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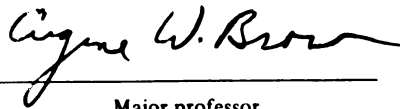
BIOMECHANICAL AND PHYSIOLOGICAL EFFECTS OF
PLYOMETRIC TRAINING ON HIGH SCHOOL
CROSS-COUNTRY RUNNERS

presented by

Mark C. Lathrop

has been accepted towards fulfillment
of the requirements for

M.S. degree in Kinesiology



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**BIOMECHANICAL AND PHYSIOLOGICAL EFFECTS OF
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CROSS-COUNTRY RUNNERS**

By

Mark C. Lathrop

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ABSTRACT

BIOMECHANICAL AND PHYSIOLOGICAL EFFECTS OF
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The purpose of this study was to compare the effectiveness of a traditional cross-country training regimen with a training program that includes plyometrics. Eighteen male and female high school cross-country runners were matched according to their previous running experience and randomly assigned to two groups. Participants followed a traditional cross-country training program for six weeks, except that two to three times a week the plyometrics group replaced some of their easy run training with 15-20 minutes of plyometric training.

The participants were tested before and after the six-week training period. A treadmill test was used to determine running economy, lactate threshold, and VO_{2max} . The participants ran across a force plate in order to determine support time, braking time, and braking change in velocity. Participants were also timed on a 3200-meter run.

Participants in both groups significantly improved their running economy and 3200-meter time (without a change in VO_{2max}), but there were no significant differences between groups on these variables. The plyometric group significantly decreased their braking change in velocity over the training period, while there was no change in the running group.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation/Symbol	Definition
AMTI	Advanced Mechanical Technology Inc.
ANOVA	Analysis of Variance
APAS	Ariel Performance Analysis System
BΔV	Braking Change in Velocity
BT	Braking Time
GRF	Ground Reaction Force
HR	High Resistance strength training with free weights
HV	High Velocity strength training (plyometrics)
LT	Lactate Threshold
MANOVA	Multiple Analysis of Variance
MART	Maximum Anaerobic Running Test
PΔV	Propulsion Change in Velocity
PLYO	Group whose participants replaced some run training with plyometrics
RE	Running Economy
RUN	Group whose participants only did run training
SD	Standard Deviation
ST	Support Time
VO _{2max}	Maximum aerobic power
% Diff.	Percentage difference between BΔV and PΔV = (PΔV - BΔV) / BΔV

CHAPTER ONE

Introduction

Overview of the Problem

Frank Shorter's gold medal marathon performance in the 1972 Munich Olympics and Bill Rodger's numerous victories in the Boston Marathon in the 1970's signaled the beginning of the running boom in the United States. With this increased participation in running, some top runners, their coaches, and other running enthusiasts (Fixx, 1979; Galloway, 1984; Henderson, 1983; Higdon, 1978; Steben & Bell, 1979) began to write about their training methods and why they were successful. Also, specialists in exercise physiology and biomechanics (Anderson, 1996; Costill, 1979; Daniels, 1998; Hickson, Rosenkoetter, & Brown, 1980; Martin, 1997) wrote about the many benefits of running as well as the best training programs to improve performance. Consequently, many recreational runners in the 1980's and 1990's began to describe their training methods with words and phrases such as long slow distance, fartlek, interval training, repetitions, lactate threshold running, and hill training. There has been a lot of research about the success of these types of training methods among elite distance runners competing in five-kilometer to marathon distances (e.g., Conley, Krahenbuhl, & Burkett, 1981; Henritz, Weltman, Schurrer, & Barlow, 1985; Wilson, Newton, Murphy, & Humphries, 1993). However, there has been less research about how a strength training program such as plyometrics affects the performance of young distance runners. Most strength training

studies have focused on the physiological effects of strength training on college age and elite runners. There is a need then to study the biomechanical as well as the physiological effects of plyometric training on high school cross-country runners.

Need for the Study

High school cross-country coaches are faced with many challenges. They have a short season (typically four to five weeks of conditioning followed by six to eight weeks of competition). Also, today's athletes often have after-school jobs that cause them to leave practice early or miss practices. Finally, coaches need to be concerned about the physical growth and development of young athletes who may be more susceptible to injuries (Apple, 1995). According to Martin (1997), a 130-pound male running ten miles at 6:30 min/mile pace contacts the ground about 5,280 times with each foot. The total impact force on each foot during this run is up to 686 U.S. tons or 624,728 kilograms of force. Thus, high school coaches need training programs that efficiently train their runners yet keeps them free of injury. However, many high school coaches train their athletes the way they were coached or follow the training program of the local or national star athlete, which may not be appropriate for their team. There is a need for these coaches to have training programs available to them that are based on sound research that address the special needs of high school athletes. High school cross-country coaches need to know the most effective ways to train runners during the limited practice time that the coaches have with their teams.

Physiological factors such as VO_{2max} (Foster, Costill, Daniels, & Finley, 1978), lactate threshold (Farrell, Wilmore, Coyle, Billin, & Costill, 1979), and running economy (Conley & Krahenbuhl, 1980) have often been used to predict endurance running performance. Anderson (1996) stated that the keys to success in endurance running are

aerobic power production and runners' resistance to fatigue. To improve in these areas, runners need to increase the level of physical stress or strain they can handle or increase the speed at which a sustainable level of stress occurs. Training programs based on improving these components have been developed. These training programs usually involve easy long runs, tempo runs (running at a pace above lactate threshold), repetitions (e.g., 8 x 200 meters with full recovery), and intervals (e.g., 6 x 400 meters with one minute rest). These types of workouts are aimed at improving oxygen delivery. However, oxygen delivery may not be the only limiting factor of performance. Muscle power, or the failure of muscle contractility, may also limit performance (Noakes, 1988). Bulbani, Wilcox, and Darabos (1986) found that anaerobic power is a good predictor of race success among cross-country runners who have similar $\text{VO}_{2\text{max}}$ values. Cross-country runners need to maintain relatively high velocity for an entire race. Thus, neuromuscular characteristics related to voluntary and reflex activation, muscular force, and elasticity take on an important role in running performance as well as anaerobic characteristics (Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999). These types of characteristics may be improved by some types of strength training, which may then lead to improved running performance.

It may seem that using resistance training to improve endurance performance violates the principle of specificity. However, endurance performance requires muscle strength and anaerobic power which is needed for climbing hills and for the final sprint at the end of a race (Bulbani et al., 1986). Increasing maximum power allows a runner to work at a lower percentage of his or her maximum $\text{VO}_{2\text{max}}$ so he or she can last longer at lower work rates (Stone, Fleck, Triplett, & Kraemer, 1991). This may be very beneficial in running as it lowers the energy costs of running. According to Di Prampero et al.

(1993), a five percent decrease in energy cost of running is responsible for an improvement of 3.8% in distance running.

Many researchers have investigated the effects of various types of strength training on runners. Some of the studies are summarized in Table 1.1. Hickson et al. (1980) and Hickson, Dvorak, Gorostiaga, Kurowski, and Foster (1988) showed that weight training can increase the endurance time to exhaustion without a change in $\text{VO}_{2\text{max}}$. Weight training has also been shown to increase lactate threshold in biking (Marcinik et al., 1991) and lead to a 15% improvement in two-mile run time (Hortobagyi, Katch, & Lachance, 1991). Other researchers reported that plyometrics can increase the acceleration and maximum speed of sprinters (Delecluse et al., 1995) and can improve maximum power as measured by the MART test (Nummela, Mero, & Rusko, 1996a). In recent studies, Paavolainen et al. (1999) and Turner, Owings, and Schwane (1999) found that plyometric training can improve running economy without a change in $\text{VO}_{2\text{max}}$, while Nicholson and Sleivert (1999) found that weight training can improve ten-kilometer time, lactate threshold, and running economy.

Since there is some theoretical basis that strength training can improve running performance, the question remains as to which type of strength training is best for high school cross-country runners. Many strength training studies have used traditional weight training which strengthens isolated muscles groups. However, multiple muscle groups are used in running. Runners need exercises that develop balance and coordination of many muscle groups (Martin, 1997). Therefore, strength training that simultaneously emphasizes and develops many muscle groups that are specific to running may be best for runners. Also, since in each step of running there is an eccentric contraction followed by a concentric contraction, a strength training program for runners

Table 1.1. Summary of Strength Training Studies

Author	Subjects	Training method	Results
Delecluse et al. (1995)	18-22 year old male physical education students	HR-free weights HV-plyometrics; 3 days/wk for 9 weeks	HR-increased acceleration HV-increased acceleration, maximum speed, better 100-m time
Hickson et al. (1980)	9 active, 18-27 year old men	Weight training-legs; 5 days/wk for 10 weeks	Endurance time to exhaustion increased (12% run, 47% bike); VO _{2max} unchanged; lactate concentration not raised
Hickson et al. (1988)	6 males, 2 females; 29-39 year old, trained	Weight training; 3 days/wk for 10 weeks; added to existing endurance training	Endurance time to exhaustion increased (11% run, 13% bike); VO _{2max} unchanged; 10 km times inconclusive
Hortobagyi et al. (1991)	28 college males	Circuit training for 40 minutes followed by 2-mile run; 3 days/wk for 13 weeks	15% improvement in two mile run time
Marcinik et al. (1991)	18 untrained males, 25-34 year old	Weight training arms and legs; 3 days/wk for 12 weeks	On bike 12% increase in lactate threshold; no change in VO _{2max}
Nicholson & Sleivert (1999)	30 male and female recreational runners	Weight training for 21 weeks	Improve 10-km time, lactate threshold, and running economy
Nummela et al. (1996b)	9 well-trained sprinters	60-600 meter intervals; weight training; plyometrics	Maximum power increased by 3.4% (as measured on MART)
Paavolainen et al. (1999)	22 elite, male distance runners, 23-24 year old	Explosive strength training: sprints, jumps, high velocity weight training; run close to lactate threshold pace	5-km time, running economy, 20 m velocity, and 5 jump improve with no change in VO _{2max}
Turner et al. (1999)	18 male and female trained distance runners, 29 year old	Plyometrics for six weeks	Running economy improved with no change in VO _{2max} or jump height

should include these types of actions. Plyometric training, or jump training, meets this criteria and would seem to be suitable for running.

Coaches have used plyometrics to train track and field athletes, football and soccer players, wrestlers, and even golfers (Bompa, 1996; Radcliffe & Farentinos, 1999). However, there has been little mention of using plyometrics with distance runners. Furthermore, there have been very few studies that have shown how plyometric training affects distance running performance. Many plyometric studies used male runners in their twenties as subjects (see Table 1.1). The present study is unique in that relatively inexperienced male and female high school runners were studied to investigate if plyometrics is an effective way of improving cross-country running performance. Also, the few studies that have been conducted on this type of training (Delecluse et al., 1995; Nummela et al., 1996; Paavolaninen et al., 1999; Turner et al., 1999) have mainly focused on physiological changes with little regard to biomechanical changes. The question remains as to whether plyometrics causes changes in the biomechanics of running which result in beneficial physiological changes. Thus, there is a need for a study that investigates the effects of plyometric training on high school cross-country runners. High school cross-country coaches would be interested in knowing if plyometrics is an effective use of their limited practice time, and researchers interested in biomechanics and running may be interested in the changes in kinetics that may occur with this type of training program.

Statement of the Problem

This study compared a traditional high school cross-country training program with a training program that replaced some traditional training with intense plyometric training sessions conducted two to three times per week for six weeks. Major outcome

variables were 3200-meter run time, running economy, lactate threshold, $\text{VO}_{2\text{max}}$, time in support, braking time, and braking change in velocity.

Hypotheses

It was hypothesized that after six weeks of plyometric training, the plyometrics group would:

- 1) spend less time in the support phase, including less braking time;
- 2) exhibit a decrease in the change in velocity during braking;
- 3) display improvement in running economy;
- 4) increase their lactate threshold velocity; and
- 5) have greater improvement in 3200-meter run time than the run-only group.

Overview of the Research Methods

Eighteen male and female high school cross-country runners from three local high schools were randomly assigned to either a plyometrics group (PLYO) or a running group (RUN) using a matched-pairs technique based on their previous running experience. During a six-week training period, participants did their regular cross-country training administered by their coach. The plyometrics group replaced some of its easy run training with 15-20 minute sessions of plyometric training two to three days per week. The run-only group ran at an easy pace during this time.

All participants were tested before and after the six-week training period. The testing consisted of three components: treadmill test, biomechanics evaluation, and a running performance measure. The treadmill test was used to determine running economy, lactate threshold, and $\text{VO}_{2\text{max}}$. In the biomechanics evaluation, participants ran across a force platform at 3.8 m/s (7:04 min/mile) pace. Anteroposterior and vertical ground reaction force-time histories were obtained in order to determine support time,

braking time, and braking change in velocity. Running performance was determined by the time to run 3200 meters on a track. MANOVA was used to determine if there was an overall effect of the intervention. If there was an overall effect, ANOVA was performed on that particular effect for each dependent variable. Alpha was set at 0.10 for MANOVA and for ANOVA.

Definitions of Terms

Amortization phase: Time from the beginning of an eccentric contraction to the beginning of the following concentric contraction.

Braking change in velocity: The change in horizontal velocity during the braking phase. It equals the braking impulse divided by the mass in kilograms of the subject.

Braking impulse: The area between the anteroposterior ground reaction force curve and the time axis during the braking phase. It equals the integral of the anteroposterior ground reaction curve during the braking phase (see Figure 1.1).

Braking phase: The initial phase of stance in which the anteroposterior ground reaction force opposes forward movement.

Braking time: The time spent in the braking phase (see Figure 1.1).

Cruise intervals: Repeated runs of 3 to 15 minutes at threshold pace, with a short one minute recovery between intervals.

Fartlek training: Swedish for “speed play.” Alternating fast-paced running with slow-paced running. Distances run at different speeds and time spent running varies and is determined by how the runner feels.

Hill training: A type of repetition training involving running hard uphill and/or downhill with a long recovery between each repetition.

Interval training: Training at a pace at 98-100% of VO_{2max} or 98-100% of maximum heart rate. Intervals can last from 30 seconds up to 5 minutes with a recovery period equal to or slightly less than the time spent running the preceding interval.

Lactate threshold: The pace or work intensity just prior to a sudden increase in blood lactate concentration.

Long slow distance runs: Easy, recovery runs at a pace at 65-75% of VO_{2max} or 70-80% of maximum heart rate.

Maximum aerobic power (VO_{2max}): Maximum ability of an individual to take up, transport, and utilize oxygen in the working muscle.

Plyometrics: A type of explosive strength training that involves an eccentric contraction immediately followed by a concentric contraction of the same muscle or muscle group.

Propulsion change in velocity: The change in horizontal velocity during the propulsion phase. It equals the propulsion impulse divided by the mass in kilograms of the subject.

Propulsion impulse: The area between the anteroposterior ground reaction force curve and the time axis during the propulsion phase. It equals the integral of the anteroposterior ground reaction force curve during the propulsion phase (see Figure 1.1).

Propulsion phase: The second phase of stance where the direction of the anteroposterior ground reaction force is in the forward direction.

Repetition training: Training at a pace greater than VO_{2max} and equal to or faster than race pace. Each repetition lasts less than two minutes with a recovery that is four times as long as work bout.

Running economy: Amount of oxygen consumed relative to a runner's body weight and speed at which he or she is running. It is the rate of submaximal oxygen consumption.

Specificity of training: Principle that metabolic and physiological adaptations are specific to the type of training done; that is strength training induces specific strength-power adaptations while aerobic exercise results in specific endurance adaptations with only a limited interchange of benefits between muscular strength and aerobic training.

Stride frequency: The number of strides per minute.

Stride length: The distance between the heel contact of one foot to the next heel contact on the same foot.

Support time: The time one foot is in contact with the force plate. Due to noise associated with force platform, contact is defined as the period of time which the vertical GRF exceeded 16 Newtons (Munro, Miller, & Fuglevand, 1987).

Tempo runs: A 20 minute run at threshold pace.

Threshold pace: Training at a pace at 86-88% of $\text{VO}_{2\text{max}}$, or 90% of maximum heart rate.

See Cruise intervals and Tempo runs.

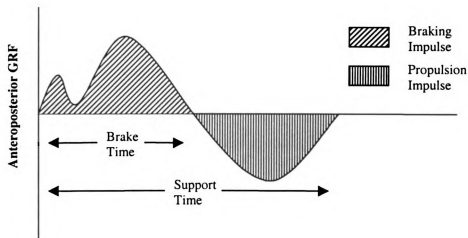


Figure 1.1. Diagram of braking and propulsion phases.

CHAPTER TWO

Literature Review

Physiological Factors of Running Performance

There are many factors that influence middle distance and distance running performance. These events range from the 800 meters which has more emphasis on speed to the marathon which requires more endurance. Coaches and researchers (Conley & Krahenbuhl, 1980; Farrell et al., 1979; Maffulli, Testa, Lancia, Capasso, & Lombardi, 1991) have found that VO_{2max} , running economy, and lactate threshold are important factors that influence distance running performance. Distance running coach and exercise physiologist, Jack Daniels (1998), wrote that training for speed, economy, and aerobic power are keys to success in 1500 meter to 3000 meter races. Another factor influencing running performance that is mentioned infrequently is the energy cost of overcoming air resistance. Pugh (1970) found that 7.5% of the total energy cost in middle distance running is due to air resistance. This paper focused mainly on factors which influence five kilometer cross-country running performance which requires a blend of speed, strength, and endurance (Martin, 1997). According to Martin success at this distance requires athletes to train for “speed-strength” and “speed-endurance.”

Maximum aerobic power. Maximum aerobic power, or VO_{2max} , has often been used as a predictor of running performance (Noakes, 1988). For example, Foster et al. (1978) found that VO_{2max} was highly correlated with one-mile, two-mile, and six-mile race times.

It has been defined as the maximum ability of an individual to take up, transport, and utilize oxygen in the working muscle (Green & Patala, 1992). Daniels (1998) added that the amount of oxygen consumed depends upon the amount of oxygen delivered and used by muscles and how well muscles deal with CO₂ and lactic acid during a run. Daniels recommended that to increase VO_{2max}, athletes must stress the oxygen delivery and utilization system by running three to five minute intervals at about 3000-meter to 5000-meter race pace. Conley et al. (1981) studied elite male runners for 18 weeks and found that VO_{2max} increased the most following interval training, while endurance training had little effect on VO_{2max}. It is important for 1500-meter to 3000-meter runners to have a high aerobic capacity so they do not need to rely on the anaerobic system until the end of the race. A high VO_{2max} is also crucial to 5000-meter runners as race pace is close to 100% of aerobic capacity. The present study investigated how plyometric training affects high school runners' aerobic capacity.

Lactate threshold. Another factor influencing running performance is lactate threshold. This has been defined as the pace just before which blood lactate levels rise sharply, or more formally, the work intensity that initiates a sudden increase in blood lactate concentration (Martin, 1997). Weltman et al. (1987) found that the lactate threshold for most male runners is at about 83% of their VO_{2max}, or 87% of their maximum heart rate. Blood lactate levels are determined by the amount of lactic acid produced and by how much lactate is used by the muscles, heart, and liver (Daniels, 1998). Runners need to keep blood lactate levels down so they can run at fast speeds but still have a low blood lactate concentration (Henritze, Weltman, Schurrer, & Barlow, 1985). Daniels often has his runners do “tempo runs” where they train at or close to their

lactate threshold. This type of workout provides quality, low stress training, which can aid in recovery from high intensity running.

Running economy. Although, coaches and physiologists have traditionally used $\text{VO}_{2\text{max}}$ as a predictor of running performance, several authors (Anderson, 1996; Daniels & Daniels, 1992; Noakes, 1988) have reported that runners with similar $\text{VO}_{2\text{max}}$ values can vary widely in their performance in distance races. Daniels (1974) studied two runners who had vastly different $\text{VO}_{2\text{max}}$ values (72 ml/kg/min and 57 ml/kg/min) but had similar two mile race times. The difference in predicted performance was attributed to a difference in running economy. Running economy reflects the level of physical stress associated with steady state running at a certain pace (Anderson, 1996). Williams and Cavanagh (1987) defined running economy as the rate of submaximal oxygen consumption, or $\text{VO}_{2\text{submax}}$, while Daniels (1998) formally defines it as the amount of oxygen being consumed relative to runners' body weight and speed they are running. For example, a runner who uses 50 ml of oxygen per kilogram of body weight per minute while running at 6:00 min/mile pace is more economical than a runner who uses 55 ml of oxygen. Therefore, runners need to improve their running economy so they can run faster without an increase in energy expenditure. Thus, some researchers (Conley & Krahenbuhl, 1980) have stated that for runners with similar $\text{VO}_{2\text{max}}$, running economy is a better predictor of performance than aerobic power.

Although the factors that influence running economy have not been scientifically identified, Martin (1997) believed that an increase in fitness, strength, and coordination may improve running economy, while Daniels (1998) recommended running repetitions (short intervals with full recovery) to improve economy. Conley et al. (1981) found that interval training of varying lengths and recovery periods resulted in a greater increase in

running economy than endurance training. In the present study, plyometric training, a type of strength training, was investigated to see how it affects running economy.

Other physiological factors. Even though $\text{VO}_{2\text{max}}$, lactate threshold, and running economy are all important factors in predicting distance running performance, it is inappropriate to use any one factor by itself in predictions. A runner could have a high $\text{VO}_{2\text{max}}$ but a poor running economy, which would result in a poorer performance than what is predicted by his or her $\text{VO}_{2\text{max}}$ value. On the other hand, a person may be a very economical runner but have a relatively low $\text{VO}_{2\text{max}}$, which could result in a poorer performance than what was predicted by looking only at running economy.

As a result, researchers such as Bulblian et al. (1986) prefer a multifactor approach that uses many factors to predict running performance. Others have studied factors that take into consideration both running economy and $\text{VO}_{2\text{max}}$. Daniels (1974) and Noakes, Myburgh, and Schall (1990) have used velocity at $\text{VO}_{2\text{max}}$, or peak velocity, to successfully predict running performance. This is the velocity at which $\text{VO}_{2\text{max}}$ is first realized and takes into account $\text{VO}_{2\text{max}}$ and running economy. Thus, two runners with similar race times would have the same peak velocity, but one may achieve this velocity with a high $\text{VO}_{2\text{max}}$ and low economy, while the other has a lower $\text{VO}_{2\text{max}}$ but is more economical.

Other researchers have studied the percentage of $\text{VO}_{2\text{max}}$ needed to maintain a particular running speed. Wilcox and Bulbulian (1984) found that over the course of a college season, female cross country runners increased their $\text{VO}_{2\text{max}}$ and improved their running economy (but not significantly). However, there was a significant reduction in runners' percentage $\text{VO}_{2\text{max}}$ at two speeds. By the end of the season, running at 241

m/min required almost the same percentage of $\text{VO}_{2\text{max}}$ as running at 215 m/min at the beginning of the year.

Biomechanical Aspects of Running

Much of the research in running has focused on the physiological aspects of running. However, some researchers have studied biomechanical factors that may influence running performance. To better understand the biomechanical analysis of running, a summary of the different components of a running cycle is reviewed.

Ecker (1985) divides a complete running cycle into three phases: the driving phase, recovery phase, and the braking phase. During the driving phase, the body is pushed forward by extending the hip, knee, and ankle. This phase continues until the foot leaves the ground. During the recovery phase both feet are in the air after the driving foot leaves the ground well behind the body's center of mass. In the braking phase, the foot opposite the one used during the driving phase touches the ground a little ahead of the body's center of mass which causes a braking effect. The body moves forward until the center of mass is ahead of the support foot, which leads to the next driving phase. Collectively the braking and driving phases are called the support, or stance phase, while the recovery phase is also known as the non-support or swing phase (Hamill & Knutzen, 1995).

Mechanical efficiency. One area of biomechanical study is mechanical efficiency. This is the ratio of the total amount of mechanical work done divided by the metabolic energy expended to do it (Norman, Sharratt, Pezak, & Noble, 1976). Highly efficient runners have a larger work output at a low physiological cost, or if the speed is fixed, they have a low mechanical work output at a low physiological cost. Since it appears mechanical efficiency could be an important factor in running performance, it has been studied by numerous researchers (e.g., Kaneko, Fuchimoto, Ito, & Toyooka, 1983;

Luhtanen, Rahkila, Rusko, Viitasalo, 1990; Norman et al., 1976). However, it is a controversial subject with varied results depending on how mechanical work and the metabolic cost are calculated. Efficiency is the biomechanical counterpart to running economy, but some have found a weak relationship between mechanical efficiency and economy (Gregor & Kirkendall, 1978; Norman et al., 1976).

Although there have been problems with mechanical efficiency, researchers have found some correlation between other biomechanical variables and factors related to running performance. For example, Williams and Cavanagh (1987) found that 54% of the variability in running economy can be explained by biomechanical variables. Anderson (1996) reports that running economy is correlated with height and body mass. The present study investigated the relationship between running economy and time in support and braking change in velocity.

Stride length and stride frequency. Stride length and stride frequency are important components in running as they determine the speed of the runner ($\text{velocity} = \text{stride length} \times \text{stride frequency}$). Increasing either will make the runner faster, although increasing stride frequency will usually result in a shorter stride length and may not change the speed. Similarly, increasing the stride length usually decreases the stride frequency, and there is little change in speed.

Brandon and Boileau (1992) found that runners with longer strides had faster 1500-meter and 3000-meter times. Daniels (1998) reported that elite runners averaged at least 90 strides per minute in distances ranging from 3000 meters to the marathon, while beginning runners have a stride frequency that is up to 15 strides per minute less than the elite runners. Also, Nelson and Gregor's (1976) longitudinal study found that nine of ten college runners tended to decrease their stride length and increase their stride rate over

the course of their four-year college careers. Because of information like this, some coaches have advised runners to increase their stride length or stride frequency (Anderson, 1994).

Coaching runners to change their stride length or stride frequency may not be beneficial as several studies have shown that runners are most economical when they freely choose their stride length (e.g., Cavanagh & Williams, 1982; Morgan et al., 1994). Apparently, runners can integrate all the relevant factors through processes related to perceived exertion to run at a stride length which minimizes energy cost. Messier et al. (1986) had runners intentionally overstride and understride, and the runners reported greater relative perceived exertion in both cases.

Despite these results, there may be some cases where changing stride length or stride frequency is helpful. Runners who overstride place their support foot too far forward (ahead of their center of gravity), and there is an increased braking effect resulting in deceleration. If the foot is too far back (understriding), there is an increase in stride frequency, but overall speed decreases (Ecker, 1985). Anderson (1996) hypothesized that overstriding requires a lot of power during propulsion which leads to excessive vertical oscillation of center of mass and a footstrike with a large braking force. Too high of a stride frequency may increase internal work due to an increased frequency of reciprocal movements such as arm swinging.

If a runner is overstriding or understriding, training and feedback can help optimize the freely chosen stride length (Morgan et al., 1994). A natural way to increase stride length may be strength training (Ecker, 1985).

Other kinematic factors. There have been numerous other kinematic factors related to running form which may influence running performance. Anderson (1996) reported

that elite runners have more acute knee angles during the swing phase while good runners plantar-flexed 10 degrees more during toe-off. He also reported that when compared to less economical runners, runners with better economy have a greater maximum angle of the thigh during hip extension, smaller knee angle at toe-off, greater maximum plantar flexion velocity and greater horizontal heel velocity at footstrike, slower thigh extension velocity, and lower knee flexion velocity. Williams and Cavanagh (1987) found that runners with better economy had a shank angle of greater deviation from vertical at footstrike, lower minimum knee velocity during support phase, more acute knee angles at midsupport, less plantar flexion at toe-off, and less arm movement.

There has been little work done on the effects of vertical oscillation on running performance. Gregor and Kirkendall (1976) studies of elite female marathoners indicated that better runners have less vertical oscillation, while Williams and Cavanagh (1987) reported a nonsignificant trend of more economical runners having a lower vertical oscillation. Luhtanen et al. (1990) explained that to increase running economy during the stance phase, runners should strive for an optimal path of center of gravity by lowering their center of gravity minimally with a small knee flexion during the eccentric phase.

Temporal aspects. There have not been consistent findings on the relationship between support time and swing phase time on running economy and performance. Nelson and Gregor (1976) found that runners improved their performance times and decreased their time in support when tested at the same speed throughout their four-year college careers. Williams, Cavanagh, and Ziff (1987) studied elite female marathoners and found that they spent less time in support than a group of novice runners running at the same speed. Paavolainen et al. (1999) found that highly economical, elite runners who did explosive strength training had shorter contact times than less economical, elite

runners who mainly did endurance training. However, Williams and Cavanagh (1987) found that there was no significant relationship between running economy and support time. The present study investigated how plyometric training affects time in support.

Ground reaction forces. Many studies (Keller et al., 1996; Munro et al., 1987; Nilsson & Thorstensson, 1989) have reported that increasing the speed of running increases the vertical ground reaction forces. However, there has been little research done on the relationship between ground reaction force curves and running performance. Williams and Cavanagh (1987) found that runners with better economy have more of a rearstriking pattern, which they hypothesized provides more cushioning than forefoot strike. This causes less demand on muscles. They also found that more economical runners had a significantly lower first peak for vertical ground reaction forces and a trend toward a smaller peak anteroposterior force and a smaller peak vertical ground reaction forces. Williams, Cavanagh, and Ziff (1987) found that when compared to novice runners, elite female runners have a lower first vertical peak and a higher second peak, a greater change in vertical velocity, and a higher peak braking force. In a related area, Kaneko et al. (1983) found that better runners have less change of velocity during contact with the ground. Martin (1997) reports that the most efficient runners decelerate the least at footstrike and get the maximum forward movement with every footstrike. The present study investigated if plyometric training decreased the braking change in velocity in runners.

Strength Training

Coaches have traditionally used a variety of training methods for their athletes. Typically coaches have mixed interval training and repetition training with long runs and tempo runs to improve running performance. There have been fewer reports of coaches using strength training with runners, particularly to train middle distance and distance runners. The current study focused on how strength training may improve distance running performance.

Definitions. There are numerous ways of describing strength. Strength has been defined as the “ability to develop force against an unyielding resistance in a single contraction of unrestricted duration” (Atha, 1981). Others have defined it as the maximum force or tension that can be developed (Martin, 1997; Radcliffe & Farentinos, 1999). How strength is defined also depends on how it is measured. Static strength is strength measured isometrically where muscle length does not change. Dynamic strength can be measured using the one-repetition maximum, or the maximum amount of weight that can be lifted one time. Explosive strength involves a fast, maximal effort which combines velocity and force (Atha, 1981). Strength is also related to power which is a combination of strength and speed. Power is the rate at which work is done and also equals force multiplied by velocity. It is the application of force through the range of motion within a unit of time (Radcliffe & Farentinos, 1999).

Strength can also be thought of as having three components: a muscular component, a neural component, and a mechanical component (Martin, 1997). The muscular component depends on the cross sectional area of the muscle, the muscle fiber length, and the muscle architecture (e.g., how much the myosin and actin overlap). The neural component involves how the stimulus strength and frequency influences motor

recruitment. The mechanical component (which cannot be changed) explains how force and lever arm distance result in the torque which produces limb rotation.

Weight training. Strength training has long been thought to be beneficial in sprinting as it is an explosive activity that utilizes fast-twitch fibers. For example, Delecluse et al. (1995) found that lifting free weights three days a week for nine weeks improved the acceleration of sprinters. Nummela et al. (1996b) found that maximum power increased by 3.4% in 400-meter runners who weight trained and did plyometrics for ten weeks. Delecluse (1997) wrote that strength, power, and speed are all important components of training for sprinters. Thus, strength training is beneficial as it can increase the hypertrophy of type II fibers, cause rapid recruitment of motor units, increase firing of motor neurons, and result in greater synchronization of motor neurons.

The benefits of strength training for sprinters may also be helpful to endurance performance. Weight training and circuit training three to five days per week for at least ten weeks has been shown to improve cycling and treadmill endurance time to exhaustion (Hickson et al., 1980; Hickson et al., 1988; Marcinik et al., 1991), improve two-mile run time by 15% (Hortobagyi et al., 1991) and improve ten-kilometer run times (Nicholson and Sleivert, 1999). Interestingly, the subjects in these studies and others (Hunter et al., 1987; Hurley et al., 1984) were able to improve without a significant change in their treadmill $\text{VO}_{2\text{max}}$. The improved endurance running performance in these studies may be due to an increased lactate threshold and running economy that some researchers found (Marcinik et al., 1991; Nicholson & Sleivert et al., 1999).

Other types of strength training. Other types of strength training that have been studied use the resistance of an athlete's own body weight to improve performance. Hill workouts and explosive strength training such as plyometrics fall in this category. Hebel

(1983) showed that regular downhill running can improve muscle peak torque and muscle endurance in knee flexors. Hill running has also been reported to increase power (Humphreys & Holman, 1985), increase spring in ankles, and develop power in the toes and feet (Hebel, 1983).

Plyometric training is another alternative to weight training. Sprinters who did nine weeks of plyometrics increased their acceleration, maximum speed, and 100-meter performance (Delecluse et al., 1995). Nummela et al. (1996a) found that weight training combined with plyometrics increased maximum power among sprinters. Paavolainen et al. (1999) and Turner et al. (1999) showed that plyometrics improved running economy. Paavolainen's subjects also significantly improved their five-kilometer run time.

Benefits of strength training. There are a variety of explanations of how strength training might enhance endurance performance. It seems counterintuitive that resistance training can benefit endurance performance as endurance training improves the ability to do low load, high-repetition exercise, while resistance training improves the ability to perform high load, low repetition exercise with seemingly little effect on endurance. To say that resistance training can benefit distance runners at first glance appears to violate the principle of specificity of training.

Typical training for distance running includes long, slow runs and shorter, faster interval training. These types of workouts increase capillary density so more oxygen can reach more parts of the working muscle, increase the size and distribution of mitochondria, and can lead to an increase in oxidative enzyme activity, which leads to a rate at which oxygen can be processed (Daniels, 1998; Tanaka & Swensen, 1998). Tanaka and Swenson also reported that endurance training decreases the size of type II fibers and changes the ratio of type IIa to type IIb fibers with IIa increasing in number

and IIB decreasing. Also, this type of training may decrease the maximum force generating capability of type I and IIA fibers. This may actually be beneficial as Tanaka and Swenson (1998) reported that it may increase fiber efficiency. This decreased force generating capability may help explain why some studies have found that endurance training hindered strength development (Dudley & Djamil, 1985; Hunter, et al., 1987).

Muscular benefits. Resistance training can increase muscle fiber size and possibly fiber number, and changes the ratio of type II fibers (Tanaka & Swenson, 1998). The percentage of type IIA fibers increase and IIB decreases. Tanaka and Swenson also reported that strength training has little or no effect on capillary density, may increase the glycogen content of trained muscles, and decrease the density of mitochondria (due to increased fiber size).

One of the benefits of supplementing endurance training with resistance training is that it may reverse some of the negative muscular changes of endurance training such as a possible decrease in fiber size (Tanaka & Swenson, 1998). It also may help reduce or reverse the decrease in force production due to a decrease in the velocity of shortening of muscle fiber from endurance training. Tanaka and Swenson asserted that faster, larger, and stronger fibers can generate more force. Thus, resistance-trained runners may be able to exercise longer at submaximal work rates by reducing the force contribution from each active myofiber or by using fewer fibers. Stone et al. (1991) agree that as each motor unit gets stronger with training, fewer motor units are needed to perform at a given submaximal workload. Tanaka and Swenson also state that stronger type I fibers may allow resistance- trained runners to delay recruitment of less efficient type II fibers. This hypothesis is supported by studies that found that strength training improves running economy (Turner et al., 1999). Also, Stone et al. (1991) reported that high volume

weight training can lead to a slight increase in aerobic power, a larger increase in anaerobic power, and an even greater increase in anaerobic capacity.

Neural benefits. In addition to the muscular benefits, there could also be neural benefits to using resistance training with distance runners. Strength training can cause motor units to become better synchronized and recruitable so more motor units are contributing with each working at a lower intensity (Sale, 1988). Also, changes in the nervous system could allow force to develop more rapidly by improving the ability of muscles to become stiff. Strength training may lead to an increased facilitation of the length-feedback component originating from the muscle-spindle which increases muscle stiffness, and by increased inhibition of the Golgi tendon which decreases muscle stiffness (Komi, 1986). Increasing muscle stiffness may be important in running as Komi, Salonen, and Jarvinen (1984) found that during moderate speed running, the Achilles tendon force reached four to five times body weight during support phase. This force was reached very rapidly, which implies that the stiffness of the triceps surae muscle must be very high during the support phase of running. Since these neural adaptations can lead to increased strength in as little as six to eight weeks, they have important implications for the present study where the training period lasted six weeks.

Plyometrics

A type of strength training that is becoming more popular among coaches is plyometrics. Plyometric training is a type of explosive strength training that involves an eccentric (lengthening) contraction immediately followed by a concentric (shortening) phase (Bompa, 1996; Chu, 1992; Radcliffe & Farentinos, 1999). It often involves some type of jumping exercise such as skipping, bounding, or hopping. It was first thought of as a secret Russian training technique. However, coaches have been using jump training

for many years. Track and field athletes in the 1920's and 1930's used jump training as part of their gym training (Bompa, 1993). In the 1950's and 1960's, Russian track and field coach Yuri Verkhoshansky used jumping exercises to train his sprinters and jumpers (Radcliffe & Farentinos, 1999). This type of training became more popular after it was used to train a Russian Olympic sprint champion, Valeri Borzov.

Although jump training is not new, it is just recently that the term "plyometrics" became popular. In the last ten years it has been used by football and basketball players, world class cross-country skiers, weight lifters, cyclists, track and field athletes, marathoners, and mountain runners. Who first used the word "plyometrics" is debated. Chu (1992) says the term was first used by Fred Wilt, an American track and field coach. Radcliffe and Farentinos (1999) state "plyometrics" first appeared in a 1966 paper by V.M. Zaciorskij, a Russian coach and exercise scientist. The origins of the term are also not agreed upon. Chu says plyometrics has Latin origins and means "measurable increases". Radcliffe and Farentinos state that it is derived from the Greek word "pleythyein" which means "to augment" or "to increase. "Plio" means "more" and "plyo" means "to move". "Metric" literally means "to measure".

Stretch-shortening cycle. It has been hypothesized that the reason plyometrics training is an effective training tool is related to elastic characteristics of muscles and the stretch-shortening cycle. Muscles in many movements (including gait) undergo a stretch-shortening cycle where an eccentric contraction that stretches muscle or muscle group is followed by a concentric contraction which shortens it (Radcliffe & Farentinos, 1999). This is exactly what occurs in plyometrics. Vertical jump studies by Cavagna, Komarek, Citterio, and Margaria (1971) and Cavagna, Zamboni, Faraggiana, and Margaria (1972) showed that muscles will contract more forcefully and quickly from a prestretched

position. These studies also showed that the more rapid the prestretch, the more forceful the subsequent concentric contraction. The stretch response is the property of a muscle tissue that enables greater muscular tension. As the parallel components of muscle fibers increase beyond resting length the tension in them increases (Radcliffe & Farentinos, 1999). This lengthening usually involves a prestretch (such as landing and then taking off again in hopping) where muscles move in the opposite direction of the desired force application.

The muscle spindle reflex also plays a role in plyometrics. When the muscle spindle detects a lengthening of the muscle, an impulse is sent to the spinal cord and then motor impulses are transmitted back to the stretched muscle causing it to contract (Bompa, 1996).

Plyometrics may enhance activation of neuromuscular components and increase efficiency of neural actions and muscular performance (Radcliffe & Farentinos, 1999; Paavolainen et al., 1999). Explosive strength training may cause alterations in neural control during stretch-shortening exercises of running in both voluntary activation and inhibitory and/or facilitatory reflexes (Paavolainen et al., 1999). Then muscle groups may increase their ability to respond more quickly and powerfully to little and quick changes in muscle length (Radcliffe & Farentinos, 1999). Thus, plyometrics enables faster and more powerful changes of direction which occur with each running step. The present study investigated if these changes result in less time in support and a decreased change in braking velocity during the support phase of running. Explosive strength training such as plyometrics may also lead to an increase activation of motor units. Since these are neural changes, this type of training may lead to improvements in just a few weeks with less hypertrophy than what is associated with weight training (Paavolainen et al., 1999).

Given the neural benefits of plyometrics, it may also have a positive effect on muscle power. This is "the ability of the neuromuscular system to produce power during maximal exercise when glycolytic and oxidative energy production are high and muscle contractility may be limited" (Paavolainen et al., 1999). This improved muscle power could be especially beneficial to cross-country runners climbing hills in the middle of a race or striving to have a strong finish when they are already fatigued.

Elastic energy return. Another potential benefit of plyometrics is that it may improve athletes' ability to utilize elastic energy return. The range of elasticity of a muscle is the ability of a muscle to change in length and in tension. It is proportional to the ability of a tissue to resist forces and return to its original shape upon releasing a load (Radcliffe & Farentinos, 1999). Cavagna (1977) wrote a classic paper on the storage and utilization of elastic energy in skeletal muscle that many others have cited. He found that muscles forcibly stretch and brake as well as propel the body. The change in length of muscles is in the opposite direction of the force developed by the muscle. When muscles are forcibly stretched, negative work is done by the muscle so mechanical energy is absorbed by the muscle. Much of this stored mechanical energy is often transferred into heat energy (when the muscle relaxes), but some of it can be used during subsequent active shortening.

Cavagna (1977) describes several pieces of evidence that support the idea that muscles use stored elastic energy based on his review of vertical jump and gait studies. First, following an eccentric contraction there is an increased mechanical efficiency of positive work done (Cavagna & Kaneko, 1977). Recall mechanical efficiency equals the ratio of positive work done to the chemical energy to do the work. Efficiency may increase following a lengthening of the muscle because part of the positive work comes

from the recoil of elastic elements, not just from the muscle converting chemical energy to mechanical energy. Also, there is power enhancement. When shortening follows a stretching, the force production is high from the beginning of the movement so there is a greater acceleration of the mass (Cavagna & Kaneko, 1977). There is also a greater amount of positive work done by a muscle when it shortens immediately after stretching than when it shortens from an isometric contraction. Cavagna (1977) cautions that the muscle does not behave as a simple spring since its elasticity changes, due to the stretching which leads to a greater compliance during subsequent shortening. Thus, the amount of elastic energy delivered immediately after stretching for a given force is greater (up to two to three times greater) than when shortening takes place from a state of isometric contraction. In counter-movement jumps, Komi and Bosco (1978) found that subjects were able to utilize 50-90% of the energy absorbed in the stretching phase. They also found further evidence of elastic energy return in drop jumps. They found that as dropping height increased, subjects were able to jump higher indicating a greater storage of elastic energy.

The elastic energy return is greatest when there is a minimum time delay between lengthening and shortening (Komi & Bosco, 1978) and the lengthening tension is not too great (Cavagna, 1977). Cavagna stated that if there is a long time delay between lengthening and shortening, the force at the end of the muscle-spring decreases, wasting part of the elastic energy as heat. Also, the greater compliance induced by the previous stretching tends to be reduced in the interval between stretching and shortening.

Elastic energy return is important in running as it occurs with each step. Negative work is being done as the foot contacts the ground during an eccentric contraction. Positive work is being done as the muscle shortens to push-off. Thus, elastic energy

stored during eccentric contractions contributes to propulsion (Cavagna & Kaneko, 1977). There is evidence that actomyosin crossbridges and tendons are storage sites of elastic energy, and that the achilles tendon and the tendon in arch of the foot can store up to 35% and 17% of the available energy, respectfully (Ker et al., 1987; Cavagna & Citterio, 1974). Williams and Cavanagh (1987) found that runners could realize as much as a 47%-62% energy savings (in $\dot{V}O_2$) due to elastic energy return since their subjects had a 24% savings in $\dot{V}O_2$ during knee bend experiments and since ground reaction forces in running are two to three times larger with a time duration half as long. Some researchers feel that varying abilities to store and release elastic energy may explain individual differences in running economy (Anderson, 1996).

Plyometrics can be effective when used with endurance run training because it involves eccentric contractions shortly followed by concentric contractions. This is what occurs with each running stride. Runners can learn to optimize their running by exploiting free elastic energy and minimizing metabolic requirements. Optimization demands precise timing and integration of temporal, kinematic, and kinetic elements which come from practice and timing (Anderson, 1996). Plyometrics provides this type of training. It can help with the timing and integration of muscle activity so elastic energy is stored and reused more effectively. Anderson also states that the balance between eccentric and concentric contractions may influence running economy since elastic energy is stored during eccentric contractions which are less costly than concentric contractions. The economy of movement can be increased by changing temporal patterns of movement, which also may help use elastic energy more effectively. The idea that plyometrics may improve elastic energy return in runners provides support for the

hypothesis in the present study that the subjects in the plyometric group will improve their running economy more than the subjects in the running-only group.

The changing temporal patterns of movement may appear in the support phase of running. Paavolainen et al. (1999) found that elite endurance runners who supplemented their regular run training with nine weeks of explosive strength training (including plyometric exercises) significantly reduced contact time during the support phase while running at a constant speed. The reduction in contact time was observed to be significant even after just six weeks of training. The control group of elite runners who did just the regular run training had a small increase in contact time during the same time period. A reduction in contact time may be beneficial to runners as Kram and Taylor (1990) found an inverse relationship between rate of energy used for running and time in support.

In summary, plyometric training may develop the nervous system so that it will react quickly to the lengthening of the muscle so that the muscle can shorten rapidly with maximal force and with the greatest utilization of elastic energy. This type of strength training may also reverse some of the negative muscular changes of endurance training and increase the strength of each motor unit so fewer motor units are needed to perform at a given submaximal workload. During the present study, the experimental group replaced some of their regular run training with plyometrics to investigate how some of these neural and muscular changes affect certain biomechanical and physiological factors such as support time, braking time, braking change in velocity, running economy, lactate threshold, and $\text{VO}_{2\text{max}}$. These factors may in turn lead to improved running performance. This study attempted to give a biomechanical and physiological explanation as to why running performance may improve with plyometrics training.

CHAPTER THREE

Methods

Research Design

The research design for this study was a nonequivalent control group pretest-posttest design (Thomas & Nelson, 1996). The independent variable was the type of training program with the treatment group (PLYO) replacing some of its run training with plyometric training two to three times per week and the control group (RUN) participating in only run training.

Several threats to internal validity should be considered. Many of these threats such as history, maturation, testing, statistical regression, subject selection, and participants dropping cross-country were controlled for by randomly assigning participants to the two groups. For example, the history effects were partially controlled for as participants were randomly assigned to two groups and participants on each high school team practiced together except for the plyometrics training sessions. However, the history of the participants was still a problem as some of the athletes chose to train outside of practice by running extra or by lifting weights. Also, some participants were involved in other sports such as biking as well as cross-country.

Testing could also have been a problem if many participants in one group ran poorly in the time trial portion of the pretest because of inexperience, not knowing how to pace themselves at this distance, for example. They may have improved greatly on the posttest

partly because of their improved knowledge of how to pace themselves; experienced athletes would not have this advantage.

Subject selection could also be a problem if one group was comprised of more physically fit people, which might make it more difficult for the fit participants to improve factors such as their performance times and VO_{2max} as unfit participants. Different levels of physical fitness were controlled for by using a matched-pair technique (Thomas & Nelson, 1996). Participants from each school were paired based on the number of years of previous competitive running experience and number of weeks run in the previous six weeks. Then each pair was randomly assigned to the treatment and control group. To help eliminate problems with fatigue during testing, participants were asked to have at least one easy day of training before the 3200-meter run and before the treadmill test.

Although many of the threats to internal validity were controlled by randomly assigning participants to the two groups, external validity could be a problem as the participants were not randomly chosen from all high school cross-country teams in the United States. So the results may be generalized only to high school students from similar types of large, urban schools whose cross-country coaches follow a similar training program as those in the study.

Participants

Cross-country coaches from mid-Michigan high schools were contacted in the spring of 2000 to determine their interest in seeking runners to participate in the study. Coaches from three area boys and girls high school cross-country teams expressed interest. Two of the schools are part of a large urban district, while the third is in a large

suburban district. All schools are class A schools, the classification for the most populous schools (more than 1100 students) in Michigan.

Approximately 50 runners received information about the study in July 2000 before one of their summer conditioning practices. Eighteen athletes volunteered to participate in the study. After completing a questionnaire on their running history (Appendix A), these subjects were paired based on their previous running experience and current fitness levels and randomly assigned to either a plyometric group (PLYO) or a running-only group (RUN). Two subjects did not complete the six-week study, which left PLYO with seven subjects (six males and one female) and RUN with nine subjects (seven males and two females). The participants and one of their parents or legal guardians were required to sign a consent form. Note: The consent form in Appendix H indicates that the participants would run five kilometers for the running performance tests, although they actually ran 3200 meters. This study was approved by the Michigan State University Committee on Research Involving Human Subjects.

General characteristics of the participants are summarized in Table 3.1. PLYO and RUN were represented by runners of similar ages, heights, and weights. The groups were also similar in years of prior running experience and prestudy running. Prestudy running is the number of weeks in the subjects ran at least three times per week in the six weeks prior to the beginning of the study. It is an indication of how much time they took off after their last period of regular running (spring track season for many of subjects).

Intervention

Run training. Both groups followed the training programs directed by the coaches at their schools. In general these programs consisted of two to three medium-hard to hard, continuous runs of four to nine miles each week, and one day of two to three miles of

interval training (intervals ranging from 400 meters to 1000 meters). “Hard” workouts were often alternated with “easy” two to four mile runs.

Table 3.1. Characteristics of Participants

	PLYO (n=7)		RUN (n=9)	
	Mean (SD)	Range	Mean (SD)	Range
Age (yrs)	15.9 (1.4)	14-18	16.4 (.73)	16-18
Height (cm)	174.9 (8.3)	162.5-186.6	172.1 (9.5)	152.1-184.1
Pretest weight (kg)	64.7 (10.0)	51.5-83.7	61.8 (7.6)	47.7-69.8
Posttest weight (kg)	64.9 (9.1)	54.7-83.1	61.2 (7.6)	47.0-70.4
Run Experience ^a (yrs)	2.7 (1.3)	2-5	2.8 (1.5)	0-5
Prestudy running ^b (wks)	4.9 (2.2)	0-6	4.5 (1.7)	2-6

^aNumber of years of competitive running prior to study. ^bNumber of weeks running in six weeks prior to study.

Two to three times a week the plyometric group replaced some of their run training with 15-20 minute plyometric training sessions. This frequency has been suggested to be optimal by several researchers (Bompa, 1996; Chu, 1992; Radcliffe & Farentinos, 1999). Some coaches and authors (Radcliffe & Farentinos, 1999) suggested that plyometric training be done on “easy” days so that muscles will not be fatigued during other parts of practice. However, if high intensity practices are preceded and followed by plyometrics on the “easy” days, then muscles will not have time to recover as the anaerobic alactic and lactic systems using glycogen as fuel are taxed every day (Bompa, 1996). In the current study, plyometrics were usually done on designated “hard” days as Bompa recommended. This gives the body at least 48 hours to recover from the high intensity practice and enabled the participants to give maximal, quality efforts at each plyometric

training session. During these training sessions, participants in RUN did an easy run so that training volume would be similar for both groups.

Plyometric training sessions were conducted by the researcher the first two weeks. The remaining sessions were monitored by the coaches with the researcher assisting periodically. Coaches were given a chart with the specific exercises for their runners to do each day and a description of each plyometric exercise (see Appendices B and C). Three subjects did much of their plyometric training on their own due to conflicts with their team's practice schedule, so they were given the same information on plyometrics as the coaches.

Plyometric training. Some basic rules should be followed when doing extensive plyometric training. Plyometrics exercises should be done on soft surfaces such as grass or dirt following a thorough warmup. Athletes should be somewhat flexible and have a good overall fitness level (Radcliffe & Farentinos, 1999). Also, eccentric training such as plyometrics can be stressful to muscle cells and should be introduced gradually. Thus, Bompa (1996), Chu (1992), and Radcliffe and Farentinos (1999) recommended that plyometrics training should gradually progress from simple, low-intensity, low-impact exercises to more complex, higher-intensity, high-impact exercises (see Table 3.2).

Radcliffe and Farentinos (1999) teach that training should undergo a "progressive overload" that gradually changes the weight or load, the height or distance jumped, and how rapidly and intensely the exercise is done. This philosophy was followed in the context of the six-week training period as well as in individual training sessions. For example, depth jumps should not be introduced at the beginning of intervention, nor should they be the first exercise done during a training session in the sixth week of plyometrics training.

Table 3.2. Plyometric Exercises Used in Present Study

Intensity Level		
<i>Low</i>	<i>Moderate</i>	<i>High</i>
Jumps		
Pogo	Double-leg butt kick	Single-leg stride jump
Squat jump	Split jump	Stride jump crossover
Box jump	Scissors jump	Depth jump
		Box jump (multiple response)
Bounds and Skips		
Prancing	Single-leg stair bound	
Galloping	Alternate-leg stair bound	
Speed skipping	Alternate-leg bound	
Ankle flip	Power skipping	
Hops		
Hurdle hops	Single-leg butt kick	Single leg speed hop
Double-leg speed hop	Single-leg hop for height	Hurdle hops (multiple response)
Richochets		
Stadium hops		

Note. Names of exercises are from Bompa (1996), Chu (1992), and Radcliffe and Farentinos (1999).

Because of the explosive nature of plyometrics, a full recovery between sets is important so that each set can be done with proper technique and at a high enough intensity (Bompa, 1996). Chu (1992) recommended a work to rest ratio of 1:5 up to 1:10. So ten seconds of exercise would be followed by 50 to 100 seconds of rest. Less recovery can be given between sets if the goal is to develop muscular endurance, as long as the athletes are still using proper technique. Radcliffe and Farentinos (1999) recommended one to two minutes of rest between high intensity sets, and 30 to 60 seconds between sets of low impact exercises. These rest times allow neuromuscular systems to recuperate.

In order for plyometrics to be effective, athletes need to use proper technique. It is important for the eccentric contractions in these exercises to be quickly followed by a concentric contraction; that is there should be a short amortization phase. Amortization is the time from the beginning of the eccentric contraction to the beginning of the concentric contraction (Radcliffe & Farentinos, 1999). If amortization is slow, more stored elastic energy is converted into heat and less energy is used in the concentric action (Cavagna, 1977). As a result of slow amortization, Cavagna found that the force developed by the muscle decreased since part of the stored elastic energy is wasted. Plyometrics can be used to train athletes to have a shorter amortization phase so they can utilize this stored energy better, which may result in greater force and power in the muscle and a decreased energy cost (Farentinos & Radcliffe, 1999).

Participants and their coaches were taught techniques that would enable the athletes to have short amortization phases. They were taught to have short, quick, landings with minimum knee flexion and contact time. Also, they were instructed to maintain a locked ankle upon landing and to land with a dorsiflexed foot and two-thirds to a full foot ground contact (Radcliffe & Farentinos, 1999). They were told to put more weight on the front of the foot and to not roll from heel to toe. To ensure proper technique, “single-response drills” were used when introducing a new exercise (Radcliffe & Farentinos, 1999). In these drills one intense effort is done, and then the athlete is stopped and checked for technique. For example, when doing a simple jumping exercise, athletes would take-off, land, and pause while the coach or researcher checked for proper posture, balance, and stability. Then the drill was repeated. In “multiple-response drills” the exercise was repeated many times. Emphasis was placed on having a short, quick landing, followed by a rapid, powerful take-off. Note that Williams et al. (1987) found

that more economical runners were able to dorsiflex their ankle faster and to a greater angle during support. Developing proper technique is important.

Plyometric exercises that were used in this study are listed in Table 3.2. They have been chosen because of their potential to develop power in the extensors and flexors in the legs, hips, and torso, which Martin (1997) states are important in running. Also, Radcliffe and Farentinos (1999) identified many of these exercises as being particularly beneficial for runners. Most of the names for these exercises are from Radcliffe and Farentinos' (1999) plyometrics book, although others (Bompa, 1996; Chu, 1992, Martin, 1997; Paavolainen et al., 1999) have used similar exercises with different names. Figure 3.1 and Figure 3.2 illustrate two of these exercises.

All of these exercises were not done every training session. Four to six exercises were selected for each plyometrics session depending upon the complexity and intensity of the exercises selected. Each training session included exercises from each category (jumps, bounds and skips, and hops). Each exercise consisted of two to four sets of 4-10 repetitions. Quality was emphasized over volume. If athletes could not do four sets at high intensity, they were instructed to do just three sets. Bounds and skips were done over a 30 to 50 yards distance instead of using repetitions. Again, over the six-week treatment period, the intensity of exercises increased from low to high. However, even when doing high intensity exercises, some low intensity exercises were done as warmups.

Data-Collection Procedures

There were three parts to the data-collection: treadmill test, biomechanics evaluation, and a test of running performance. Data was collected in two sessions separated by at least one day. The test of running performance was done in session one. The treadmill test and biomechanics evaluation were done during session two.



Figure 3.1. Photograph of cross-country runners skipping.



Figure 3.2. Photograph of a subject performing hurdle hops (with tires).

Treadmill test. The treadmill test was done at the Human Energy Research Laboratory at Michigan State University. Subjects began running at a pace that was below their lactate threshold velocity. Then they were in a steady state so lactate threshold was not a confounding variable in measuring running economy. The starting

speed was set at four stages (2 mi/hr) below the speed at which lactate threshold was predicted to be reached. Each subject's lactate threshold (LT) velocity was predicted by the following equation (adapted from Weltman et al., 1987) using the subject's 3200-meter time on the pretest:

$$\text{LT velocity} = [493 - 22.78 \times (3200\text{-m time})] \times 60/1609.$$

The same initial starting speed was used on the posttest. Subjects ran at the initial speed for five minutes. The next stages were three minutes long with the speed increasing by 0.5 mi/hr each stage. After each stage the treadmill was stopped for one minute while a fingertip blood sample was obtained. The three-minute stages continued until it was determined that lactate threshold had been reached. Then the speed was kept constant while the grade was increased by 2% every minute until $\text{VO}_{2\text{max}}$ was reached. Blood lactate levels were analyzed with a Yellow Springs Instruments 2300 Stat Plus automated blood lactate analyzer (Yellow Springs, OH). Lactate threshold was determined to be reached if there was a significant increase (greater than 0.3 mmol/L) from baseline lactate levels on two consecutive stages. Ventilation and VO_2 were recorded every minute from the average of three consecutive 20 second measurements from a Sensor Medics 2900 metabolic measurement cart (Yorba Linda, CA). Running economy was determined by averaging the VO_2 values the last two minutes of the initial five-minute stage. $\text{VO}_{2\text{max}}$ was determined as the largest mean VO_2 value obtained during three consecutive 20-second VO_2 measurements. Heart rate was continually assessed by a heart rate monitor (Polar Advantage).

Biomechanics evaluation. Measurements of component forces and temporal data were obtained in the Biomechanics Research Station at Michigan State University using a

0.51 x 0.56 m AMTI force platform (Waterton, MA). Figure 3.3 shows a photograph of the biomechanics testing area.

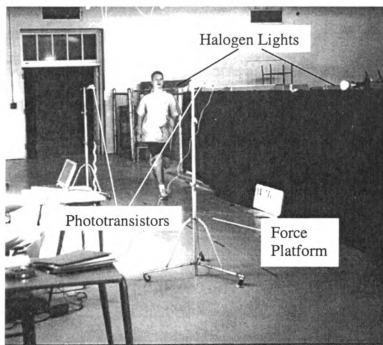


Figure 3.3. Photograph of biomechanics testing area.

Data was sampled at 1000 Hz and amplified with an AMTI amplifier. The force platform was mounted flush with a 15-meter wooden platform. Some subjects used a longer runup by running down a hallway and up a six inch high ramp onto the testing area. Phototransistors (Vernier Software) paired with halogen lights were placed two meters on either side of the force plate to verify speed. Figure 3.1 illustrates the testing area.

Subjects were videotaped while running and were told that the videotape would be used to conduct a biomechanical evaluation of their running form. They were not informed of the presence of the force platform. Subjects were instructed to run as naturally as possible across the testing area at a constant speed of 3.8 m/s (7:04 min/mi).

After several practice runs, each subject ran across the testing area 20 to 50 times in order to achieve the goal of ten acceptable trials. Subjects were asked to move their starting position forward or backward if the researcher noticed that they missed the force platform. Acceptable trials were those where the subject's entire foot landed on the force platform without a noticeable adjustment of stride and the subject was within 5% of the test speed. The actual number of acceptable trials for each subject ranged from 4 to 18 trials. Force-time histories for all three orthogonal directions were recorded on a computer (Ariel Dynamics) and analyzed with Ariel Performance Analysis System (APAS) software.

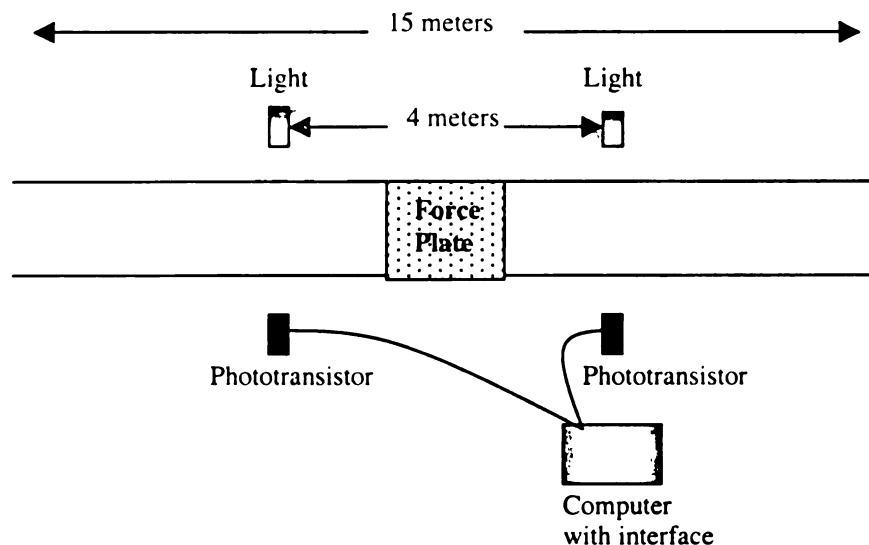


Figure 3.4. Biomechanics testing area.

Performance test. The running performance test was conducted at the subjects' high schools. Participants ran 3200 meters (eight laps) on their high school track. All

participants started together and were given split times at the end of each lap. Times were measured with a Timex Ironman chronograph.

Data Analyses

Means and standard deviations were calculated on each variable using standard methods. Correlation coefficients were calculated to determine relationships among variables. To determine if there was an overall effect of the intervention on the primary dependent variables, 3200-meter time, running economy, VO_{2max} , time in support, and braking change in velocity were analyzed with multiple analysis of variance (MANOVA) using Pillai's trace test statistic. If there was a significant F-value, analysis of variance (ANOVA) was calculated on each dependent variable to determine differences within groups or between groups. Alpha was set at 0.10 for MANOVA and for each ANOVA test.

CHAPTER FOUR

Results

Training

The participants in the plyometric group (PLYO) reported completing an average of 13 ± 3.6 of the 15 scheduled plyometric training sessions. Participants in both groups ran about the same number of miles per week (PLYO- 25.4 ± 7.8 ; RUN- 27.3 ± 12.42). However, the large variability of average miles run per week within groups should be noted. Individuals' average weekly mileage during the six-week training period ranged from 12-34 miles per week in PLYO and 9-47 miles per week in RUN. There was also a large variability of miles run by subjects in individual weeks throughout the training period. One subject in each group reported running 0 miles one week, while a subject in RUN reported running 80 miles one week. The maximum number of miles run in one week reported by a subject in PLYO was 54 miles. Details of individual training data is in Appendix D.

Results of Significance Tests

All sixteen subjects completed the biomechanical and physiological tests. However, lactate threshold velocities were not obtained for everyone. On the posttest a time for running 3200 meters was not obtained for one subject in PLYO and two subjects in RUN due to scheduling conflicts and an injury.

To determine an overall effect of the primary dependent variables, running economy, VO_{2max} , 3200-meter time, support time, and braking change in velocity were

analyzed with MANOVA using Pillai's trace test statistic. Results show there was a significant main effect of Time, $F(11,4) = 1725, p < .0001$. Thus, when examined as a whole, there was some change in the dependent variables from pretest to posttest. There was not a significant main effect of Group or of the Group by Time interaction.

The five dependent variables were then each analyzed in a Group (PLYO vs. RUN) x Time (Pretest vs. Posttest) two-way mixed ANOVA. There was a main effect of Time for running economy, $F(1, 14) = 44.47, p < .0001$, 3200-meter time, $F(1,14) = 8.13, p = .013$, and braking change in velocity, $F(1, 14) = 6.19, p = .026$. There was also a Group x Time interaction effect for braking change in velocity, $F(1, 14) = 3.31, p = .09$. There were no significant differences between groups on any of the other dependent variables.

Correlations

Correlations were calculated between the different dependent variables and changes in dependent variables from pretest to posttest. There were high correlations between 3200-meter time and lactate threshold velocity ($r = -.84$ on pretest; $r = -.92$ on posttest), and moderately high correlations between 3200-meter time and VO_{2max} ($r = -.65$ on pretest; $r = -.79$ on posttest). The participants with the higher lactate threshold velocities and VO_{2max} , tended to have lower 3200-meter times.

There was a moderate correlation ($r = -.42$) between change in lactate threshold velocity and change in 3200-meter time. Participants who displayed a greater increase in lactate threshold velocity from pretest to posttest tended to have a greater decrease in their 3200-meter time from pretest to posttest. Also, there was a moderate correlation ($r = .43$) between the change in 3200-meter time and previous years of running experience.

Participants who had spent more years training for running tended to have less change in 3200-meter time from pretest to posttest.

There was also a moderate correlation between lactate threshold velocity and braking time ($r = .40$) on the posttest, but there was no relationship between these variables ($r = .04$) on the pretest. There was a low correlation between 3200-meter time and support time ($r = -.39$) on the posttest, but there was no relationship between these variables on the pretest. However, there was a moderate correlation ($r = .45$) between the change in 3200-meter time and change in support time. Larger decreases in support time were associated with larger decreases in 3200-meter times. There was low correlation ($r = .22$) between lactate threshold velocity and support time. There was no relationship ($r < 0.20$) among the other variables.

Performance Variable

Means and standard deviations of 3200-meter times are summarized in Table 4.1. The participants significantly improved ($p < 0.10$) their time to run 3200 meters from pretest to posttest. The plyometric group's average 3200-meter time improved by 31 seconds or 3.9%, while there was a 69 second or 8.0% improvement in RUN. Improvements in individual 3200-meter times ranged from 5 seconds to 69 seconds in PLYO, and ranged from 12 seconds to 5 minutes 9 seconds in RUN. The subject in RUN who decreased her 3200-meter time by more than five minutes had no previous competitive running experience. One subject in PLYO ran six seconds slower on the posttest while a subject in RUN ran 13 seconds slower. Individual results for 3200-meter times are listed in Appendix E.

Table 4.1. Mean 3200-meter Times Before (Pretest) and After (Posttest) Six Weeks of Training

Group	Pretest		Posttest	
	Mean 3200-m time (min:sec) (SD)	Range	Mean 3200-m time (min:sec) (SD)	Range
PLYO ^a	13:16 (1.25 ^b)	11:27- 16:05	12:45 (1.09)	11:22- 14:53
RUN ^c	13:51 (2.8)	11:31- 20:24	12:42 (1.8)	11:03- 16:12

^an = 7 on pretest, n = 6 on posttest. ^bStandard deviations for 3200-meter times are in minutes. ^cn = 9 on pretest, n = 7 on posttest.

Biomechanical Variables

Problems with biomechanics data. During testing a good trial was defined as a trial where the subject ran within 5% of the preestablished running speed, and the subject's entire foot landed on the force plate without a noticeable adjustment in stride. Subjects ran up to 50 trials in order to obtain the goal of ten good trials. Due to time constraints, the actual number of good trials obtained for each subject ranged from four to eighteen trials.

An additional criteria for an acceptable trial was that the subject's horizontal velocity from initial contact to departure from the force platform was approximately unaltered. This means that the braking change in velocity ($B\Delta V$) and the propulsion change in velocity ($P\Delta V$) were approximately equal. If $B\Delta V$ were greater than $P\Delta V$, then the subject was decelerating across the force plate. If $P\Delta V$ were larger, then the subject was accelerating across the force plate. Figure 4.1 illustrates how accelerating and decelerating affected anteroposterior ground reaction force curves.

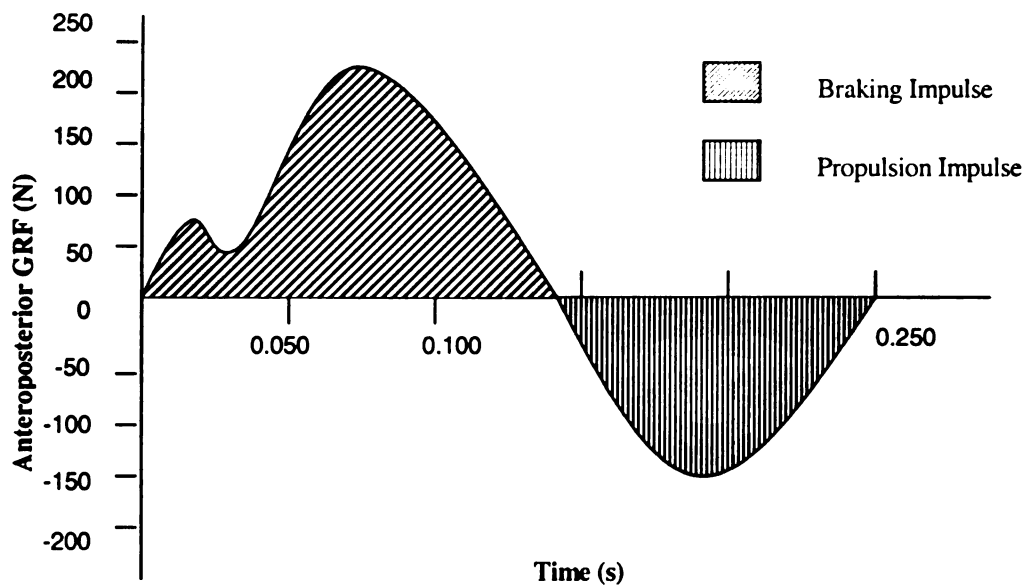


Figure 4.1a. Example of deceleration across the force platform: braking impulse (area under the curve) is greater than propulsion impulse.

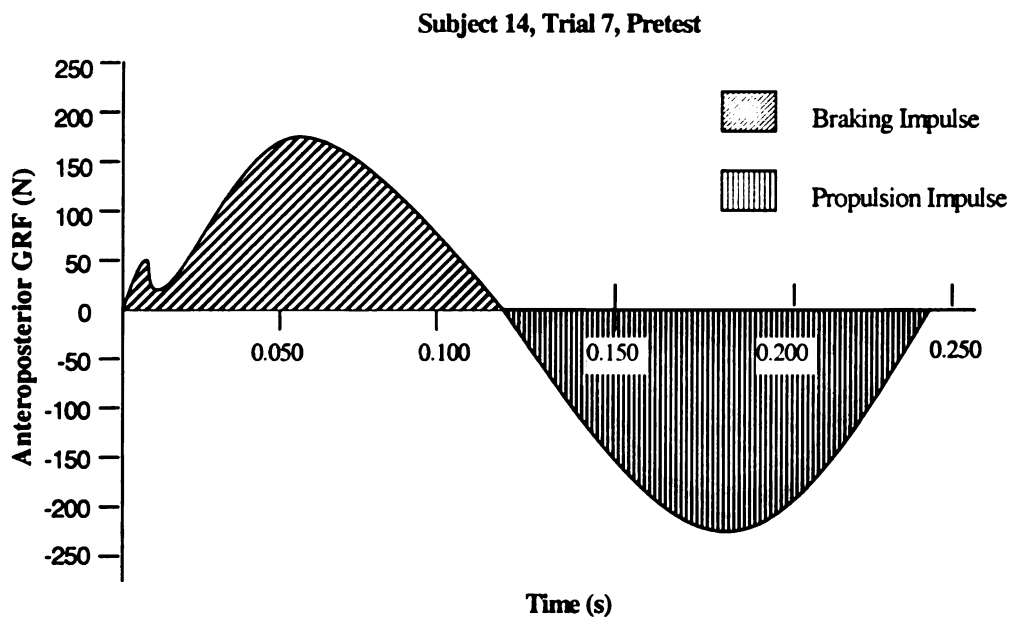


Figure 4.1b. Example of acceleration across the force platform: braking impulse (area under the curve) is less than propulsion impulse.

Figure 4.1. Examples of anteroposterior ground reaction force-time histories.

If $P\Delta V$ was within 25% of $B\Delta V$ the subject was considered to be running at an approximately unaltered speed. This criteria reduced the number of acceptable trials considerably. Fourteen of the sixteen subjects performed at least one trial where $B\Delta V$ and $P\Delta V$ were within 10% of each other on the pretest and posttest. On the remaining two subjects' best trials (in terms of $B\Delta V$ and $P\Delta V$ difference), there was a difference of 18% and 23% between $B\Delta V$ and $P\Delta V$.

Another problem with analyzing the biomechanical data is the large variability that each subject displayed from trial to trial on numerous biomechanical variables. An example of this variability is shown in Table 4.2 with one subject's pretest data. This subject ran through the testing area 32 times, and he had 12 trials (shown in Table 4.2) where his entire foot landed on the force platform. Although these trials were run at approximately the same speed (3.7 - 3.9 m/s) through the testing area, there was still some variability between trials on many biomechanical variables. For example, support time (ST) ranged from 0.250 seconds to 0.275 seconds, while $B\Delta V$ ranged from 0.17 m/s to 0.33 m/s. The variability in this subject's data was typical of other subjects in the study.

Due to the large variability between trials of individual subjects, it is not appropriate to average just the best two or three trials and use that value for further analysis. Since it is assumed that all subjects were running at the same constant speed, it was decided that the best representation of each subject's ground reaction force data was the trial where the propulsion change in velocity had the least percentage difference from the braking change in velocity. If two trials had the same percentage difference between

B Δ V and P Δ V, then the trial with the lower braking change in velocity was used.

Therefore, only one trial for each subject on the pretest and posttest was analyzed further.

Table 4.2. Ground Reaction Force Pretest Data for Subject Number 14

Trial	ST (s)	BT (s)	BT as % of ST	1st Vert. Peak (N)	2nd Vert. Peak (N)	B Δ V (m/s)	P Δ V (m/s)	% diff. ^a
7	0.259	0.123	47	782	1355	0.17	-0.27	59
8	0.275	0.138	50	776	1309	0.22	-0.23	5
9	0.271	0.141	52	782	1321	0.22	-0.23	5
11	0.262	0.131	50	759	1355	0.18	-0.27	50
12	0.250	0.137	55	880	1292	0.22	-0.20	-9
13	0.255	0.123	48	747	1378	0.17	-0.26	53
16	0.260	0.132	51	718	1321	0.20	-0.25	25
18	0.269	0.133	49	660	1373	0.18	-0.28	56
23	0.251	0.147	59	1112	1251	0.33	-0.12	-64
26	0.254	0.142	56	857	1303	0.26	-0.18	-31
29	0.261	0.143	55	724	1321	0.24	-0.19	-21
31	0.267	0.133	50	794	1297	0.20	-0.23	15
Mean	0.261	0.135	52	799	1323	0.22	-0.23	12
SD	0.008	0.008	0.03	115	37	0.05	0.05	0.39

Note. ST = Support time; BT = Braking time.

^a% Diff. is the percentage difference between B Δ V and P Δ V;

$$\% \text{ Diff} = (|P\Delta V| - B\Delta V) / B\Delta V$$

Biomechanics results. All subjects' pretest data were combined in order to compare this study to data from other studies. Subjects were in the support phase an average of 0.247 seconds, with the transition from braking to propulsion coming at 50.3% of stance. The second vertical peak ground reaction force was 2.5 times body weight. The mean braking change in velocity for all subjects was 0.24 m/s. These values are comparable to results from other studies where subjects ran at similar speeds to those in the current study (Keller et al., 1996; Munro et al., 1987; Nachbauer & Nigg, 1992).

Means and standard deviations of three biomechanical variables for both groups on the pretest and posttest are listed in Table 4.3. As a whole, the participants significantly decreased ($p < .10$) their braking change in velocity (B Δ V) from pretest to

posttest. Six of the seven subjects in PLYO decreased their braking change in velocity from pretest to posttest while the remaining subject had no change. Overall, there was an 8% decrease in BΔV in PLYO over the training period. Five of the nine subjects in RUN decreased BΔV, two increased BΔV, and two had no change. As a group, there was no change in BΔV in RUN. There was a trend of support time (ST) decreasing (3.2%) over the training period in PLYO while there was no change in support time in RUN. Five of the seven subjects in PLYO decreased time in support, while five of nine subjects in RUN decreased time in support. There was little change in braking time (BT) in either group.

Table 4.3. Biomechanics Variables Before (Pretest) and After (Posttest) Six Weeks of Training

Variable	PLYO (n = 7)				RUN (n =9)			
	Pretest		Posttest		Pretest		Posttest	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
ST (s)	0.249 (0.027)	0.228- 0.295	0.241 (0.027)	0.205- 0.289	0.245 (0.024)	0.201- 0.280	0.245 (0.023)	0.219- 0.270
BT (s)	0.122 (0.015)	0.102- 0.144	0.121 (0.007)	0.112- 0.133	0.125 (0.013)	0.114- 0.141	0.126 (0.013)	0.109- 0.146
BΔV (m/s)	0.25 (0.03)	0.23- 0.29	0.22 (0.04)	0.17- 0.26	0.23 (0.03)	0.20- 0.29	0.23 (0.03)	0.18- 0.28

Note. ST = Support time; BT = Braking time; BΔV = Braking change in velocity.

Physiological Variables

Physiological data is summarized in Table 4.4. As a whole, the participants displayed a significant improvement in running economy ($p < .10$) from pretest to posttest. Running economy improved by 4.7% in PLYO and by 6.8% in RUN. Changes

in running economy among individuals in PLYO ranged from 0.73 to 2.44 ml/kg/min and ranged from 0.90 to 4.73 ml/kg/min among individuals in RUN.

Lactate threshold velocities were obtained on both the pretest and posttest on six of seven subjects in PLYO and seven of nine subjects in RUN. Some subjects started running at a velocity above their lactate threshold or had highly variable blood lactate levels at different speeds which made it difficult to determine lactate threshold. With this in mind, lactated threshold velocity improved by 5.5 % in PLYO and by 10% in RUN.

Average VO_{2max} was not changed during the training period in either group. However, there were individual changes. In PLYO individual changes in VO_{2max} ranged from a decrease of 14% to an increase of 8.9%. Changes in VO_{2max} in RUN ranged from a decrease of 4% to an increase of 24%.

Table 4.4. Physiological Variables Before (Pretest) and After (Posttest) Six Weeks of Training

Variable	PLYO (n = 7)				RUN (n = 9)			
	Pretest		Posttest		Pretest		Posttest	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
Run Econ. (ml/kg/min)	40.36 (5.3)	29.72-44.90	38.46 (4.9)	28.99-42.46	40.12 (12.40)	13.3-53.26	37.39 (11.23)	13.74-51.46
LT vel. ^a (mi/hr)	7.3 (0.5)	6.5-8.0	7.7 (0.4)	7.0-8.0	6.9 (1.46)	5.0-9.0	7.6 (1.18)	6.0-9.0
VO_{2max} (ml/kg/min)	59.3 (8.5)	43.51-68.50	59.1 (8.1)	43.87-69.51	60.6 (8.4)	49.62-72.0	62.0 (6.5)	53.23-69.15

^aIn PLYO $\bar{n}$ = 6 on pretest and posttest; in RUN, $\bar{n}$ = 8 on pretest and $\bar{n}$ = 7 on posttest.

CHAPTER FIVE

Discussion

In this study eighteen high school cross-country runners were divided into a plyometric group (PLYO) and a running group (RUN). All participants did six weeks of regular cross-country training, while the plyometric group replaced some of their running with plyometrics. It was expected that plyometric training would facilitate neuromuscular response to better utilize elastic energy stored during the eccentric contractions of each footstrike. These neural changes could potentially improve biomechanical and physiological factors such as time in support, braking change in velocity, and running economy. It was conjectured that the plyometric group would have improved running performance.

Participants in PLYO did not significantly decrease their time in support or braking time as hypothesized. The hypotheses that participants in PLYO would significantly decrease their braking change in velocity and improve their running economy was supported by the present study. However, these changes in PLYO did not lead to a greater improvement in 3200-meter run time in PLYO than in RUN as hypothesized. This researcher found a trend of a decrease in support time over the training period, while no change in support time was found for the RUN group. In PLYO support time decreased eight milliseconds (3.2%) from pretest to posttest, while there was no overall change in support time in RUN. It is unclear if plyometrics led to significant changes in lactate threshold velocity as there were difficulties in collecting lactate

threshold data in some of the participants so this variable was excluded from the ANOVA.

The expected outcome that six weeks of plyometric training would lead to greater biomechanical, physiological, and performance changes in PLYO than in RUN was not supported by this study. Participants in both groups significantly improved their running economy and 3200-meter time (without a change in VO_{2max}), but there were no significant differences between groups on those variables. Participants in PLYO decreased braking change in velocity by 0.03 m/s (8%), while there was no change in RUN from pretest to posttest. These results should be interpreted and applied with caution as this study just met the minimum number of subjects per group that Schutz and Gessaroli (1987) recommend for a design with five dependent variables.

The results of this study are comparable to other studies (Dudley & Djamil, 1985; Hurley et al., 1984) that stated training for endurance and strength does not negatively affect endurance performance. Also, it is typical that the participants displayed improved running economy and running performance without changes in VO_{2max} . Hickson et al. (1988) found that combining strength training and running improved short-term endurance without changing VO_{2max} , while Nicholson and Sleivert (1999) found that running and weight training improved ten-kilometer times and running economy with no significant changes in VO_{2max} . Likewise, Paavolainen et al. (1999) reported that endurance training combined with plyometrics and weight training significantly improved running economy and five-kilometer times due to improved neuromuscular characteristics.

A difference between this study and other strength training studies is that in the present study both the plyometric group and the running-only group had similar

improvements in running economy and in running performance. In studies such as Nicholson and Sleivert (1999) and Paavolainen et al. (1999), the runners who strength trained displayed greater changes in their running economy and running performance than the subjects who only trained by running. However, in those studies, strength training involved only weight training (Nicholson and Sleivert) or weight training and plyometrics (Paavolainen et al.) instead of using plyometrics as the sole training method as in the present study. Also, these studies were done over a longer training period (21 weeks and 9 weeks, respectively), which may explain in part why the differences were not seen in the present study as the subjects trained for just six weeks. However, Paavolainen et al. also reported a significant improvement in running economy in the strength-training group after three weeks and after six weeks of running and strength training. The group that primarily did run training did not have any significant changes in running economy throughout the nine-week study.

Another possible reason for differences in the results of the current study and other strength training studies on runners is the general characteristics of the subjects. The participants in the current study were relatively inexperienced high school runners. Most other running and strength training studies have used college-aged athletes or older athletes who are more experienced and have greater running abilities.

There is some support for the hypotheses that support time and braking change in velocity would significantly decrease in PLYO. Plyometrics involves an eccentric contraction quickly followed by a concentric phase. Plyometric training requires muscles to respond quickly to small changes in muscle length which occur with each running step. During the support phase when running at a constant speed, runners decrease their forward velocity by braking and then increase their velocity during propulsion

(acceleration) to the original speed. Ideally runners want to minimize the amount of braking done during support.

There is some evidence that one training adaptation of plyometrics is to cause runners to reduce their time in support and to reduce the amount of braking and propulsion done during the support phase. Runners in PLYO significantly decreased their braking change in velocity and showed a trend of decreased time in support, while there were no such changes in RUN. After training, subjects in PLYO were braking less, which could have resulted in some type of energy savings. However, in the current study there was no evidence of an energy savings. Running economy improved similarly in both groups despite differences in braking change in velocity, suggesting that decreased braking change in velocity did not result in any significant change in energy need. In a study by Paavolainen et al. (1999), though, the experimental group that did nine weeks of explosive strength training along with run training decreased support time and running economy significantly, while there were no significant changes in the control group that mainly did run training.

Cautions in Interpreting Results

The large number of dependent variables and the relatively small number of subjects should be considered when interpreting the results of this study. In order to use MANOVA, Schutz and Gessaroli (1987) recommended a minimum of seven subjects per group when analyzing five dependent variables in two groups tested over two time periods. As a rule of thumb, though, Schutz and Gessaroli recommended a minimum of ten subjects per group (5 dependent variables x 2 groups) for the present study design, which had groups of seven and nine subjects. Therefore, significance results should be viewed with caution.

There were also difficulties in analyzing the biomechanics data. It is well known that there is large variability between trials within subjects in ground reaction force data. An example of this variability is presented in Chapter Four. Because of this variability, researchers recommend doing analysis on eight (Bates, Osternig, Sawhill, & James, 1983) to twenty-five (Devita & Bates, 1988) trials in order to obtain accurate ground reaction force data. Lees and Field (1985) found that there is also a lot of day-to-day variability within subjects. They recommended pooling data from two or more days. A shortcoming of the current study is that only one trial was used to represent each subject's running pattern.

One reason for the large variability in the ground reaction force data within subjects in this study is that runners were not challenged to run close to their maximum speed. When individuals run at or close to their maximum speed, they have very few movement patterns which would enable them to reach their top speed. However, in the present study, subjects were running at a slow pace, so there was the potential for greater variability in their ground reaction force parameters. Lees and Bouracier (1994) discuss how runners may have numerous "movement solutions" to the assigned task of running at a particular submaximal speed through a testing area. Subjects are free to choose from a variety of solutions to this "movement problem" or task and receive positive feedback on each trial when they fulfilled the requirements of the task. Lees and Bouracier also found that the amount of variability in stride patterns is related to the experience of the subjects. Experienced runners had standard deviations in braking and propulsion impulses that were significantly less than those standard deviations for inexperienced runners across twenty trials. As a result, experienced runners were more consistent with their stride pattern and tended to have smaller braking and propulsion impulses.

Another concern in interpreting the results of this study was the variability in time spent training. It was assumed that the participants would do most of their training during cross-country practice so that the amount of training time would be similar for all participants. The intention of this study was that the only difference in training groups would be that the participants in PLYO would spend part of their training time doing plyometrics, while the participants in RUN would continue running during this time. However, as reported in Chapter Four, the number of miles run each week varied greatly between subjects. The participants appeared to have a wide range of goals and motivations for running. Some subjects reported running on weekends, and on some days they ran a second time outside of practice. One subject in RUN reported biking 40-50 miles per week while also running 38 miles per week. Other subjects missed practice and did not run at all on certain days. Injuries, conflicts with jobs, family vacations, and band camp were several reasons reported for missing cross-country practices. Because of these conflicts it was difficult for coaches to completely control training time. Variability in training time should be kept in mind when interpreting the results of this study.

Recommendations for Further Research

There is a need for further research on the effects of plyometric training on high school distance runners. Since subjects in both groups of the present study had both positive and negative responses to training, researchers should take in to consideration the experience level and running ability of their subjects when designing a study. Individuals in the present study had varied responses to training which may have been influenced by their previous running experience and their running ability. Further studies need to be conducted to investigate how strength training adaptations are influenced by these factors.

For example, subjects could be grouped based on previous years of running experience to determine if this factor influences the response to plyometrics.

It also would be beneficial to require participants to engage in run-only training for three to four months prior to the beginning of the strength training phase so participants would be more likely to achieve a steady state level of fitness. Furthermore, there is a need to determine how many weeks of plyometrics are needed to obtain significant changes, if any, among inexperienced, high school cross-country runners.

When collecting ground reaction force data on runners, researchers need to be aware of the large variability in ground reaction force data and analyze up to 25 successful trials over at least two days. It would have been beneficial in the present study if more trials were collected over more than one day. More trials may help ensure that subjects obtain a “movement pattern fixation” as described by Lees and Bouracier (1994). Also, biomechanists should be aware of the variability in ground reaction force data between inexperienced and experienced runners. Groups should be equally represented by all levels of experience.

Researchers should set up testing areas so that there is immediate feedback on whether or not subjects are running at a constant speed across the force plate. In the present study there were numerous trials that appeared successful at the time that later had to be eliminated from further analysis because subjects were accelerating or decelerating. Pacer lights to guide runners and using two sets of timing systems would help to ensure runners were running across the testing area at a constant speed.

Implications and Conclusions

Keeping in mind the above difficulties with this study, there are some implications that can be made with regards to this study. Six weeks of plyometric training

may lead to biomechanical changes in some high school runners. Specifically, replacing some running with plyometrics may decrease braking change in velocity and time in support. In the current study these biomechanical changes did not lead to any significantly greater improvements in running economy or in running performance. However, other studies lasting longer than six weeks show that running, combined with strength training such as plyometrics, can lead to greater improvements in running economy, lactate threshold, and run performance than can training with run-only training.

The present study indicates that among relatively inexperienced high school cross-country runners, six weeks is not a long enough training period for plyometrics to realize a significant advantage over run-only training. Given the confines of a busy racing schedule and the limited practice time in a typical high school cross-country season, it is unrealistic for coaches to spend much more than six weeks on plyometric training. An implication for high school cross-country coaches then is that they should focus their training on running. However, this researcher found that replacing some running with plyometrics will not have a negative effect on running performance. Plyometric training could be used as a mental break from running for some young runners weary from logging high mileage. Plyometrics may be more beneficial for improving performance among older, more experienced runners, although this has not been evaluated. Further research needs to be conducted to determine the role that age and running experience have on the effects of plyometrics.

In conclusion there is not one type of training that best improves running performance. A variety of factors influence running performance. These factors include $\text{VO}_{2\text{max}}$, lactate threshold velocity, running economy, and muscle power. As a result,

cross-country coaches should use a variety of training methods when training the runners on their team. Suggested training methods are summarized in Table 5.1.

Table 5.1. Types of Training for Cross-Country Runners

Type of Training	Reasoning	Sample Workout
Easy Distance Run	Improves cell adaptation and ability to spare glycogen and rely on fat as fuel.	Seven-mile easy run.
Tempo Run	Increases lactate threshold.	Run 20 minutes at a pace greater than lactate threshold velocity.
Repetitions	Improves running economy.	8 x 200 meters with full (2-3 min) rest; pace greater than 1 mile race pace.
Intervals	Increases VO_{2max} .	6 x 800 meters with rest equal to or less than time of interval; run at max heart rate or at a pace equal to current 5-km race pace.
Hill workout	Improve muscle power	8 x 150 meters up incline with full (2-3 minute) rest.
Strength training	May improve muscle power; may increase RE^a , LT^b ; may decrease $B\Delta V^c$, ST^d ; use to increase motivation.	Three sets of five plyometric exercises (see Appendix B).

^aRE = Running economy. ^bLT = Lactate threshold. ^cBΔV= Braking change in velocity.

^dST = Support time.

By using a variety of training methods, runners can improve their endurance, speed, and strength. The variety of workouts may also help young runners stay motivated to come to practice. The end result could be a more enjoyable cross-country running experience and improved running performance.

APPENDIX A

Running History Form

Subject Number:

Running History and Running Performance Test

Name: _____

Date of pretest: _____

Date of posttest: _____

Location: _____

Weather (Pretest): _____

Weather (Posttest): _____

RUNNING HISTORY

Please answer as accurately as possible.

1. Number of years running _____
2. Did you run track this year? If yes, how many weeks of rest did you have after track season?

3. In the past six weeks,
 - a. How many weeks have you run? _____
 - b. Estimated average number of days run per week. _____
 - c. Estimated average number of miles run per week. _____
4. To the best of your knowledge, record your best times at the following distances.
800 meters _____ 2 mile (or 3200 meters) _____
1 mile (or 1600 meters) _____ 5 K _____

RUNNING PERFORMANCE TEST-3200 METERS

<u>Pretest</u>	<u>Posttest</u>	<u>Change</u>
1600 m time _____	_____	_____
2800 m time _____	_____	
last lap split ()	()	_____
3200 m time _____	_____	_____

APPENDIX B

Plyometric Training Schedule

SIX WEEK PLYOMETRIC TRAINING SCHEDULE FOR CROSS-COUNTRY RUNNERS

General Guidelines

1. Plyometric training should be done on nonconsecutive days. (There should be at least one day of rest or nonplyometric training between each plyometric training day.)
2. A complete warmup and stretching routine should be completed before each plyometric session.
3. Plyometrics should be done on a soft surface such as dirt or grass.
4. Exercises should progress from simple, low intensity, low impact exercises to more complex, higher intensity exercises.
5. In order for plyometrics to be effective, proper technique must be used:
 - Athletes should have short, quick landings with minimum knee flexion and contact time.
 - A locked ankle should be maintained upon landing and athletes should land with two-thirds to a full foot ground contact. More weight should be on the front of the foot.
 - Short, quick landings should be immediately followed by a rapid, powerful take-off.
6. A full recovery (30 seconds to 2 minutes) should be used between sets.
7. When first learning an exercise, single-response drills should be used. This is where there is a pause after each landing to check technique. Once the exercise has been learned, multiple-response drills should be used where there are numerous successive jumps with no pause between landing and taking off again.
8. The numbers preceding the exercises indicate the number of sets and repetitions. For example, 3 x 6 squat jump means three sets of six repetitions of squat jumps. For exercises such as skipping, a distance is given instead of number of repetitions. For single leg exercises the required number of repetitions and sets should be done on each leg.

9. Try to follow the number of sets and repetitions that are given. However, the exact amount of each exercise may have to be adjusted to meet the abilities of the athletes. Emphasize quality over quantity. If the athletes are unable to perform the assigned number of repetitions or sets of an exercise with the appropriate technique then the sets or repetitions may have to be reduced.
10. The notation in parentheses indicates where to find a complete explanation of an exercise in the “Plyometric Exercises” handout in Appendix C. For example, J-2 refers to jump number two, “Squat jump.”

WEEK	DAY ONE	DAY TWO	DAY THREE
1	3 x 30 yds Prancing (B-1) 3 x 8 Pogo (J-1) 3 x 30 yds Skip for power (B-3) 3 x 20 sec Richochet (H-3) 3 x 4 Hurdle hops (H-1)	3 x 30 yds Galloping (B-2) 3 x 8 Pogo 3 x 4 Hurdle hops 3 x 30 yds Skip for power 3 x 6 Box jumps (J-3)	off
2	3 x 40 yds Prancing 3 x 6 Squat jump (J-2) 3 x 30 yds Double-leg speed hop (H-2) 3 x 40 yds Skip for power 3 x 8 Box jumps	3 x 40 yds Galloping 3 x 40 yds Skip for speed (B-3) 3 x 6 Double-leg butt kick (J-4) 3 x 30 sec Richochets 4 x 6 Squat jumps	off
3	3 x 40 yds Skip for speed 3 x 8 Double-leg butt kick 2 x 6 Single-leg butt kick (H-5) 3 x 8 Stadium hops (H-4) 2 x 6 Single-leg stair bound (B-5)	4 x 50 yds Skip for power 3 x 50 yds Ankle flip (B-4) 2 x 30 sec Richochets 3 x 6 Split jump (J-5) 3 x 6 Single-leg butt kick	off
4	3 x 50 yds Ankle flip 3 x 8 Split jump 4 x 30 yds Double leg speed hop 2 x 8 Single-leg stair bound 3 x 20 steps Alternate leg stair bound (B-6)	3 x 50 yds Galloping 3 x 50 yds Skip for speed 4 x 20 sec Ricochets 3 x 10 Stadium hops 2 x 5 Single-leg hop for height (each leg) (H-6)	4 x 50 yds Ankle flip 3 x 8 Split jump 4 x 30 yds Double leg speed hop 3 x 8 Single-leg stair bound 3 x 20 steps Alternate-leg stair bound
5	4 x 50 yds Skip for speed 3 x 5 Single-leg stride jump (J-7) 4 x 12 Stadium hops 3 x 6 Scissors jump (J-6) 3 x 6 Single-leg hop for height (each leg)	3 x 50 yds Galloping 4 x 4 Hurdle hops (Multiple response) (H-8) 3 x 8 Box jump (Multiple response) (J-10) 1 x 4 Depth jump (J-9) 3 x 6 Alternate leg bound (B-8)	Repeat day one of this week.
6	4 x 50 yds Ankle flip 3 x 8 Scissors jump 3 x 6 Single-leg stride jump 3 x 20 steps Alternate-leg stair bound 2 x 5 Single-leg speed hop (H-7)	4 x 50 yds Skip for speed 3 x 8 Box jump (Multiple response) 1 x 6 Depth jump 5 x 4 Hurdle hops 4 x 30 sec Ricochets 3 x 8 Alternate leg bound	3 x 50 yds Galloping 3 x 10 Scissors jump 3 x 5 Stride jump crossover (J-8) 3 x 5 Single-leg speed hop 4 x 50 yds Ankle flip

APPENDIX C

Descriptions of Plyometric Exercises

PLYOMETRIC EXERCISES

JUMPS (J)

1. POGO

Start: Stand with knees slightly bent, chest out, and shoulders back.

Action: Jump straight up, projecting hips up, with just a small knee flexion while in the air. Use ankles to lock feet into toes-up position and maintain this position throughout jumps.

2. SQUAT JUMP

Start: Stand upright with feet about shoulder-width apart. Interlock fingers and place palms against the back of the head.

Action: Flex downward to a half-squat position; then immediately explode upward as high as possible, extending the hips, knees, and ankles to maximum length as quickly as you can. Upon landing, quickly jump up again.

3. BOX JUMP (Single response)

Start: Stand facing an 18-24 inch box with feet shoulder-width apart.

Action: Flex downward to a half-squat position and immediately jump up and land softly with both feet on the box; step down and repeat.

4. DOUBLE-LEG BUTT KICK

Start: Stand upright with knees slightly bent, chest out, and shoulders back.

Action: Flex downward quickly with a slight knee bend and then immediately jump up and pull the heels upward and slightly backward into the buttocks while tucking the toes up. Repeat the jump immediately.

5. SPLIT JUMP

Start: Kneel on the ground with one leg extended forward with the knee over the middle of the foot and the other leg back with the knee bent and underneath the shoulders and hips.

Action: Jump as high as possible. Land in the same position, bending the knees to absorb the shock. Immediately repeat the jump. Be sure to keep the shoulders back and in line with the hips. Switch legs after the required number of repetitions.

Jumps (Continued)

6. SCISSORS JUMP

Start: Assume the same position as the start of the split jump.

Action: Jump up as in the split jump, but switch leg positions when in the air, flexing the back knee as it is brought forward. Upon landing, immediately repeat jump, again reversing the position of the legs.

7. SINGLE-LEG STRIDE JUMP

Start: Stand to the side and at one end of a bench. Place inside foot on top of the bench, and hold arms downward at sides.

Action: Bring arms upward and initially push with both legs; then push off hard with foot on bench to jump up as high as possible, bringing outside knee up. Upon landing use the inside foot for support and power; the outside foot should have a quick landing before beginning the next jump. Continue to the end of the bench and then turn around and come back on other leg.

8. STRIDE JUMP CROSSOVER

Start: Start as in single-leg stride jump with one foot on a bench.

Action: Bring arms up and push off hard as in the single-leg stride jump. Jump as high as possible and bring the leg that was on the bench to the opposite side of the bench. Then the outside leg will land on the bench and the inside leg will land on the ground. Now the body and legs should be in the opposite position as the starting position. As soon as the original driving leg contacts the ground repeat the jump upwards. Perform the jumps as quickly as possible.

9. DEPTH JUMP

Start: Stand on the edge of an elevated surface (box or bench) that is 12 to 36 inches high. Knees should be slightly bent, and arms at the sides.

Action: Drop (not jump) from the box to the ground. Upon landing flex the knees slightly and quickly jump up. Try to anticipate the landing and jump up as quickly as possible, minimizing time on the ground.

10. BOX JUMP (MULTIPLE RESPONSE)

Start: Stand facing a 12 to 24 inch box approximately an arm's length away. Arms should be at side.

Action: Use the arms to assist a powerful jump upwards and forward onto the box. Immediately drop or jump down to the original starting position and repeat jump.

BOUNDS AND SKIPS (B)

1. PRANCING

Start: Stand with a slight knee bend and hips tilted forward.

Action: Athletes will be projecting the hips forward with a two-foot takeoff and a two-foot landing. Push the hips outward and upward upon takeoff with one leg landing in front of the other. Upon landing repeat the takeoff with the opposite leg landing forward. Move arms as in running. Both feet must land simultaneously so keep ankles locked in a toes-up position.

2. GALLOPING

Start: Stand with one leg in front of the other.

Action: Push off with the back leg and foot, keeping the ankle locked upon takeoff and landing. Keep the same leg behind the hips and project the hips forward, with the other leg staying forward. After required distance, switch position of the legs and repeat. Emphasize forceful, quick extensions of the back knee and ankle, with light cyclic striding actions of the lead leg.

3. SKIPPING-POWER AND SPEED

Start: Stand with one leg slightly forward.

Action: In *power skipping*, skip for maximum height, emphasizing a powerful pushoff, flicking the ankles.

In *speed skipping*, stay close to the ground and reduce air time. Emphasize frequency not distance.

Bounds and Skips (Continued)

4. ANKLE FLIP

Start: Stand with right foot forward.

Action: This is an exaggerated running stride. Push off hard with the right foot and bring the left foot forward. As the back leg comes through extend the front leg for duration of the push off. Hold this extended stride for a brief time and then land on the left foot. Repeat pushoff with the left foot. Make each stride long and keep ankles locked.

5. SINGLE-LEG STAIR BOUND

Start: Balance on right leg on the second step of stairs.

Action: Drop down to the step below landing on the left leg. Immediately push off with the left foot, driving the right leg onto a step or two above the original starting step. Continue this sequence (right leg, drop to left, bound up onto right) for predetermined set of repetitions. Then repeat, starting with left leg up.

6. ALTERNATE-LEG STAIR BOUND

Start: Begin with one leg back.

Action: Run (bound) up the steps with maximum extension of the support leg, and maximum knee drive of the swing leg. Emphasize quick, explosive takeoffs, spending as little time as possible on each step.

7. ALTERNATE-LEG BOUND

Start: Begin with left foot forward and arms at the side.

Action: This is similar to the ankle flip, only strive for more height and distance. Push off with the back leg, driving the knee forward and upward to gain as much height and distance as possible. Land on the right leg in the forward position and repeat sequence (pushing off with the other leg). Keep the ankles locked upon landing and minimize ground contact time. Use arms as in running.

HOPS (H)

1. HURDLE HOPS (Single response)

Start: Stand with knees slightly bent and arms at the side in front of a series of three to five barriers (e.g. 12 to 36 in hurdles) spaced approximately three feet apart.

Action: Use a quick countermovement and jump forward over the first barrier. Tuck the toes, knees, and heels upward. Keep the body vertical and straight. Land with full-foot contact, bending at the knees slightly. Pause to reset the correct starting position and then jump over the next hurdles. Once landing and takeoff technique is correct, perform jumps without pause.

2. DOUBLE-LEG SPEED HOP

Start: Stand with knees bent and arms at the side.

Action: Use a quick countermovement and jump up and forward, tucking the knees while in the air. Upon landing, takeoff quickly. Strive for height and distance while maintaining a high repetition rate.

3. RICOCHETS

Start: Stand with arms at side.

Action: Hop forward and backward, minimizing horizontal and vertical distance. Emphasize speed, with quick takeoffs and landings. For variety do on a hill or on stairs.

4. STADIUM HOPS

Start: Stand in a semi-squat position on front portion of a step. (Alternative: do on a hill). Hold arms slightly behind body.

Action: Follow a quick flexion of knees with an explosive jump up two or three steps. Continue hopping up the required number of repetitions. Make landing quick and light.

5. SINGLE-LEG BUTT KICK

Start: Stand with knees slightly bent, chest out, and shoulders back. Lift one knee by bringing heel up towards buttocks.

Action: Use a quick countermovement and jump off of one leg as high as possible. Tuck the toes and heels of the takeoff leg upward toward the buttocks. Maintain an upright posture during the entire movement. Repeat continuing to land and takeoff on the same leg. After designated number of repetitions switch legs.

Hops (Continued)

6. SINGLE-LEG HOP FOR HEIGHT

Start: Stand with knees slightly bent and arms at the side. Balance on the right leg while keeping the left leg flexed with the toes up, knee up in front of the body, and the heel up in front of the hip.

Action: Do the hops similar to the hurdle hops, flexing the knees while in the air, but landing and taking off on one foot. These may be done over small cones.

7. SINGLE-LEG SPEED HOP

Start: Begin as in single-leg hop for height.

Action: Hop for speed and distance, taking off and landing on one leg. Minimize contact time with ground by keeping ankles locked and having a quick landing and takeoff.

8. HURDLE HOPS (MULTIPLE RESPONSE)

Do these similarly to single response hurdle hops except emphasize a brief landing and takeoff period. To increase difficulty increase height of hurdles up to 36 inches.

For additional information on plyometric training see:

Bompa, T.O. (1996). Power training for sport: Plyometrics for maximum power development. Oakville, Ontario: Mosaic Press.

Chu, D.A. (1992). Jumping into plyometrics. Champaign, IL: Leisure Press.

Radcliffe, J.C., & Farentinos, R.C. (1999). High-Powered plyometrics. Champaign, IL: Human Kinetics.

Pictures of the plyometric exercises used in the current study can be found in these books. Names of most exercises were taken from Radcliffe and Farentinos' book.

APPENDIX D

Individual Characteristics and Training Data

General Characteristics of Participants

PLYO	Gender	Age (yrs)	Ht. (cm)	Pre Wt. (kg)	Post Wt. (kg)	Run Exp. (yrs) ^a	Prestudy run (wks) ^b	Ave. mi/wk running ^c	Range (mi/wk) ^d	No. of plyo days ^e
4	Male	15	170.7	64.2	64.5	2	5	34	20-45	12
6	Male	17	180.9	60.9	61.8	2	5	30	11-51	8
7	Male	14	186.6	69.2	69.0	2	6	30	15-44	10
8	Female	18	162.5	60.0	59.5	5	6	25	25-25	12
10	Male	16	178.0	83.7	83.1	4	0	12	0-19	19
12	Male	16	168.0	51.5	54.7	2	6	18	5-25	15
18	Male	15	177.6	63.2	62.0	2	6	29	16-54	15
Mean		15.9	174.9	64.7	64.9	2.7	4.9	25.4	-	13
SD		1.35	8.25	9.95	9.12	1.25	2.19	7.79	-	3.65
RUN										
2	Male	18	178.7	68.2	69.5	5	7	26	8-46	0
3	Male	16	175.1	71.6	70.4	4	5	41	33-51	0
9	Female	16	166	58.5	57	0	3	19.5	11.5-29.5	0
11	Male	16	171	57.2	57.9	2	2	21	18-24	0
13	Male	17	167	57.6	57.1	3	5	17	11-26	0
14	Male	16	178	61	60.5	3	6	27	19-44	0
15	Female	16	152.1	47.7	47	2	2.5	9	0-23.5	0
16	Male	17	184.1	69.8	68.5	4	6	47	20-70	0
17	Male	16	177.2	64.7	62.6	2	4	38	20-80	0
Mean		16.4	172.1	61.8	61.2	2.8	4.5	27.3	-	0
SD		0.73	9.50	7.57	7.55	1.48	1.73	12.42	-	-

^aRunning experience; number of years training for running prior to study;

^bNumber of weeks running in six weeks prior to beginning of study;

^cAverage number of miles run per week during study;

^dRange of miles run in one week during study;

^eNumber of plyometric training sessions done during study.

APPENDIX E

Individual Data for Running Performance

Running Performance Data

Sub. No.	3200 m time (min:s)		
PLYO	Pretest	Posttest	Change
4	12:29	12:03	0:26
6	11:27	11:22	0:05
7	13:07	12:47	0:20
8	16:05	14:53	1:12
10	13:20	12:29	0:51
12	12:50	12:56	+ 0:06
18	13:39	-	-
Mean	13:16	12:45	0:31
SD	0.06	0.05	
RUN			
2	12:08	11:15	0:53
3	11:31	11:07	0:24
9	20:24	15:15	5:09
11	12:21	12:04	0:17
13	13:24	-	-
14	13:01	-	-
15	15:59	16:12	+ 0:13
16	11:34	11:03	0:31
17	14:24	12:04	2:20
Mean	13:51	12:42	1:08
SD	0.12	0.09	

Note. Dashes indicate that data was not obtained on that trial.

APPENDIX F

Individual Data for Biomechanics Variables (Best Trial)

Individual Data for Biomechanics Variables
Best Trial (Based on braking and propulsion difference)

Sub. No.	Time in Support (s)			Braking time (s)			Braking Change in Velocity (m/s)		
PLYO	Pretest	Post	Change	Pretest	Post	Change	Pretest	Post	Change
4	0.232	0.224	-0.008	0.102	0.115	0.013	0.23	0.21	-0.02
6	0.236	0.246	0.010	0.120	0.128	0.008	0.26	0.26	0
7	0.295	0.289	-0.006	0.144	0.119	-0.025	0.28	0.26	-0.02
8	0.278	0.261	-0.017	0.141	0.133	-0.008	0.29	0.25	-0.04
10	0.228	0.230	0.002	0.116	0.119	0.003	0.23	0.20	-0.03
12	0.241	0.232	-0.009	0.117	0.121	0.004	0.23	0.21	-0.02
18	0.231	0.205	-0.026	0.115	0.112	-0.003	0.24	0.17	-0.07
Mean	0.249	0.241	-0.008	0.122	0.121	-0.001	0.25	0.22	-0.020
SD	0.027	0.027		0.015	0.007		0.025	0.035	
RUN									
2	0.244	0.263	0.019	0.120	0.129	0.009	0.29	0.24	-0.05
3	0.257	0.268	0.011	0.127	0.139	0.012	0.20	0.24	0.04
9	0.238	0.219	-0.019	0.127	0.115	-0.012	0.20	0.18	-0.02
11	0.231	0.230	-0.001	0.120	0.118	-0.002	0.25	0.23	-0.02
13	0.230	0.218	-0.012	0.114	0.109	-0.005	0.23	0.23	0
14	0.271	0.261	-0.010	0.141	0.136	-0.005	0.22	0.20	-0.02
15	0.201	0.219	0.018	0.104	0.112	0.008	0.22	0.22	0
16	0.251	0.270	0.019	0.130	0.146	0.016	0.23	0.22	-0.01
17	0.280	0.258	-0.022	0.145	0.130	-0.015	0.24	0.28	0.04
Mean	0.245	0.245	0.000	0.125	0.126	-0.001	0.23	0.23	0.00
SD	0.024	0.023		0.013	0.013		0.028	0.028	

APPENDIX G

Individual Data for Physiological Variables

Individual Data for Physiological Variables

Sub. No.	Run Econ. (ml/kg/min)				LT velocity (mi/hr)				VO _{2max} (ml/kg/min)		
PLYO	Pretest	Post	Change		Pretest	Post	Change		Pretest	Post	Change
4	42.5	40.7	-1.84		8	8	0		63.8	69.5	5.7
6	44.9	42.5	-2.44		7.5	8	0.5		66.4	65.1	-1.3
7	44.0	41.6	-2.36		6.5	7.5	1		68.5	58.7	-9.8
8	29.7	29.0	-0.73		-	-	-		43.5	43.9	0.4
10	37.2	34.9	-2.34		7.5	7	-0.5		54.5	56.5	2.1
12	41.1	39.0	-2.09		7.5	7.5	0		59.5	61.7	2.2
18	43.0	41.5	-1.49		7	8	1		59.1	58.1	-1.0
Mean	40.4	38.5	-1.90		7.3	7.7	0.3		59.3	59.1	-0.3
SD	5.3	4.9			0.5	0.4			8.5	8.1	
RUN											
2	37.1	36.2	-0.9		8	-			56.7	61.8	5.1
3	44.1	39.8	-4.3		8.5	8	-0.5		65.3	65.6	0.3
9	13.3	13.7	0.4		5	6.5	1.5		49.6	53.2	3.6
11	44.8	41.9	-2.9		6.5	8	1.5		62.7	62.3	-0.4
13	41.6	38.0	-3.6		6	7	1		53.3	66.3	13.0
14	46.3	41.9	-4.4		7.5	9	1.5		65.9	60.6	-5.3
15	29.1	26.7	-2.4		6	6	0		50.3	50.3	0.0
16	53.3	51.5	-1.8		9	9	0		72.0	69.2	-2.8
17	51.5	46.8	-4.7		-	-	-		69.9	68.4	-1.5
Mean	40.1	37.4	-2.7		6.9	7.6	0.7		60.6	62.0	1.3
SD	12.40	11.23			1.46	1.18			8.4	6.5	

Note. Dashes indicate data was not obtained for that trial.

APPENDIX H

Consent Form

Informed Consent Form

Biomechanical and Physiological Effects of Plyometric Training on High School Cross-Country Runners

There are many different types of training that cross-country coaches use with their athletes. For example, a mixture of long slow distance runs, intervals on a track, and hill running are important components of most high school cross-country practices. A component that is often not included is strength training as the effects of strength training on young distance runners' performance is unclear. This study will compare the effects of run only training with a specific kind of strength training, plyometrics, on jumping ability, distance running performance, and several physiological and biomechanical factors. It is not known which approach is best.

If you agree to participate in this study, you will be randomly assigned to one of two groups: a plyometrics group or a run only group. If you are assigned to the run only group, you will participate in regular cross-country practice with your high school team. If you are in the plyometrics group, you will replace some of your regular cross-country practices with plyometric training two to three times a week for six weeks. Plyometrics involves exercises such as jumps, skips, and hops.

You will be asked to participate in a series of tests before and after the six weeks of training. Session one of testing will consist of a 5-hop test, a vertical jump test, and a five kilometer run on a local cross-country course. Session two will consist of a cardiovascular fitness test and a biomechanical evaluation. These tests will take approximately an hour for each participant to complete and will be done at the Human Energy Research Laboratory and the Biomechanics Research Station at Michigan State University. Cardiovascular fitness, a good predictor of endurance performance, will be measured by a best effort on a treadmill. This will include several small fingerpricks to obtain blood lactate levels. The biomechanics evaluation will consist of running approximately 40 yards at a constant speed while being videotaped. Stride length, stride frequency, and contact time with the ground are some of the factors that will be studied.

There are minor risks involved in the testing. The risks are no greater than completing a physical fitness test. You may experience slight discomfort during the measure of blood lactate. You may become faint or tired during the fitness test on the treadmill and during the five kilometer run. However, these tests will be like running during practice or in a race. You could strain or pull muscles, sprain ankles or develop stress fractures from the plyometric training. However, athletes will be properly warmed up and instructed on appropriate techniques for doing these exercises to help prevent injuries. Plyometric training has been used in high school sports and in physical education classes for many years.

Participation is voluntary and you may choose to not participate at all, refuse to participate in certain tests, or discontinue participation at any time without penalty. Every effort will be made to protect you from having harmful problems during the testing. Pregnant women should not participate in the study. If you are injured as a result of participation in this research project, Michigan State University will provide emergency medical care if necessary. If the injury is not caused by the negligence of MSU, you are personally responsible for the expense of this emergency care and any other medical expenses incurred as a result of this injury.

To insure your confidentiality, your identity will only be known by the principal and secondary investigator and a limited number of research staff who assist in the treadmill test and biomechanics evaluation. You will be assigned a number and referred to by your subject number

when analyzing and reporting data. In general, data analyses will consist of comparing groups and not individuals. Pictures and a videotape of selected subjects may be shown for educational purposes without identifying the names of the athletes. Coaches will not be given data about their runners. You will be given your individual results which you may share with your coach if you wish. Group averages will also be provided to you so you can compare your scores to the group. Confidentiality will be protected to the maximum extent permissible by law.

The benefits of participating in this study include receiving information about your cardiovascular fitness, stride length and stride frequency, five kilometer running performance, and jumping ability before and after six weeks of cross-country practices. All participants will be mailed a summary of the results of this study upon completion.

If you or your parents have any questions about the study you may contact any of the following individuals:

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I have been provide information about this study and have had the opportunity to ask questions about this study. I agree to participate in this study by signing my name on the line below.

Parent/Guardian

Date

Subject

Date

Note: This form must be signed by BOTH the athlete and the parent/guardian to give consent for the athlete to participate in the study. Please remember to bring this form on the first day of testing.

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