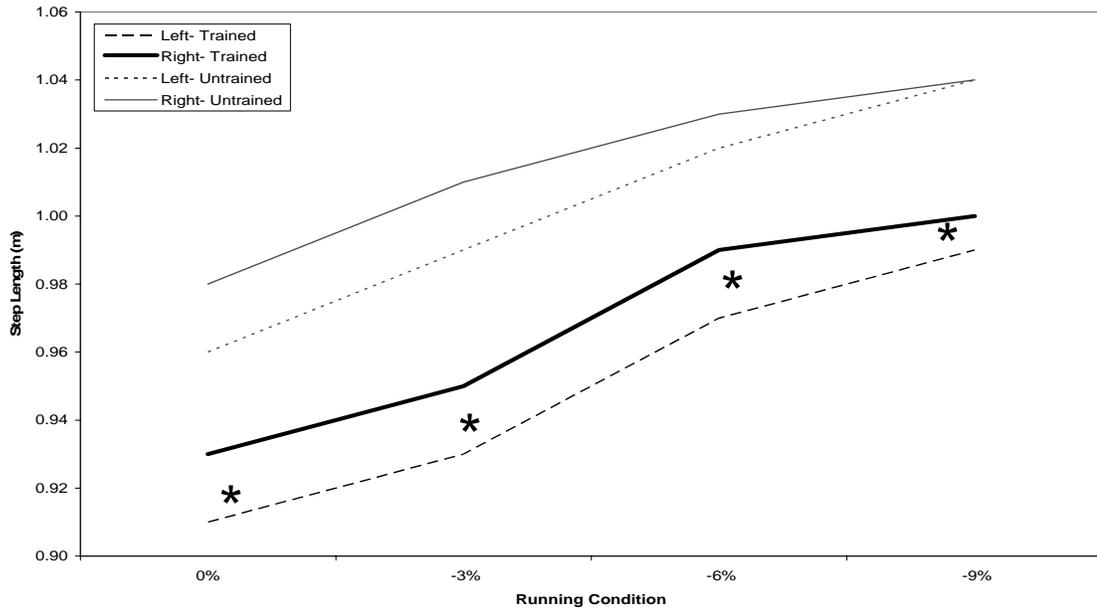


Figure 4.6. Step length comparison across grades for training groups.

## CHAPTER FIVE

## DISCUSSION

Introduction

The primary goal of this study was to determine the effect of downhill running on impact shock and asymmetry over varying grades. Specifically, it was hypothesized that asymmetry would change with decreasing running grade. Asymmetry was assessed using a previously established Symmetry Index (SI) score with bilateral tibial impact shock magnitudes measured using uniaxial piezoelectric accelerometers.

The secondary and tertiary goals of this study were to determine if there was significant symmetry difference between lower-limb preference groups and between training groups, respectively. Subjects were categorized as either right or non-right lower limb preferred, based on a series of unilateral assessments. Right preference referred to subjects who performed at least three unilateral lower-limb preference tests with their right foot. Non-right preference referred to subjects who performed three or more unilateral lower-limb preference tests with their left foot or with both their left and right feet. Subjects were also categorized as either downhill trained or non-downhill trained. Downhill trained referred to subjects whose training consistently included downhill “braking” specific training, and those who had participated in specific regional trail races involving extensive downhill “braking” strategies, such as the Bridger Ridge Run, Devil’s Backbone or the Old Gabe 25/50K. It was hypothesized that a difference in SI measures would be present between the preference groups. It was also hypothesized that a difference in SI measures would be present between the training groups.

With respect to the primary goal, for all subjects, downhill running did not significantly increase or decrease asymmetry. When grouped by preference or training, there was no significant effect of grade for SI. For the right-preferred group, SI remained fairly consistent across grades, whereas the SI of the non-right preferred group tended to increase, though not significantly. For the downhill trained group, SI tended to increase across grade conditions, but this difference was not significant, and the downhill untrained group did not show a trend toward changing SI. Furthermore, there was no significant difference in SI over grade conditions when comparing preference groups. However, a divergence in mean SI values was seen between right and non-right preferred runners. When accounting for variation in stride length or step frequency, a significant difference in SI between downhill trained and untrained groups was observed.

### Subject Characteristics

Seventeen subjects (10 female, 7 male) volunteered to participate in this study from the community of Bozeman, Montana. Subjects were recruited for their limb preference and training history (downhill or non-downhill running) and placed into appropriate groups based on their responses to unilateral lower limb preference tests (preference grouping, Appendix A) and a training questionnaire (training grouping, Appendix B).

This recruitment technique resulted in more subjects being categorized in the mixed-preference group than the right-preference group, which could be a limitation of this study. Limb preference is subjective, and accurate determination of lower limb preference may be limited by the number and type of tests performed in this study. This

study adapted a scale which had been previously established to measure lateral dominance in which five assessments of the lower limb function are used (Dusewicz and Kershner, 1969). However, some of the parameters measured using this scale can be described as preferential and not inherent. Preference, also known as laterality, is defined as a subjective, preplanned choice of limb use (Touwen, 1972), such as the first foot used when climbing stairs. Lateral dominance is defined as the central nervous system (CNS) phenomenon of default use and superior performance of one side of the body compared to the other (Coren & Porac, 1978; Harris, 1958). Sadeghi et al. (2000) have suggested that dominance should be used in gait research in reference to the automatic reactionary response to an action. However, the limb used for repetitive kicking of a ball or leading natural gait should be defined as preferred rather than dominant because actual CNS dominance is difficult to test for. Due to the difficulty of testing for dominance, “preference” vocabulary, as opposed to “dominance,” was chosen in the present study.

Initially, it was desired to have an even number of subjects for the left and right preference groups. However, it proved rather difficult to fulfill this goal. It has been estimated that less than 10% of the human population is left-handed (Hebbal & Mysorekar, 2003). Asymmetry may be revealed by handedness and footedness, however the two are not perfectly related. Previous research suggests that while right handedness and right footedness are strongly linked, left footedness is not as dependent on left handedness (Peters & Durdning, 1979; Hebbal and Mysorekar, 2003). This study may therefore have been limited by possible cross-over between preference groups.

### Tibial Impact Shock Measurements

Orientation and attachment of the accelerometers on the anteromedial aspect of the tibia was identical to the successful technique previously established by Hamill et al. (1995). Magnitudes of TIS for the present study, ranging between 2.06-10.7g, are comparable to previous findings (Flynn et al. 2004; Mercer, Vance, Hreljac & Hamill, 2002; Mizrahi et al., 2000b). It was assumed for the purposes of this study that the orientation of the accelerometer at foot impact did not change with grade. Therefore, it was further assumed that impact shock magnitudes were recorded with minimal angular distortion of the uniaxial accelerometer. However, it is possible that angular changes at the ankle and knee may distort the actual magnitude of shock experienced at the tibia. Buczek and Cavanagh (1990) reported that as grade changed, knee and ankle angle changed. The orientation of the tibia with respect to the ground at heel strike may be a contributing factor to alterations in impact shock magnitudes with changing grade. Future work should attempt to control for tibial orientation using kinematic analysis during downhill running.

Footwear variations also need to be considered when measuring TIS magnitudes. Butler, Davis and Hamill (2006) compared the effect of 'motion control' and 'cushion trainer' shoes on kinematic parameters of running biomechanics, including tibial accelerations. In their study, they found that peak tibial acceleration was reduced by 1.2g for runners wearing the 'cushion trainer' shoes compared to when they wore 'motion control' shoes. These differences indicate that shoe cushioning type can be a critical factor in impact shock measurements at the shank. Therefore, it is imperative to use a

consistent shoe model for all subjects during accelerometry measurements. In this study, all subjects were equipped with identical gender-specific models of Brooks Radius™ cushioned trainers during data collections. The shoes were only worn during the familiarization and data collections sessions and subjects indicated comfort and appropriate shoe fit before data collections took place. However, a limitation of this study could still be based on shoe model selection due to potential differences in foot type. Those who have low arches or experience severe overpronation may be more susceptible to injury while wearing cushion trainers during running, due to the lack of stability in rearfoot motion. However, in this study, it was assumed that the familiarization and data collection sessions were short enough in duration that the likelihood of altered gait was minimal to null.

#### Asymmetry Comparisons

A divergence in SI between training groups was observed, and when accounting for the covariates of stride length and step frequency, there was a significant difference between downhill trained and untrained groups. Downhill trained groups showed more asymmetry across running conditions than did their untrained counterparts. Such asymmetry may be due in part to a specificity of training effect.

Further analyses indicated a significant difference in step length between left and right steps for trained subjects, and a significant difference in step length between larger and smaller steps for untrained subjects, which likely contributed to asymmetry magnitudes. A unilateral forward stepping technique may explain this variation. Such a technique consists of one limb primarily used for propulsion, indicative of a longer step

length, and the opposite limb primarily used for balance with a shorter step length. The ‘balance’ limb may experience lower shock magnitude because of its reduced knee extension and hip flexion (Derrick, 2004; Derrick et al, 1998). Hence, observed increases in SI magnitude for the downhill trained group and the noticeable difference between SI magnitudes of training groups may be explained by a possible training effect of repeated downhill running sessions. Those who are habitual downhill runners, especially those who run several races a year which include steep downhill running conditions, may tend to pick a side that they typically favor for the forward step, and the opposite foot as the trailing balance limb.

The idea of gait asymmetry being explained in light of a balance-propulsion relationship has been previously suggested by others (Sadeghi, Allard & Duhaime, 2000). For gait studies, Matsuska et al. (1985) reported that the left limb of subjects was primarily responsible for controlling mediolateral balance. Similarly, Hirokawa (1989) associated propulsion with the right limb and support with the left. When one step length is longer than the other, as seen in individuals with limb length variations (and possibly among those trained for downhill running), asymmetrical impact shock characteristics are likely present. Variations in stride length have been reported in previous research to contribute to changes in impact shock magnitude (Derrick, Hamill & Caldwell, 1998), and individual step length variations may strongly contribute to changes in the magnitude of asymmetry for individual subjects. Therefore, the present findings are in line with previous research of impact shock characteristics of gait.

Subjects were allowed to choose their speed at each condition in order for them to run at preferred stride length and frequency. However, they were somewhat restricted in

that they were not allowed to deviate more than 5% from their level running speed. Previous work by Buczek and Cavanagh (1990) demonstrated similar methodologies by requiring their subjects to run at 4.5 m/s +/- 5% for both level and downhill running. They reported a significant decrease in knee flexion angle during downhill running compared to level running despite maintaining equivalent running speed. Yokozawa et al. (2005) also noted that hip and knee flexion values were significantly altered following heel strike while running downhill. Changes in gait kinematics are likely a natural response for prevention of injury during downhill running. Also, such kinematic changes may be the result of a decreased need for propulsion due to the assistance of gravity on a runner's forward motion. Specific changes in stride length have been suggested to account for changes in measured TIS. Mercer et al. (2005) reported that when stride length was kept constant over varying running speeds, impact force and attenuation did not change. However, when allowed to select their own stride lengths, subjects tended to select longer stride lengths at faster speeds, and impact force and attenuation both increased as speed increased.

A limitation of the current study is that treadmill speed was allowed to vary slightly from 0% grade to -9% grade. This alteration did not maintain control for stride length, and the primary effect of downhill running may have been masked because of stride length alterations. However, it is likely that subjects presented an increased stride length at downhill grades because of comfort. Restricting speed and stride length may be counter-intuitive when trying to establish natural effects of grade on impact shock and asymmetry. Kinematic alterations are not consciously controlled by most runners over varying terrain and running conditions. A protective effect of changing posture and joint

angle kinematics may be intuitive for most runners in natural settings and restricting these changes may increase the likelihood of injury, such as tibial stress fractures.

A difference in step length between limbs is strongly related to changes in asymmetry, and it was apparent that as downhill grade increased, asymmetry increased for those who were trained to run at steep downhill grades. It has been reported that energy costs of downhill running are much less than that of level or uphill running (Minetti, Moia, Roi, Susta & Ferretti, 2002). A reason for this may lie in the reduced need for propulsion due to the assistance of gravity over downhill terrain. However, Minetti et al. (2002) suggested a possible safety factor that contributes to decreased speed at steep downhill grades that is not metabolically controlled. For example, downhill racers do not tend to use their full aerobic capacity when running downhill. Reduced downhill running speed may be caused by an inherent desire to reduce pain and damage to joints and tissues. The reduction of knee flexion angle during downhill running has been suggested to increase impact shock, which would subsequently increase the likelihood of injury (Mercer et al., 2005). Reducing speed may be a subconsciously-controlled mechanism for avoiding such injuries. Indeed, slower speeds have been reported to reduce impact shock (Mercer et al., 2002). This tendency may be further adapted with downhill running training. As runners become more familiar with downhill terrain and conditions, they may develop better control of their body's acceleration by maintaining a moderate braking/propulsion mechanism while running downhill. Neuromuscular control could be trained to tolerate steeper grades at faster speeds, and unilateral braking patterns, as well as asymmetrical step lengths, appear to be some of the effects of downhill-specific training.

Previous researchers have suggested with strong conviction that use of bilateral measurements is important in gait analysis techniques (Sadeghi et al., 1997; Sadeghi, Allard et al., 2000). The measure of evaluating asymmetry in the present study has been used frequently in previous works (Zifchock et al., 2006; Robinson et al., 1987). The range of SI measures of the present study is similar to those of Zifchock et al. (2006) and within the suggested range of normal asymmetry. The measure quantifies asymmetry as an absolute percentage, and the difference between parameters is not characterized by lateral preference. Some studies have used positive and negative evaluations of asymmetry. For example, Perttunen et al. (2004) compared ground reaction force asymmetry for subjects with limb length discrepancy. Also, Kim and Eng (2003) measured asymmetry by kinetic means for persons with stroke, comparing paretic and non-paretic limbs. It may be beneficial when comparing asymmetry of mixed preference groups to use non-absolute measures of symmetry indices because of the possible effects of laterality. However, when qualitatively comparing SI for preference groups in the present study using non-absolute quantification, there did not appear to be a trend of different asymmetry between groups. Also, the training groups were of both right and non-right lower limb preference, and reducing the subject numbers to include only one of these preference groups would reduce the power of the present study. The laterality tests established for the present study may need to be modified for future work in the assessment of asymmetry in regards to lower-limb preference. However, there may not be an association between laterality and TIS sidedness (the laterality presented with comparison of TIS magnitude), and assessment of which limb to measure kinematic and kinetic parameters during unilateral gait analysis may need to be reevaluated.

## CHAPTER SIX

## CONCLUSION

Researchers have reported an inverse relationship between impact shock magnitude and decline grade. The purpose of this study was to determine the relationship between impact shock magnitude and lower-limb symmetry while running on varying downhill grades.

It was hypothesized that lower-limb asymmetry, as calculated with tibial impact shock, will increase with greater decline grade running due to an amplification of inter-limb differences. It was also hypothesized that SI values will be different between lower limb right and non-right preferred running populations. It was also hypothesized that SI values will be different between experienced and inexperienced downhill running populations.

Results from this study indicate that asymmetry does not change as grade decreases. Asymmetry did not significantly differ between limb preference groups. However, when accounting for variation in stride length and step frequency, asymmetry did show significant differences between downhill trained and untrained groups. Downhill trained subjects tended to have a greater SI across running conditions compared to untrained subjects. This is thought to be due to a learned habit of unilateral braking and propulsion characteristics which may be unique to runners who specifically train for downhill running.

A post-hoc step length analysis of the time differences between right and left TIS for each subject at each grade condition revealed significant asymmetry. Changing stride

length is known to affect TIS magnitude, and further differentiation between right and left step lengths in this study has revealed a significant contribution to asymmetry. These findings have implications for training and injury prevention for runners who are starting a trail-running regimen or are consistently training on downhill terrain. Maintenance of symmetry may reduce the likelihood of injury over an extended period of time. On the other hand, a learned asymmetry may be beneficial for speed and performance when running on steep downhill grades.

Future research should focus on methods of reducing SI by kinematic means. Comparison of intra-limb TIS when maintaining step length may shed light on whether or not other mechanisms cause downhill running asymmetry. Different groups should also be compared, such as runners who primarily run on trails and those who primarily run on roads. Longitudinal observational studies following distance runners should also be performed to see if natural asymmetry leads to gait pathologies and increased stress on bones of the lower limbs.

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APPENDICES

APPENDIX A  
PREFERENCE AND SPEED ASSESSMENT

|                                      |       |      |
|--------------------------------------|-------|------|
| Subject ID                           |       |      |
| Height (m)                           |       |      |
| Weight (kg)                          |       |      |
| Leg length (cm)<br>(from ASIS to MM) | Right | Left |
|                                      |       |      |

| <u>Foot dominance</u>  |       |      |                                   |                    |
|--|-------|------|-----------------------------------|--------------------|
| Manipulating/kicking a ball  | Right | Left | H Sadeghi et al 2000 Gait Posture | Mobility dominance |
| Rolling a golf ball around with bare foot while sitting in a chair | Right | Left | H Sadeghi et al 2000 Gait Posture | Mobility dominance |
| Stepping up on a chair   | Right | Left | H Sadeghi et al 2000 Gait Posture | Mobility dominance |
| Lead limb when taking off to start a run                           | Right | Left | H Sadeghi et al 2000 Gait Posture | Mobility dominance |
| Choice of foot for picking up golf ball                            | Right | Left | H Sadeghi et al 2000 Gait Posture | Mobility dominance |

| <u>Speed Selection</u>                           | Level | -3% | -6% | -9% |
|--|-------|-----|-----|-----|
| Mph  |       |     |     |     |
| m/s= (mph) *<br>0.44704                          |       |     |     |     |
| ± 5% of level<br>= level (m/s) *<br>0.05 + level |       |     |     |     |

APPENDIX B  
DEMOGRAPHIC SURVEY

Subject Reference Identification \_\_\_\_\_

Age \_\_\_\_\_

Sex \_\_\_\_\_

Shoe size \_\_\_\_\_

Current running shoe model \_\_\_\_\_

How many years have you been running? \_\_\_\_\_

Approximately how many miles do you run per week? \_\_\_\_\_

Where do you usually run? \_\_\_\_\_

Does your regular weekly training volume contain downhill running? Yes / No

If yes, how much?: \_\_\_\_\_

Have you raced recently (within the last two weeks)? Yes / No

If yes, when and what race? \_\_\_\_\_

Please rate your current muscle/joint soreness (1 = not sore; 10 = very sore)

\_\_\_\_\_

Do you currently have any injuries? Yes / No

If yes, please list: \_\_\_\_\_

\_\_\_\_\_

Have you ever had a running-related injury? Yes / No

If yes, please explain: \_\_\_\_\_

\_\_\_\_\_

Are you left/right/ambidextrously handed? \_\_\_\_\_

APPENDIX C  
SUBJECT CONSENT FORM

**SUBJECT CONSENT FORM****FOR PARTICIPATION IN HUMAN RESEARCH  
MONTANA STATE UNIVERSITY**

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**PROJECT TITLE:** EFFECTS OF DOWNHILL RUNNING ON TIBIAL  
IMPACT SHOCK AND ASYMMETRY

**PROJECT DIRECTOR:** Megan L. Killian, Graduate Student, Biomechanics  
Dept. of Health and Human Development  
Movement Science Laboratory  
Montana State University, Bozeman, MT 59717-3540  
Phone: (949) 683-9041; FAX: (406) 994-6314;  
E-mail: [mlkillian@montana.edu](mailto:mlkillian@montana.edu)

**FUNDING:** This project is not currently funded.

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**PURPOSE OF THE STUDY:**

The purpose of this study is to examine the relationships between grade and impact shock during downhill running. Involvement in this project includes two visits to the Movement Science Laboratory (basement of Romney Building, MSU campus). Time commitment will be less than one hour each. The laboratory experiments will consist of the following:

- Treadmill running at level and multiple downhill grades.
- Measurement of impact shock using a lightweight device attached to the skin of the lower leg.

**STUDY PROCEDURES:**

After reading and signing the Informed Consent Document, you will be asked to change into shorts appropriate for running. You will then have your body weight and body height determined using a standard physician's beam-scale. You will perform a familiarization session so that you are accustomed and comfortable to running on the treadmill at different negative grades. You will be asked to return at a later date to fulfill your completion of this study. Upon return, you will be asked to complete a 5 minute running warm up on the treadmill. Next, a lightweight accelerometer (one per leg) will be secured to the surface of your shin. This device will be fastened using two sided tape, balsa wood and an elastic taping material, tightened to your comfort level.

Once you have become familiar with the treadmill setting, you will be allowed to self-select your pace at all grades, running for approximately three minutes at each grade. Next, you will be asked to run for 4 minutes at your preferred speed on a level grade. You will then be asked to run for 4 minutes on four different downhill grades (from -3% to -9%). A collection time of constant running for 16 minutes will be required to perform the assessment.

**POTENTIAL RISKS:**

It is possible that you may experience some discomfort in the placement of the accelerometer device. However, after the device is secured, any discomfort will be minimal. Throughout the testing session, if you feel uncomfortable with any procedure, you may feel free to stop the test at any time.

**BENEFITS:**

In addition to receiving personalized feedback on the impact shock patterns witnessed during your assessment, the results of this study may contribute to more effective prevention of injury in the general running population. Additionally, study participants may request a summary of the study findings by contacting the Project Director, Megan Killian, by phone (949-683-9041) or by E-mail ([mlkillian@montana.edu](mailto:mlkillian@montana.edu)).

**CONFIDENTIALITY:**

The personal information, and all recorded data will be regarded as privileged and confidential materials. Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. Subject identities will be kept confidential by coding the data using subject pseudonyms. The code list will be kept separate and secure from the actual data files.

**FREEDOM OF CONSENT:**

*Participation in this project is completely voluntary.*

You may withdraw consent for participation in writing, by telephone, or in person without prejudice or loss of benefits (as described above). Please contact the Project Director, Megan Killian, by phone (949-683-9041) or by E-mail ([mlkillian@montana.edu](mailto:mlkillian@montana.edu)) to discontinue participation.

In the UNLIKELY event that your participation in the project results in physical injury to you, the Project Director will advise and assist you in receiving medical treatment. No compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of your participation in this project. Additionally, no compensation is available from Montana State University for injury, accidents, or expenses that may occur as a result of traveling to and from your appointments at the Movement Science / Human Performance Laboratory.

*Further information regarding medical treatment may be obtained by calling the Project Director, Megan Killian, at 949-683-9041. You are encouraged to express any questions, doubts or concerns regarding this project. The Project Director will attempt to answer all questions to the best of their ability prior to any testing. The Project Director fully intends to conduct the study with your best interest, safety and comfort in mind. Additional questions about the rights of human subjects can be answered by the Chairman of the Human Subjects Committee, Mark Quinn, at 406-994-5721.*

**PROJECT TITLE:****EFFECTS OF DOWNHILL RUNNING ON TIBIAL IMPACT SHOCK  
AND ASYMMETRY****STATEMENT OF AUTHORIZATION**

I, *the participant*, have read the Informed Consent Document and understand the discomforts, inconvenience, risks, and benefits of this project. I, \_\_\_\_\_  
(*print your name*), agree to participate in the project described in the preceding pages. I understand that I may later refuse to participate, and that I may withdraw from the study at any time. I have received a copy of this consent form for my own records.

**Signed:** \_\_\_\_\_ **Age** \_\_\_\_\_

**Date** \_\_\_\_\_

*Subject's Signature*