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Effect of Racing Flats on Running Economy in Male Adolescent Runners

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EFFECT OF RACING FLATS ON RUNNING ECONOMY IN MALE ADOLESCENT RUNNERS

By

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ABSTRACT

Effect of Racing Flats on Running Economy in Male Adolescent Runners

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The purpose of this study was to investigate whether running economy differs in racing flats versus standard running shoes in high school cross-country runners. In order to measure running economy the oxygen cost of running (mL $O_2 \cdot kg^{-1} \cdot min^{-1}$) was measured in 20 male adolescent runners (mean age = 16.25 ± 0.97 years, 5 km best time = 17.52 ± 0.78 min) when running two separate trials at a controlled speed. The speed was determined by estimating treadmill running speed at 85% of each runner's VO_{2max}. Each trial required the participants to run while wearing the Mizuno Wave Elixir 6™ standard running shoe and the Mizuno Wave Universe 4™ racing flat. The results indicated that after running both trials at the same speed, the high school runners demonstrated a significant 2% reduction ($P < .001$) in the oxygen cost of running when comparing the racing flat (60.94 ± 5.83 $mL \cdot kg^{-1} \cdot min^{-1}$) to the standard running shoe (62.14 ± 5.87 $mL \cdot kg^{-1} \cdot min^{-1}$). The results of the current study suggest that the use of the Mizuno Wave Universe 4™ racing flat significantly improved running economy, most likely due to differences in shoe mass between the racing flat and standard running shoe.

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CHAPTER 1

INTRODUCTION

Early work from Hill and Lupton (1923) investigated the relationship between muscular work and oxygen utilization. Using their laboratory observations, the early investigators attempted to identify the physiological and metabolic traits required for successful endurance running performance; suggesting that "a man may fail to be a good runner by reason of a low oxygen intake, a low maximum oxygen debt, or a high oxygen requirement; clumsy and uneconomical movements may lead to exhaustion, just as well as may an imperfect supply of oxygen" (Hill and Lupton, 1923).

Daniels (1985) suggests that minimizing these unwanted or counter-productive movements, thereby promoting an efficient utilization of available energy, will produce optimum performance in endurance running events. While efficiency refers to the relationship between total work done and energy expended, there is a more precise relationship between the energy demands of running and running velocity which has emerged in the scientific literature. This relationship between the energy demand of running and running velocity is termed "running economy" (RE). Because the energy demands of running at a particular velocity can be represented in terms of caloric expenditure, through an analysis of oxygen consumption (VO_2), it is appropriate to refer to the "aerobic demand" of a particular running pace when describing RE (Daniels, 1985).

Previous literature reveals that RE is a modifiable determinant of endurance performance. When investigating RE as a determinant for success, modest correlations between endurance running performance and RE have been documented (Morgan et al., 1989 and Plank et al, 2005). These modest correlations have supported further investigation of possible factors influencing RE.

Physical growth and development influences RE. Krahenbuhl et al. (1989) conducted a longitudinal study on RE in 10 year old males at various running paces. These same participants returned for testing 7 years later. The aerobic demand of running decreased approximately 13%, despite the absence of any running training (Krahenbuhl et al., 1989). This improvement in RE with increasing age may be due to growth and maturation. Smaller children and adolescents seem to have disadvantageous stride rates and stride lengths imposed by their shorter limbs (Krahenbuhl and Williams, 1992).

RE may also be modifiable through appropriate training. Franch et al. (1998) were able to identify significant improvements in RE as the result of either continuous long-distance training (30 $min \cdot d^{-1}$) or long-interval training (4-6 intervals of 4-min with 2-min recovery between intervals) in adults. Improvement in RE brought on by long-term regular training seems to also occur in adolescents in conjunction with the aforementioned influences of growth and development (Daniels et al., 1978 and Krahenbuhl and Williams, 1992).

An additional influencing factor of RE is footwear. Relationships between VO_2 and shoe mass is supported by literature suggesting that the work involved with moving the lower limbs may constitute up to 1/3 of the total cost of running (Myers and Steudel, 1985). Research by Martin (1985) found increases in VO_2 of

3.3 and 7.2% with the addition of either 0.25 kg or 0.5 kg to each foot, respectively. This mass effect is similar to results from other studies and supports documented estimations that the aerobic demand of running increases approximately 1% per 100g of added mass per foot (Burkett et al., 1985, Divert et al., 2008 and Frederick, 1984).

In addition to the mass effect of footwear on the aerobic demand of running, there is evidence that non-weight effects may also influence RE. Perl et al. (2012) had their experienced runners run 180 $m \cdot min^{-1}$ trials in both an Asics GEL-Cumulus 10™ standard running shoe and a Vibram Five Finger™ minimalist shoe. By adding weight to the minimalist shoes the researchers were able to correct for the mass differences of the shoes, and further demonstrated that the use of minimalist shoes resulted in a 2.41-3.32% decrease in the aerobic demand of running at 180 $m \cdot min^{-1}$ (Perl et al., 2012). These data support previous research suggesting non-weight effects of footwear as factors affecting RE (Catlin and Dressendorfer, 1979, Daniels et al., 1981 and Frederick 1984).

These small variations in RE due to footwear manipulation may result in substantial performance effects for competitive runners. It has been proposed that an increase in VO_2 of 1% may translate to a 2.94 $m \cdot min^{-1}$ decrease in running speed; leading to the notion that slight decreases in VO_2 would increase sustainable speed and produce meaningful improvements in performance time (Burkett et al., 1985, Hanson et al., 2011 and Perl et al., 2012).

The purpose of the current study is to investigate the effect of racing flats on RE in adolescent male cross-country runners. With initial investigations concentrating on adult running populations there is an opportunity to provide data on an adolescent population to aid in the understanding and application of footwear manipulation as it relates to RE.

While the shorter limbs of this young population may be to their disadvantage when comparing their RE to that of adult runners it is this trait that promotes the investigation of footwear manipulation and its effect on their RE. Smaller and more proximally located limb mass results in lower kinetic energy requirements to move the limbs and thus may lower the relative aerobic demand of leg movement (Anderson, 1996; Myers and Steudal, 1985). This suggests that the population in question may in fact gain less benefit from footwear manipulation due to the greater proximity of their distal limb segments to their center of gravity compared to adult runners.

However, another trait of the adolescent male population is their overall smaller size which accompanies their smaller limbs and incomplete physical development. With the proposal that foot size relative to body size might influence RE, there is also the possibility that increasing the amount of mass located on the feet may decrease RE to a greater extent in this population as the shoe mass represents a greater relative increase in load per unit of body or segment mass (Anderson, 1996).

The aim of the current study is to investigate the effect of racing flats on RE through a comparison of the aerobic demand of running at maximal lactate steady state in the Mizuno Wave Elixir 6™ standard running shoe and the Mizuno Wave Universe 4™ racing flat. The influencing factors of shoe mass, design and population characteristics lead to the hypothesis that the racing flats will result in a significant decrease in the aerobic demand of treadmill running at speeds corresponding to maximal lactate steady state.

Purpose of the Study

The purpose of this study is compare the effects of the Mizuno Wave Elixir 6™ standard running shoe (SHOE) and the Mizuno Wave Universe 4™ racing flat (FLAT) on the aerobic demand of running at a constant speed.

Research Hypothesis

There will be a significant improvement in running economy in male adolescent cross-country runners when wearing the Mizuno Wave Universe 4™ racing flat compared to the Mizuno Wave Elixir 6™ standard running shoe.

Significance of the Study

The adolescent running population is under-represented in the RE literature. With data suggesting that injury rates may increase due to greater ground reaction forces and loading rates, there is an even greater need of studies examining the effects of shoe mass and design on specific populations (Logan et al., 2010). Hypothetically, proper design of racing flats would produce significant improvements in running performance by altering the aerobic demand of running. This study will provide empirical data of the proposed rewards of utilizing racing flats to improve RE, shaping future recommendations to ensure that the safety and efficacy of the claims are better understood.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Maximal Oxygen Uptake

A.V. Hill and his colleague H. Lupton (1923) stressed the importance of VO_{2max} for endurance performance using data collected from their subject H. The subject had been able to run ¼ mile at 455 $m \cdot min^{-1}$ (17 mph), however his average speed decreased as race duration increased. His maximal efforts for ½ mile and 2 mile runs were at speeds of only 392 and 306 $m \cdot min^{-1}$ (14.6 and 11.4 mph), respectively. Hill and Lupton proposed that “the maximum duration of an effort of given intensity is related to the intensity in a manner depending simply upon the supply of oxygen” (Hill and Lupton, 1923). In other words there seemed to be a VO_{2max} ceiling for every individual runner which would play a greater role in running performance as duration of the effort increased. Greater VO_{2max} values would represent a runner’s ability to utilize more oxygen per minute; providing more oxygen for the aerobic energy processes and permitting the runner to produce greater speeds over a given distance. With this newfound emphasis of oxygen as an indicator of performance, Hill and Lupton (1923) labeled VO_{2max} as the primary aerobic parameter for endurance running.

This relationship between running speed and VO_2 is clearly seen in metabolic equations provided by the American College of Sports Medicine (ACSM, 2000). The equation for estimating VO_2 for running speeds over 134 $m \cdot min^{-1}$ (5.0 mph) is:

$$VO_2 = (.2 \times S) + (.9 \times S \times G) + 3.5$$

In their equation, VO_2 while running is dependent upon speed (S) and gradient (G). Speed is represented in $m \cdot min^{-1}$ and gradient is the percent grade of the running surface expressed as a fraction. This equation suggests that if running on comparable courses a runner must operate at a higher VO_2 in order to elicit higher speeds. The metabolic equations provided by the ACSM are general guidelines which may have a standard error as high as 7% and their accuracy may be affected further by environmental conditions or changes in biomechanical efficiency (ACSM, 2010). If environmental conditions are controlled for in a laboratory setting, any further variability may be explained in part by alterations in running efficiency, which is the topic of another aerobic parameter. Also, when considering the use of the metabolic equations it is important to remember that these equations are for steady state exercise, not maximal work rates. Based on the above equation however, it is easy to suggest that by simply raising the VO_{2max} of a runner their running speeds will undoubtedly increase. Unfortunately, it is not that simple as the other aerobic parameters play important roles in determining which VO_2 an athlete can sustain during an endurance competition and how their speed is related to their VO_2. The knowledge that VO_{2max} is not the sole determinant of endurance running performance should not distract athletes from understanding the intricacies of VO_{2max} or seeking to develop it. While it is not the only parameter which must be considered, there is ample evidence to support its role as a primary determinant of performance.

When investigating the physiological characteristics of adolescent cross-country runners, Lee N. Cunningham (1990) provided data supporting the use of VO_{2max} as a primary determinant of performance. He found that the 12 male runners exhibited a significantly higher VO_{2max} (74.6 ± 2.2 ml•kg^{-1}•min^{-1}) than the 12 females (66.1 ± 7.4 ml•kg^{-1}•min^{-1}). Additionally, Cunningham observed that the males' average 5 km race time (17:27 ± 1:21 min:sec) was approximately 2 minutes and 18 seconds faster than the race time of their female counterparts (19:45 ± 1:06 min:sec). It was suggested that this variability between VO_{2max} and running performance could be related to variations in body composition and/or training. While the male runners did report a significantly higher running distance per week (68.9 ± 5.2 vs. 59.1 ± 6.8 km), these groups of runners showed no significant difference in training experience (~4.8 years). Even when body weight was expressed in ml•kg^{-1}•min^{-1} and then corrected for lean body mass (ml•kgLBW^{-1}•min^{-1}) there were still VO_{2max} differences between groups (12 and 5%, respectively); suggesting additional influencing factors in oxygen transport variability.

VO_{2max} involves a series of steps and is therefore influenced at various levels by the physiology of the individual. There are three physiological factors that are believed to limit VO_{2max}: 1) pulmonary diffusion capacity, 2) maximal cardiac output and 3) oxygen carrying capacity of the blood (Bassett and Howley, 2000).

While the pulmonary diffusion capacity doesn't seem to be a limiting factor in untrained or even moderately-trained subjects, there is a clear pulmonary limitation in highly-trained athletes which can be overcome with O_2- enriched air

(Powers et al., 1989). Powers et al. (1989) investigated the effects of a hyperoxic gas mixture on VO_{2max} by having both trained and highly-trained subjects perform two VO_{2max} tests while breathing either room air (20.93% O_2) or the hyperoxic mixture (26% O_2). While there was no significant change observed in the VO_{2max} of the trained group (56.5 vs. 57.1 $ml \cdot kg^{-1} \cdot min^{-1}$), there was an increase in VO_{2max} from 70.1 to 74.7 $ml \bullet kg^{-1} \bullet min^{-1}$ along with an increase in arterial saturation O_2 saturation (90.6 to 95.9%) in the group of highly-trained runners when the hyperoxic mixture was used. This may be the result of highly trained athletes exhibiting a higher maximal cardiac output; leading to decreased pulmonary transit time and greater arterial desaturation (Dempsey et al., 1984). Nonetheless, the ability to increase exercise capacity, as defined by VO_{2max}, with supplemental O_2 verifies the existence of a pulmonary limitation.

Cardiac output (Q) is considered the second limiting factor and is the product of heart rate (HR) and stroke volume (SV). In a study involving ten untrained college students and ten collegiate distance runners there was no difference in HR_{max} between the groups during a graded exercise test (GXT) on a treadmill (Zhou et al., 2004). There were however, significantly greater SV_{max} and Q_{max} values for the collegiate runners (145.0 ± 7.79 vs. 127.9 ± 14.0 $ml \cdot beat^{-1}$ and 26.3 ± 1.73 vs. 21.3 ± 1.58 $L \cdot min^{-1}$, $p < 0.01$, respectively). The investigators were also able to show a significant positive correlation between VO_{2max} and Q_{max} ($r = .993$, $p<.01$) in the trained group. Thus, the greater VO_{2max} in the trained group was due in large part to greater values in Q_{max} and SV_{max}.

The third possible limiting factor of VO_{2max} is the oxygen carrying capacity of the blood. This limiting factor is supported by research involving induced erythrocythemia, or blood doping, in highly trained runners (Buick et al., 1980). Eleven runners (age = 21.1 ± 2.8 years, VO_{2max} = 5.11 ± 0.49 $L \cdot min^{-1}$) underwent VO_{2max} testing before and after phlebotomy, after reinfusion of a 50 ml saline solution and after reinfusion of 900 ml of blood. Twenty-four hours after reinfusion there were significant increases in VO_{2max} (5.11 to 5.37 $L \cdot min^{-1}$) and run time to exhaustion (7.20 to 9.65 min). This investigation on the effect of blood doping on aerobic work capacity clearly demonstrates that oxygen transport capacity imposes limits upon VO_{2max}.

These limitations brought on by the three 'central' limiting factors serve as illustrations of the basic physiological qualities that a runner must seek to improve through training in order to hope for improvements in VO_{2max}. There have been numerous studies investigating the effects of different training programs on VO_{2max} development. Helgerud et al. (2007) studied the effects of 4 different aerobic training protocols in 40 moderately-trained young adult males (24.6 ± 3.8 years). After ensuring that each of the 4 training strategies resulted in non-significant differences for total oxygen uptake the subjects were divided into either the 1) long slow distance running (LSD) group, 2) lactate threshold running (LT) group, 3) 15/15 interval running (15/15) group or the 4) 4 x 4-min interval running (4x4) group. After a training period of 8 weeks there was a significant increase in VO_{2max} for both the 15/15 (5.5%) and 4x4 (7.3%) groups. Both interval groups worked at higher intensities than the continuous LSD (45 min @

70% HR_{max}) and LT (24.25 min @ 85% HR_{max}) groups. The 15/15 group was required to run forty-seven 15 second intervals (90-95% HR_{max}) interspersed with 15 seconds of active recovery (70% HR_{max}) and the 4x4 group ran four 4 min intervals (90-95% HR_{max}) with 3 min active recovery (70% HR_{max}) between each interval. Because total oxygen uptake was similar between trials the authors concluded that when seeking to improve VO_{2max} a runner cannot compensate for the absence of high-intensity training by simply increasing volume. The high cardiovascular demands of interval training seem to promote significant VO_{2max} adaptations through changes in SV and Q. Given the correlations already described between Q_{max} and VO_{2max} it was no surprise that the investigators also found significant ($p \leq .05$) increases in SV and Q in the 15/15 and 4x4 groups. These findings further support Q as a primary influencing factor of VO_{2max} and although there is evidence that previously untrained individuals may experience increases in VO_{2max} during low- or moderate-intensity continuous running (Suter et al., 1995) these data support the notion that competitive runners should incorporate exercise at higher training intensities (80 to 90% VO_{2max} or greater) for the greatest improvements (Denadai et al., 2006 and Wenger & Bell, 1986).

There are three additional aerobic factors however, that have also been shown to affect endurance performance. The existence of these additional parameters should provide relief for coaches and athletes as there seem to be developmental limits to VO_{2max}. When investigating VO_{2max} development, Daniels et al. (1978) observed significant improvements of 5 to 15% in VO_{2max} in untrained subjects after approximately four to eight weeks of training. In the same study, the well-trained runners who participated in the running program displayed no significant changes in VO_{2max}, but did demonstrate a 6 sec improvement in 800 meter run time and a 97 sec improvement in the 3,200 meter run time. Changes in VO_{2max} seem to be an early adaptation to training that does not accurately reflect the overall physiological effect of long-term aerobic training. An illustration that highlights the role of the forthcoming aerobic parameters in endurance running involves data collected from a single runner. Between 1991 and 1995, A.M. Jones (1998) biannually collected data on a world-class 3,000 m female runner. Over the course of data collection the runner's 3,000 m personal best (PB) time improved from 9:23 to 8:37 (min:sec). This large improvement in PB from 1991 to 1995 occurred despite a concurrent decrease in VO_{2max} over the same period (from 72.8 to 66.7 $ml \cdot kg^{-1} \cdot min^{-1}$). Additional data from this study on lactate threshold and running economy may assist in explaining how running performance can improve with either no changes, or even decreases, in VO_{2max}.

Lactate Threshold and VO_2 Kinetics

Lactate threshold (LT) symbolizes a shift in substrate utilization during exercise. As a runner continues to run at an elevated intensity, or increases intensity for a short time, there is an accumulation of blood lactate from the working muscles. When runners operate at sub-maximal work rates for extended periods of time they reach what is termed "steady state." This "steady state" represents a balance between hydrogen (H^+) availability and H^+ oxidation (McArdle, Katch and Katch, 2001). During strenuous exercise there is an accumulation H^+ in the muscle tissue as a result of excessive H^+ formation, due to increased activity of non-oxidative energy processes and insufficient H^+ oxidation. These H^+ ions then combine with pyruvate to form lactate. An accumulation of lactate therefore signifies the onset of non-oxidative energy processes as the primary pathways for energy production. If lactate accumulation exceeds its removal rate, acid-base regulation becomes exceedingly difficult. Normal blood pH (a measure of H^+ concentration and acidity) is approximately 7.4. It is at this pH that human chemical and physiological processes best operate. With the increase in H^+ and subsequent formation of lactate, blood pH drops considerably to as low as ~6.8 (Hermansen and Osnes, 1972). When blood pH drops (acidosis) below ~7.0 a runner may experience nausea, headache, or dizziness. This acidosis may also cause sensations of discomfort or pain within the active muscles, in essence forcing the runner to decrease or stop intense exercise so that homeostasis may be reinstated.

Another term which is mistakenly used interchangeably with LT is Onset of blood lactate accumulation (OBLA). While both LT and OBLA represent measures of lactate accumulation in blood and are measured in millimoles of lactate per liter of blood ($mM \cdot L^{-1}$), they should be distinguished as different measurements. LT represents the point, or intensity, at which a small increase in blood lactate concentration is found (above 1.0 $mM \cdot L^{-1}$). OBLA signifies an intensity associated with even greater (4.0 $mM \cdot L^{-1}$) blood lactate levels (Yoshida et al., 1987). When Japanese researchers investigated the relationship between LT, OBLA and VO_{2max} in their subjects (n=19, Female, 20.0 ± 2.3 years) they found significant correlations between both LT and OBLA, and VO_{2max} (r = .84

and r = .80, p ≤ .01, respectively). Lactate threshold also displayed a higher correlation with 12 min run distance (r = .73, p ≤ .01). These higher correlations led the researchers to suggest that LT is the best lactate index when considering blood lactate accumulation as an aerobic parameter of endurance running performance (Yoshida et al., 1987). That same 3,000 m runner who improved her PB despite a decrease in VO_{2max}, showed large improvements in her LT. Her speed at LT (V_{LT}) improved from 250 to 300 $m{\cdot}min^{-1}$ (or from 9.3 to 11.2 mph) by 1995 (Jones, 1998). These data, when considered together with the data from earlier studies relating LT to running performance, suggest that part of her improvement was due to this LT shift. Additional research conducted on 18 experienced male (28 ± 9.0 years) runners showed lactate threshold to be positively correlated to running performance (r ≥ .91) over various distances (3.2 km to 42.2 km, Farrell et al., 1979). V_{LT} demonstrated higher correlations to performance at each race distance than any of the other physiological variables measured, including VO_{2max}. An improvement in LT represents both an ability to sustain a greater speed without excess blood lactate accumulation and to experience lower rates of lactate accumulation at any given speed.

When Esfarjani and Laursen (2006) manipulated the intensity of interval sessions they found significant improvements in V_{LT} (+11.7%) as the result of repeated (5 to 8 intervals) running at the velocity associated with VO_{2max} (vVO_{2max}) for a moderately prolonged period of time (~3:20 min:sec). However, increasing the interval intensity to 130% of vVO_{2max} and decreasing the duration to 30 sec per interval did not result in any significant change of V_{LT}. To elicit the greatest adaptations on LT requires working at or near the LT, but not necessarily above it. This study demonstrates how going above vVO_{2max}, or one's aerobic ceiling as related to velocity, begins to elicit non-oxidative energy processes and may hinder the development of some of the sought after oxidative adaptations that influence LT. Running at, or near, vVO_{2max} submits the muscle to a gradual rise in lactic acid, increasing blood lactate and forcing physiological adaptations to both improve lactate removal and promote lower lactate production rates.

Oxygen uptake (VO_2) kinetics represents another aerobic parameter which is less prevalent in the literature. This is due in large part to VO_2 kinetics not being considered a 'primary' determinant of running performance but rather as having a moderate relationship to endurance performance (Kilding et al., 2006). In order to measure VO_2 kinetics researchers measure the rate at which VO_2 rises at the onset of exercise. The time required to attain various VO_2 levels is referred to as the primary time constant (*t*) and has been shown to decrease with endurance training in both untrained (Phillips et al., 1995) and trained individuals (Norris & Peterson, 1998). When 36 moderately trained male endurance runners were tested through six rapid transitions from walking (66.7 $m \cdot min^{-1}$) to running at a speed correlating with 80% of their ventilatory threshold (V_T), there was a moderate correlation ($r = -.55$, $P = .001$) between *t* and 5 km running performance (Kilding et al., 2006). The same could not be said when the group was divided into high- and low-performance groups based on 5 km trial time and it was ultimately suggested that VO_2 kinetics alone are a poor determinant of 5 km racing performance. Rather, VO_2 kinetics may be more useful for longitudinal physiological assessments better reflecting adaptations to regular training in individual athletes rather than in large groups of runners.

VO_2 kinetic adaptations have been found to increase significantly as the result of either continuous low-intensity training or high-intensity interval training (Berger et al., 2005). Berger et al. (2005) investigated the effects of cycling at either 60% VO_{2max} for 30 min or completing twenty, 1 min intervals at 90% VO_{2max}. The subjects reported 3 – 4 times per week over the course of the 6 week program. Participants of both training programs experienced significant decreases in *t* (-25-34%, $p \leq .05$) when compared to the control group.

These two aerobic parameters (lactate threshold and VO_2 kinetics) are primarily influenced by peripheral adaptations. The shift in LT which accompanies aerobic training is believed to be the result of both decreased rates of lactate production (Katz and Sahlin, 1988) and improved blood lactate removal (Donovan and Pagliassotti, 1990) while VO_2 kinetics are likely determined by the muscles ability to utilize oxygen, thus becoming a measure of muscle oxidative potential (Whipp & Mahler, 1980).

These observed training adaptations in LT and VO_2 kinetics, point toward the development of a greater oxidative capacity of the muscle as the most likely explanation. That peripheral adaptation may be associated more with LT and VO_2 kinetics rather than with VO_{2max}, was first proposed by J.O. Holloszy and E.F. Coyle (1984). Consistent observations on muscular adaptations to training have promoted mitochondrial alterations as the primary peripheral adaptation associated with fluctuations in LT and VO_2 kinetics. Any alterations to mitochondrial volume and enzyme activity are significant in that they would allow for a greater oxidative capacity within the muscles. An increase in mitochondrial density would allow for lesser homeostatic imbalance at the onset of exercise by allowing trained runners to exercise with an increasing reliance on these oxidative processes. Due in part to increases in mitochondria within the muscle as a result of aerobic training, this adaptation would promote a greater utilization of the oxidative rather than the non-oxidative systems to meet the energy demands of running; O_2 uptake would be improved and lactate production would be reduced. In a supporting study, the effects of a 6-month moderate-intensity jogging program resulted in a significant increase (+20%, $p \leq .05$) in mitochondrial volume density (Suter et al., 1994). The participants were enrolled in a running program requiring them to run at 75% VO_{2max} for 120 $min \cdot wk^{-1}$ over the course of the 6-month study. Muscle biopsies were taken from the vastus lateralis of the thigh both pre- and post-training. This increase in mitochondrial volume density highlighted the effects of a moderate running program and supported previously documented improvements (+38 to 43%) which utilized cycling programs of high-intensity (85 – 95% VO_{2max}) to elicit even greater mitochondrial adaptations (Hoppeler et al., 1985 and Rosler et al., 1985).

Similar training studies have been conducted in the investigation of mitochondrial enzyme activity. Gurd et al. (2010) followed 9 (3 females and 6 males) during a six week high intensity interval training program. These athletes were required to complete ten, 4 min intervals done at 90% VO_{2max}, with 2 min of passive recovery between intervals. The researchers found significant ($P < .05$) increases in maximal activities of citrate synthase (CS, + 28%) and β-hydroxyacyl-coenzyme A dehydrogenase (HADH, +28 %). These important mitochondrial enzymes serve as catalysts within muscle mitochondria with CS serving as an index of the citric acid cycle and HADH serving as an index of β-oxidation (Wiegand & Remington, 1986 and Ngo et al., 2012). Elevated activity of these enzymes represents a specific peripheral adaptation to regular endurance training, believed to enhance fat metabolism and provide greater amounts of energy to the working muscles through the oxidative pathways (Hansen et al., 2005 and Klausen et al., 1981).

Work Efficiency

According to J.T. Daniels (1978), efficiency refers to the amount of work done and the energy expended in doing it. When this 'efficiency' is investigated as the part of work being performed in order to increase running velocity the term 'running economy' (RE) is better suited. RE describes the relationship between running velocity and energy expenditure and represents a more specific part of the work performed under precise energy demands. RE is a combination of physiological and biomechanical factors that determine the body's effectiveness in transferring energy into locomotion.

This important parameter was first described in early studies of the 1920's when VO_{2max} was being investigated and deemed the 'primary determinant' of endurance performance. As recalled in the early work of Hill and Lupton (1923) there was a significant emphasis placed on VO_{2max}. However, even these researchers acknowledged the presence of efficiency and economy when they stated that “a man may fail to be a good runner by reason of a low oxygen intake, a low maximum oxygen debt, or a high oxygen requirement; clumsy and uneconomical movements may lead to exhaustion, just as well as may an imperfect supply of oxygen” (Hill and Lupton, 1923 p. 158).

These ‘clumsy and uneconomical movements’ are investigated between runners by comparing oxygen consumption rates at given intensities, or speeds. A more economical runner would demonstrate lower oxygen consumption rates at a given speed; signifying a lower energy expenditure while running at that speed. The rational being that if a runner were to improve their RE, more of the energy produced through their oxidative processes would be transferred to their running velocity and performance would be improved.

When considering the performance improvements in Jones’ 3,000 m runner, it has already been proposed that a shift in lactate threshold was partly responsible. In addition, the RE of the 3,000 m runner improved from 1991 to 1995. She lowered her oxygen consumption, and thus energy expenditure, while running at 267 $m \cdot min^{-1}$ (~10 mph) from 53 to 47.6 $ml \bullet kg^{-1} \bullet min^{-1}$ (Jones, 1998). It is reasonable to suggest that her race performance improved due in part to both the 20% increase in speed at lactate threshold and 10% decrease in oxygen consumption during the steady state running test.

Morgan et al. (1989) were successfully able to demonstrate the use of RE as an indicator for running success. When comparing the most recent 10 km PB’s of ten well-trained runners there was a significant correlation ($r = .64$, $p \leq .05$)

between run time and running economy. The ten runners were considered well trained and were homogenous in VO_{2max} (64.8 ± 2.1 ml•kg^{-1}•min^{-1}). Though some studies provide little supporting evidence of RE as a significant parameter of endurance performance (Cunningham, 1990, Plank et al., 2005), it has become apparent that due to inter-individual variability of VO_{2max} there may only be observed correlations as runners become more homogenous in VO_{2max}. RE exerts its largest influence as a parameter of endurance performance through its interaction with VO_{2max}. In the same study, Morgan et al. (1989) further identified a significant correlation ($r = -.87$, $p \leq .01$) between 10 km run time and velocity at VO_{2max} (vVO_{2max}). Because vVO_{2max} represents the combination of RE and VO_{2max}, the higher observed correlation serves only to solidify the position of the two factors as 'primary' aerobic parameters. If a runner were able to improve RE, therefore decreasing O_2 consumption while running at various speeds, a corresponding increase in VO_{2max} would lead to an even more pronounced improvement in vVO_{2max} and performance. Simply put, O_2 consumption would be lower at any respective speed and their maximum O_2 uptake capacity would be elevated.

Comparing two of their runners' vVO_{2max} and 10 km race performances, Morgan et al. (1998) illustrated how two runners with similar VO_{2max} values (Δ = 1.2 ml•kg^{-1}•min^{-1}) exhibited substantially different 10 km race times (runner A = 30:47 and runner B = 34:18 min:sec). After collecting oxygen consumption data at various speeds it became clear that runner A was more economical, displaying a lower oxygen consumption rate at all running speeds (Δ = -13.4 ml•kg^{-1}•min^{-1}).

Accordingly, runner A achieved higher vVO_2 speeds at each VO_2 stage and was able to outperform runner B; as manifested through the subject's 10 km run time.

Franch et al. (1998) examined the effects of various training intensities on RE. The subjects were divided into one of three groups: 1) continuous distance (DT), 2) long-interval training (LIT) or 3) short-interval training (SIT). Each subject ran 3 $d \cdot wk^{-1}$ for 20 $min \cdot d^{-1}$ for 3 weeks followed by an increase in session duration to 30 $min \cdot d^{-1}$ for 3 more weeks. The average HR's for the DT, LIT and SIT groups during their training runs were not significantly different and were reported as 93%, 94% and 92% HR_{max}, respectively. There was variation in mean running speed, in hopes of exhausting the runners, between groups and therefore also variation in distance covered. In each training session the DT group covered the greatest distance and lowest mean speed (6,381 m, 250 $m \cdot min^{-1}$) followed by the LIT (5,664 m, 277 $m \cdot min^{-1}$) and SIT (3,409 m, 340 $m \cdot min^{-1}$) groups. Running economy was found to increase significantly in both the DT (+3.1%, $p \le .05$) and LIT (+3.0%, $p \le .05$) groups as a result of training, but not in the SIT group. Similar to the results of higher training intensities in the LT training studies there is less benefit to RE with short, supra-maximal intervals. The mechanisms behind this improved RE as a result of either DT or LIT training is not yet clear. The factors affecting RE are still under investigation.

Running Economy

When attempting to understand RE there are various biomechanical and physiological factors that must be considered. Theoretically, the biomechanical effectiveness of a runner may be influenced by their anthropometric dimensions.

Oyster and Wooten (1971) took various anthropometrical measurements from 107 female college students. The largest significant correlation was found between ponderal index (PI, ratio of mass divided by height^3) and running velocity ($r = .50$). When also considering the correlation found between weight and running velocity ($r = -.37$) the authors suggested a slightly negative effect of weight on running speed. In support of these findings, Bale et al. (1986) were able to show significant differences in PI and weight between various levels of 10 km runners. They were able to collect data from 20 elite, 20 good and 20 average 10 km runners. Inclusion into each level required a certain 10 km race time. The elite, good and average runners exhibited 10 km race times of under 29:30, between 30:00 and 35:00, and between 35:00 and 45:00 (min:sec), respectively. The elite runners were found to be significantly ($p < .05$) shorter than the good runners (175.1 ± 3.8 vs. 179.9 ± 3.0 cm) and lighter than the average runners (64.4 ± 2.4 vs. 69.2 ± 3.7 kg). Elite runners tended to demonstrate lower PI; as they were generally shorter and lighter than the average and good runners. The investigation of anthropometric measurements as they relate to running performance is difficult for researchers to investigate due to the combination of such a large number of variables which may mask the true individual correlations. Currently, successful distance runners are thought to be ecto- or ectomesomorphic (lower body fat and weight), however there is no single anthropometric value that can be used to predict running performance.

In his review of Biomechanics and Running Economy, Tim Anderson (1996) points out that some movement patterns include nonproductive movements and suggests that total work might be reduced as the result of learning how to apply forces of appropriate magnitude in productive ways. The difficulty in applying this logic lies in the inter-individual variability of many of the biomechanical factors thought to influence productive movements. Differences in musculature, body mass distribution, and skeletal dimensions display enough variance to create substantial difficulty for researchers attempting to understand their roles in RE. Instead, the emphasis has been placed on the study of gait patterns. In their investigation of the biomechanical variables thought to influence RE, Moore et al. (2012) found that beginner runners naturally develop a more economical running gait as they become more economical. Over the course of a 10 week training program, 14 inexperienced runners (Female, 34.1 ± 8.8 years) met once a week for a group training session. During the other sessions each runner employed a run/walk training program in order to be able to run continuously for 30 min by the end of the program. RE was measured as a combination of the recorded VO_2 values while running at 125, 139 and 152 $m \cdot min^{-1}$. Over the 10 week program RE significantly ($p < .05$) improved as VO_2 decreased from 224 ± 24 to 205 ± 27 $ml \cdot kg^{-1} \cdot km^{-1}$. A significant decrease in calf flexibility (27˚ ± 6.3˚ vs. 23.9˚ ± 5.6˚, $P < .05$) was found over the course of the training program adding support to the notion that decreased flexibility may improve running economy by promoting the use of elastic energy from stiffer muscle and tendon structures; minimizing metabolic requirements for energy production (Craib et al., 1996, Jones, 2002, and Anderson, 1996). Also, accounting for ~94% of the change in RE were changes in three kinetic/kinematic variables: 1) a less extended knee at toe off (knee angle as foot leaves the ground), 2) later peak dorsiflexion (maximum ankle angle) during the stance phase and 3) slower eversion (movement of the sole of the foot away from the median plane) velocity at foot touchdown. These biomechanical alterations that accompanied regular training suggest a naturally occurring "self-optimization" as there was no instruction on running form manipulation. This "self-optimization" coincides well with an individuals naturally selected stride length and stride frequency.

It has been shown thus far that every individual runner tends to choose an 'optimal' stride length and frequency, as a result of their individual mechanics, that promotes the lowest VO_2 while running. Runners seem to choose optimal stride lengths and frequencies which result in a lower VO_2 (improved RE) when running at any given speed. Furthermore, the manipulation of either stride length or stride frequency has been shown to result in an increase in VO_2 (decrease in RE) at constant running speeds (Cavanagh et al., 1982 and Mercer et al., 2008). While it is clear that biomechanical factors are largely responsible for changes in RE, there is no evidence that the teaching of "proper" or "efficient" running styles further promote improvements in RE. When investigators studied the effects of a 12-week "pose method" instruction program on gait and RE, they were able to alter gait patterns with instruction (Dallam et al., 2005). The study divided sixteen male sub-elite triathletes (35.6 ± 5.1 years) into either the control group or the experimental group. The control group was instructed to maintain their normal training routine. The experimental group maintained their normal training while participating in an additional 1 $hr \cdot wk^{-1}$ instructional session on the "pose method" which emphasized: 1) S-shaped body at foot strike, 2) mid-foot striking, 3) vertical foot removal after foot strike, 4) minimal arm use and 5) slight forward trunk lean, in an attempt to improve RE through a decrease in stride length and concomitant decrease in vertical oscillation (Romanov and Robson, 2003). After the 12 week instruction period the experimental group did display a significant decrease in stride length (137.25 ± 7.63 vs. 129.19 ± 7.43 cm, $p < .05$) and vertical oscillation (8.44 ± 1.0 cm vs. 6.92 ± 1.0, $p < .05$) following the 12 week instruction period (Dallam et al., 2005). Initial observation would suggest that the lower stride rates resulted in less vertical oscillation and therefore less energy wasted in 'unproductive' movements which do not propel the athlete forward. Ultimately however, these athletes did not display a simultaneous improvement in their RE, as steady-state VO_2 significantly ($p < .05$) increased. RE was represented by the average VO_2 while running at both 215 and 250 $m \cdot min^{-1}$ and increased from 3.28 ± 0.36 to 3.53 ± 0.29 $L \cdot min^{-1}$ (Dallam et al., 2005). These data show the adaptability of an athlete's gait patterns while emphasizing the efficiency of self-selected running mechanics. The teaching of proper running form may be of little use or even detrimental to RE.

Moore et al. (2005) were able to show how biomechanical adaptations to regular training promote the development of RE. Additional exploration into the factors influencing RE points to changes in ventilatory demand as a potential physiological factor that may be alterable with training. Patton and Vogel (1977) investigated the effects of a 5 $d \cdot wk^{-1}$ running program that alternated runs of 2 and 4 miles. After a period of 6 months it was found that when running at 161 m·min^{-1} (6 mph) the subjects displayed a significant decrease in sub-maximal minute ventilation (V_E, 85.1 ± 1.8 vs. 74.5 ± 1.7 L·min^{-1}, $p < .01$). These individuals were breathing less air in order to complete a given amount of work; they were more economical. This observation seems somewhat redundant; as any adaptations associated with improved RE would lead to decreased V_E in trained runners simply due to lower O_2 demands at any speed. Therefore, it was not completely unexpected when Franch et al. (1998) found a lower V_E (~ 11 L·min^{-1} lower) in their long-interval (LIT) and continuous distance (DT) running groups that also displayed significant improvements in RE (3.0% and 3.1%, respectively). Franch et al. (1998) had investigated three groups: 1) LIT (4-6 intervals of 4-min, mean speed 277 m·min^{-1}, 2) DT (20 to 30 min, mean speed 248 m·min^{-1} and 3) SIT (short-interval, 30-40 intervals of 15 sec, mean speed 340 m·min^{-1}). With only the SIT group displaying no significant improvement in RE and reporting a significant correlation between V_E and RE ($r = .77$, $P < .001$) the researchers suggested that the improvements in V_E that accompanied LIT or DT training attributed to improved RE. While a correlation in itself does not imply any specific cause and effect relationship, the findings of Aaron et al. (1992) suggest that the muscles involved in respiration (diaphragm, external intercostal muscles, internal intercostal muscles, scalene muscles, and other accessory muscles) take in approximately 10% of the oxygen taken up by the body during exercise at VO_{2max}. Therefore, Franch et al. (1998) further speculated that the observed 11 L·min^{-1} decrease in V_E should correspond to a decrease in VO_2 of ~ 30 ml·min^{-1}, and accounting for 25% of their observed decrement in aerobic cost.

Regular training seems to influence RE through both physiological (oxygen cost of breathing) and biomechanical (kinetic/kinematic variables) adaptations.

Running Economy Response

The possibility of an acute response from equipment manipulation offers the perspective athlete the possibility of eliciting instant performance enhancing effects. In General, there are attempts made by many runners to enhance performance through the use of lightweight racing footwear and clothing. The current literature suggests an average weight effect on VO_2 of ~1% for every 100 g added to each foot. Philip E. Martin (1985) investigated the physiological and biomechanical response to running at 200 $m \cdot min^{-1}$ (7.5 mph) with added weight (n = 15, Male, highly-trained). Each subject ran five RE trials at the determined speed with 1) no added weight, 2) .5 kg added to thighs, 3) 1 kg added to thighs, 4) .5 kg added to feet and 5) 1 kg added to feet. When compared to the unloaded condition, VO_2 increased from 37.99 ± 2.44 $ml \bullet kg^{-1} \bullet min^{-1}$ to 38.62 ± 2.18 $ml \bullet kg^{-1} \bullet min^{-1}$ (.5kg) and 39.33 ± 2.21 $ml \bullet kg^{-1} \bullet min^{-1}$ (1 kg) when adding weight to the thigh. Loading the weight onto the feet provided even more dramatic results. When compared to the same unloaded condition, adding the .5 kg to the feet increased the VO_2 by 3.3% (39.26 ± 2.23 $ml \bullet kg^{-1} \bullet min^{-1}$) while adding 1 kg increased VO_2 by 7.2% (40.71 ± 2.28 $ml \bullet kg^{-1} \bullet min^{-1}$). The increases in VO_2 with the addition of both .5 and 1 kg to either the knee or feet were statistically significant, with the greater values from foot loading supporting the notion that weight added to the foot will educe larger responses in VO_2 (Frederick, 1984). These results were similar to previous studies with reported increases in VO_2 of approximately 4.5 to 6% per kg of added weight to the feet (Jones et al., 1984 and Frederick et al., 1984). Catlin and Dressendorfer (1979) reported an even greater increase in energy cost (9.4%) while running at 250 m·min^{-1} (9.3 mph) with .35 kg added to the feet. There is a strong possibility that the larger effect was partly due to design differences that were sufficient to alter RE beyond the standard weight effect since Catlin and Dressendorfer investigated weight effects using different shoe models (Martin, 1985 and Frederick, 1984).

Nigg et al. (2003) were able to find systematic and consistent changes in VO_2 as a result of altering the shoe sole material while keeping the difference between the hard and soft soled shoes at a minimal 6g. In the study, 20 male runners were recruited to run 6 min trials while using shoes of either the hard or soft sole material. Individual differences in VO_2 as much as 2% were reported and the researchers speculated that each individual runner may have a specific sole material that improves VO_2. Interestingly, the runners who experienced individual increases in VO_2 also experienced higher vastus medialis pre-activation, thus supporting the investigators' hypothesis that changes in sole material also result in a subject specific change in muscle activation of selected lower extremity muscles. Though none of the results were significant, Nigg et al. (2003) suggested that the inter-individual variability in the subjects' VO_2 response to varying sole stiffness may be too great to reach significance in group studies and that manipulation of shoe design in VO_2 response studies may be better served on an individual basis. The systematic results produced by each individual will undoubtedly fuel future research in attempts to understand how and why inter-individual variation of VO_2 responses exists when manipulating shoe design or sole material.

Adolescent Participation

Between 2007 and 2011 there has been a substantial increase in high school cross-country participation. According to data collected by the National Federation of State High School Associations (NFHS) there were approximately 246,948 male cross-country participants during the 2010-2011 school year (NFHS, 2011). This 11.7 % increase in cross-country participation, compared to the 2007-2008 school year (221,109 male participants), represents the growth of a very specific and unique athletic population. Upon examination of the current available literature regarding this population there is evidence of similar adaptations to the aerobic parameters as reported in adults.

Daniels et al. (1978) followed various groups of young male runners between the ages of 10 to 18 years. All of their young subjects were involved in active middle-distance running over the course of the study period. Though there was a significant increase in absolute VO_2 over the course of the study, as the young males matured and grew, there was also a parallel increase in body weight. The linear increases in these two parameters ultimately resulted in no significant changes in VO_{2max} when corrected for body mass ($ml \cdot kg^{-1} \cdot min^{-1}$).One particular group (n = 7) was followed for 5 years, specifically between the ages of 12 and 17 years. As expected based on the composite results of their data demonstrating increases in both absolute VO_2 and body mass, this group displayed no significant changes in VO_{2max} during this period (62.7 ± 5.2 vs. 61.2

± 4.4 ml·kg^{-1}·min^{-1}). These reported VO_{2max} values are rather high when compared to values attained from other adolescent groups. From their group of 120 random 14 to 17 year old boys Nagle et al. (1977) reported a mean VO_{2max} of 54.0 ml·kg^{-1}·min^{-1}. When comparing these data, the VO_{2max} values reported by Daniels et al. (1978) are approximately 15% higher than the VO_{2max} from the larger random sample of boys. This higher VO_{2max} falls within the previously suggested range for VO_{2max} increases as a result of training in adults. Daniels et al. (1978) therefore speculated that the majority of the discrepancy between the reported values was due to the effect of regular training. Plank et al. (2005) also found increases, albeit at the lower range of the spectrum generally associated with adult development, in VO_{2max} as the result of training in adolescent runners. The researchers followed 9 experienced (4.2 ± 2.1 years) male cross-country runners over the course of their 13 week season and found that the VO_{2max} of the young runners increased 6 % (61.6 ± 3.5 vs. 65.3 ± 2.9 ml·kg^{-1}·min^{-1}).

When considering those 7 young runners (age 12 to 17 years) from the Nagle et al. (1977) study, large improvements in 2 mile time trial performance (12:30 ± 52.2 to 10:35 ± 32.8 min:sec), most likely as the result of improvements in RE, were also documented. Over the course of the 5 year period, their VO_2 while running at 202 m·min^{-1} (7.5 mph) decreased significantly from 52.8 ± 3.6 to 42.2 ± 2.7 ml·kg^{-1}·min^{-1}. Ample literature suggests that younger runners may be less economical than adults and that growth contributes a large part to improvements in RE throughout adolescence (Rowland et. al., 1987 and Unnithan and Eston, 1990). In 1996 Maliszewski and Freedson suggested that RE differences between adults and children were in fact only significant at absolute speeds, but not at relative speeds. When having their child (n = 21, 9.8 ± 0.8 years) and adult (n = 25, 25 ± 4.6 years) subjects run at 160 $m \cdot min^{-1}$ the children displayed significantly higher VO_2 rates (40.57 ± 2.56 vs. 34.91 ± 3.23 $ml \cdot kg^{-1} \cdot min^{-1}$). However, when adjusted to a relative speed of 3.71 leg lengths per second for each subject, there was no significant difference in VO_2 (37.73 ± 2.83 vs. 38.97 ± 3.45 $ml \cdot kg^{-1} \cdot min^{-1}$). Thus, when dealing with absolute speeds and absolute running performance it seems that increases in body size and leg length during adolescence may be largely responsible for improvements in RE, simply by allowing the growing runner to cover more distance with every stride.

VO_2 kinetics have not yet been studied in depth within the adolescent running population, data from cycling studies within this population suggest similar VO_2 kinetic rates to adults. Lai et al. (2008) studied VO_2 responses in healthy male adolescents (n = 9, 14–17 years old) under varying workloads. For the adolescents, the observed t (time constant) while working at moderate (t = 63 ± 11 sec), high (t = 29 ± 9 sec) and very high (t= 36 ± 9 sec) workloads were all comparable to values attained in adult males (33 ± 16, 32 ± 17 and 34 ± 11 sec, respectively). With previous research showing enhanced VO_2 kinetics through faster t values in adults, it is not unreasonable to suggest that adolescents may adapt similarly through structured training. This however, has not been supported within the literature and represents a significant hole in understanding the aerobic parameters in adolescents. The only current study investigating the effect of training status on VO_2 kinetics was done by Marwood et al. (2011) and found no significant difference between the trained and untrained groups (27.8 ± 5.9 and 28.9 ± 7.6 sec, respectively). Their trained group consisted of 15 soccer players who reported an average of six to seven hours of training per week, while the untrained group reported little or no regular physical activity. It was possible that the cross-sectional design of the study limited the applicability of the data since improved VO_2 kinetics are generally regarded as an individual adaptation to regular training rather than a group descriptor. Future research investigating the longitudinal effect of training in the adolescent population would provide valuable data when attempting to understand VO_2 kinetic responses and adaptations to training.

While there are no studies involving V_{LT} as it relates to running performance in adolescent athletes, there is evidence that LT remains a strong predictor of performance and a primary aerobic parameter for endurance running success in adolescents. Fernhall et al. (1996) evaluated the relationship between run performance and various physiological variables in adolescent runners. The group of boys (n = 11, 16.5 ± 0.9 years) who participated in this study displayed a VO_{2max} of 67.7 ± 6.7 $ml\cdot kg^{-1}\cdot min^{-1}$ and 3 mile race time of 16.2 ± 0.92 min. The researchers found a significant correlation between VO_2 at LT and race performance (r = -.74). This correlation was superior to their correlation found between VO_{2max} and race performance (r = -.70). It is interesting to note that their definition of LT required a blood lactate accumulation of 4 $mmol\cdot L^{-1}$, which more accurately reflects the previously stated definition of OBLA. Despite this blurring of definitive terms, this group clearly demonstrated that the ability to maintain homeostasis during endurance exercise, by eliciting high VO_2 rates while minimizing lactate accumulation, remains an important parameter for success in endurance running within the adolescent population.

Support of RE improvements within the adolescent running population is also limited. Along with their VO_{2max} and lactate measurements, Fernhall et al. (1996) had also measured RE while having their young runners run at 215 $m \cdot min^{-1}$ (8 mph). Unfortunately, their sample data resulted in both an insignificant ($p > .05$) and low correlation ($r = .10$) relationship between RE and race performance. Plank et al. (2005) however, found a significant correlation ($r = .78$) between RE and end of season 5 km time trial performance. The 9 male (15.9 ± 1.0 years) runners showed no significant change in RE over the course of the training season. Pre- and post-season measurements of VO_2 had been taken while having the young athletes run at 235 $m \cdot min^{-1}$ and although RE seemed to decrease by season's end (53.1 ± 3.9 vs. 55.1 ± 4.3) there was no significance ($p = .051$). Through proper training RE would be expected to improve, and although the change in running economy was not significant, it was very close to being significant. The mechanism behind this slight drop in RE is unknown, but it does not change the finding of RE as a significant predictor of performance in these adolescent runners.

The manipulation of footwear and its effect on RE has not yet been studied within this growing population. Recent findings by researchers at Brigham Young University suggest that a more in-depth understanding of shoe design and performance indicators is required. Though the results are limited to the shoe designs used in the study, Logan et al. (2010) have provided evidence that changing footwear can alter loads placed on the body. While having their runners run over a force plate at 400 $m \cdot min^{-1}$ they were able to detect significant increases in loading rate, peak vertical impact force and peak braking forces with the use of racing flats. Racing flats, which are generally lightweight and offer little support, are common within the various running populations. Their use to improve running performance stems from the belief that footwear weight and design may improve RE and performance. These findings, of increased loading rates and forces, are novel in that they provide a potential risk factor that may accompany footwear manipulation. The sporadic and acute use of racing flats may subject the body to loads which it is unaccustomed to, possibly increasing the risk of acute injury. As understanding of the effect of footwear on RE and performance continues to take shape runners will be able to make more educated decisions by weighing the potential costs and benefits of their training practices. This study aims to be the first to investigate the effect of racing flats on RE in adolescent runners and will provide relevant information as runners, coaches and researchers continue to understand how footwear manipulation may affect the parameters influencing endurance running performance.

CHAPTER 3

METHODS

Subject characteristics

Twenty male cross-country runners between the ages of 14 and 17 years were recruited from the local running community through word of mouth. Parental permission for participation in the research protocol was given by the parents or guardians of each participant. Youth assent to participate in research was signed by each participant. All participants were considered sufficiently healthy to participate in VO_{2max} and running economy trials based on their completion of either the New South Wales Exercise and Physical Activity Readiness Assessment of Children and Young Adolescents (14 years) or the Canadian Society for Exercise Physiology Physical Activity Readiness Questionnaire (15 - 17 years) with their parent/guardian. The protocol was approved by the University of Nevada, Las Vegas Institutional Review Board (protocol number 1203-4083).

Instrumentation

Participant body composition data were taken through Bioelectrical Impedance Analysis, using a BIO ANALOGICS HealthPORT ELG III Metabolic Analyzer and accompanying BIO ANALOGICS Health Management System software (Beaverton, OR, USA).

A Precor USA C954/C956 commercial treadmill (Bothell, WA, USA) was used for the VO_{2max} and RE trials. Expired air samples and HR data were analyzed continually through the use of an Applied Electrochemistry Moxus Metabolic System (Bastrop, TX, USA) and accompanying Applied Electrochemistry Oxygen (S – 3A) and Carbon Dioxide (CD – 3A) analyzers (Naperville, IL, USA). HR was transmitted from a Polar transmission belt with a Polar RS800CX Sports watch (Lake Success, NY, USA) being worn by the participant as a HR back-up measure and for recovery monitoring.

The footwear conditions which were compared in the RE trials were available every half-size between sizes 8 and 12. The shoe models were the Mizuno Wave Elixir 6 (Norcross, GA, USA) and the Mizuno Wave Universe 4 (Norcross, GA, USA).

Collection of the Data

The data collection process was done through 2 scheduled visits to the Exercise Physiology Laboratory in MPE 312 with at least 2 days, but no more than 6 days separating the visits. Visit 1 consisted of the completion of the pre-participation screening questionnaire, the Parental Permission and the Youth Assent forms. Age, Height and Weight was recorded in the laboratory. The participant was asked to lay supine on a treatment table with their right foot uncovered in order to measure body composition through bioelectrical impedance analysis, requiring the attachment of electrodes on the dorsum of both the right foot and right hand in the following locations: between the 2^{nd} and 3^{rd} knuckle of the hand, on the middle of the wrist, between the 2^{nd} and 3^{rd} distal metatarsal joints of the foot and on the middle of the ankle. Once anthropometric and body composition data was obtained the participant completed their VO_{2max} test.

A continuous graded exercise test protocol (Modified Taylor Protocol) was followed. Participants were allowed to briskly walk at a self selected speed for approximately 2 minutes in order to warm-up. When the participant felt comfortable with beginning the procedure they were instructed to run at 11.25 $km \cdot h^{-1}$ and 0% grade. The inclination was increased 2.5% every 2 minutes until volitional fatigue (Rivera-Brown et al., 1994). RPE was taken every 2 minutes using the OMNI 10 point scale. Gas exchange measurements were recorded at 30 second intervals with the highest 60 second rolling VO_2 average used as the reported VO_{2max} value assuming that the following criteria for the attainment of

VO_{2max} were also met: 1) respiratory exchange ratio (R) ≥ 1.0, 2) HR ≥ 95% predicted max (208 - .7[age]) and 3) RPE ≥ 9. Upon completion of the graded exercise test the participant was allowed to self select a walking or jogging speed for their cool-down.

Visit 2 consisted of the RE trials under the 2 different shoe conditions. The weight of the participant was recorded in the laboratory in the same fashion as was recorded during the first visit. The participant ran in both the Mizuno Wave Elixir 6 and Mizuno Wave Universe 4. The determination of shoe order was randomly predetermined and counterbalanced. The RE trials were run at approximately 85% of the participants VO_{2max}, as determined from the first visit. The RE trials were run at a 0% grade with the approximate speed determined through the use of the ACSM metabolic equation for running at 85% of VO_{2max} where VO_{2max} is in $ml \cdot kg^{-1} \cdot min^{-1}$, S is speed in $m \cdot min^{-1}$ and G is gradient expressed as a fraction (10% would be 0.10):

$$.85(VO_{2max}) = .2(S) + .9(S)(G) + 3.5$$

Each participant was allowed to warm-up and at a self selected walking speed and then proceeded to run a 6 minute trial in each pair of shoes. The running speed display of the treadmill was covered and the subjects remained blind to the speed of the running trials. Gas exchange measurements were recorded in 30 second intervals. Running economy VO_2 was calculated from the average VO_2 of the final 2 minutes of each 6 minute stage. Following the 6 minute trial each participant was allowed to self select a walking speed to cool-down at for 1 to 2 minutes. Between shoe conditions the participant was given at least 6 minutes of passive recovery. In an attempt to further promote adequate recovery the participant was only allowed to continue to the second condition after this 6 minute recovery period, when their recovery HR was below 110 bpm and when they felt ready to complete the second 6 minute stage.

Statistical Analysis Methods

The data was analyzed using a paired t-test analysis (IBM SPSS statistics 20 software). The dependent variable investigated was VO_2. A bivariate correlation using the Pearson Correlation Coefficient (IBM SPSS statistics 20 software) was used to investigate any correlations between anthropometric measurements and performance data.

Limitations

The study was limited by the absence of lifestyle controls leading up to data collection. Although the runners were asked to prepare for the trials in the same manner that they would prepare for a race or demanding practice (e.g., sufficient sleep the night before and sufficient calorie consumption before), there were specific nutrition or sleep requirements imposed on the participants. In an attempt to control for daily RE variability which has been shown to range from ~1.5 to 5% the subjects performed both of the counterbalanced run trials on the same visit (Brisswalter and Legros, 1994, and Pereira and Freedson, 1997). While there is currently no literature on intra-individual variation within the same testing session, there is evidence that a 30 min maximal (~89% VO_{2max}) run does not increase aerobic demand of running or disrupt running mechanics to significantly affect RE (Morgan et al., 1990).

Delimitations

The study was limited to the investigation of a RE response due to footwear manipulation in adolescent male runners. The specific targeting of male runners with ages between 15 and 17 and the placement of a 5 km run time requirement was attempt by the researcher to limit the physiological variability in VO_{2max} and RE between participants which would be even more pronounced if the sample were completely random. While attempts were made to allow the inclusion of as many runners as possible who fit the gender and performance requirements, due to shoe availability athletes were only permitted to participate if their shoe size fell between size 8 and size 12. Runners with shoe sizes outside of this range were not included in the current study. Additionally, the results are applicable solely to the comparison of the specific shoe models used within the study. Due to the high variability in shoe design and weight that consumers face, the selection of 2 specific shoe models allowed for a standardized protocol and comparison of not only shoe weight, but also shoe design between all participants. The results of the study were also limited to an understanding of VO_2 responses to footwear manipulation and not directly to any performance responses to footwear manipulation.

CHAPTER 4

RESULTS

The anthropometrical and performance baseline data obtained from the runners' first laboratory visit are included in Table 1.

Table 1 Anthropometric and Performance Characteristics of the Subjects

	Male Runners *N = 20*
5,000 m Season Best (min)	17.52 ± 0.76
Age (yrs)	16.25 ± 0.97
Body Mass (kg)	64.27 ± 6.58
Height (m)	1.76 ± 0.08
Body Fat (%)	10.12 ± 2.81
VO_{2max} Test Time (min)	13.69 ± 1.43
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	70.56 ± 4.37

Values are Mean ± SD

Nineteen of the twenty runners satisfied all 3 requirements for the attainment of VO_{2max}. There was one runner who did not meet the HR requirement of HR ≥ 95% of their age-predicted maximum HR according to the equation 208 - .7(age). The runner was 17 years old at the time of testing with a maximum HR observed at 181 bpm; representing 91% of their age-predicted maximum HR. Though the failure to meet all 3 criteria would not qualify them as having attained VO_{2max} by the current study's definition, the runner did satisfy the other 2 criteria for VO_{2max} and they were included in the running trials. Their peak VO_2 as obtained from the

VO_{2max} running test was included in the VO_{2max} results and used for the determination of their running test speed.

When comparing the physiological data from the running trials the VO_2 associated with running in the SHOE (62.14 ± 5.87) was significantly higher ($p < .001$) than the VO_2 while running in the FLAT (60.94 ± 5.83 $ml \cdot kg^{-1} \cdot min^{-1}$, see figure 1).

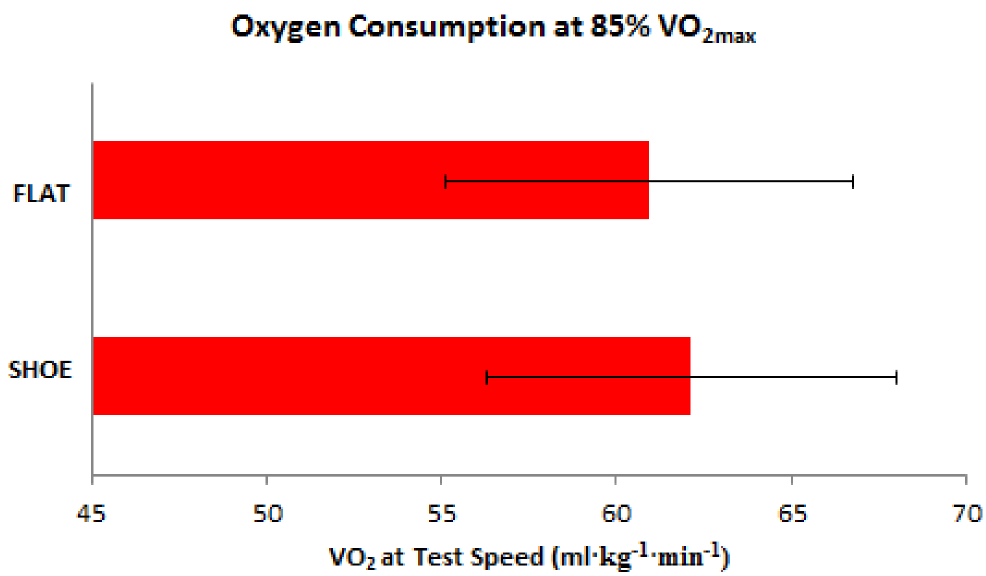

Figure 1 - Mean VO2 data comparing the SHOE and FLAT conditions. VO2 was significantly ($p < .001$) lower in the FLAT. Standard errors are represented by horizontal bars.

This 2% difference in VO_2 was accompanied by a significantly ($p < .05$) lower RPE while running in the FLAT. Using the Omni 10 point scale, the runners RPE while running at 85% VO_{2max} in the FLAT was about 1 point lower than when wearing the SHOE (5.3 ± 1.5 vs. 6.0 ± 0.8). There was no observed difference in HR between the trials (180.1 ± 9.8 vs. 181 ± 10.6 bpm). There were no significant correlations found between height and change in VO_2 ($r = -.155$, $p =$

.562) or weight and change in VO_2 ($r = .138$, $p = .563$). Individual subject data is included in Appendix A.

CHAPTER 5

SUMMARY, CONCLUSIONS,

AND RECOMMENDATIONS

Discussion of Results

Supporting the hypothesis that male adolescent runners can manipulate running economy on a treadmill through footwear manipulation, the major finding of the current study was that when running at a constant speed in the Mizuno Wave Universe 4™ racing flat there was a significant decrease in VO_2 compared with running in the Mizuno Wave Elixir 6™ training shoe.

This improvement in running economy may be explained in large part by the differences in shoe mass between the racing flat and training shoe used. Divert et al. (2008) found a significant difference in VO_2 when running in shoes weighing either 300g or 700g per pair. While running at 216 $m \cdot min^{-1}$, the adult males (24 ± 5 years) in their study exhibited a significantly ($p < .05$) higher VO_2 in the 700g pair of shoes (42.1 ± 2.3 vs. 40.6 ± 3.1 $ml \bullet kg^{-1} \bullet min^{-1}$). The current study also found VO_2 to be significantly higher in the shoes with the greater mass. The training shoes had a larger mass than the racing flat for each respective size. Depending on the size of the shoe the difference in mass between the shoes and flats were between 300g and 340g per pair, as measured in our laboratory.

Additionally, previous literature from Frederick (1984) would suggest a 1% difference in VO_2 for every 100g of added mass per shoe with the relative effect of this added mass increasing concurrently with speed, gradient and magnitude of the weight carried. The difference in mass of 150g to 170g per shoe in the current study would suggest a shoe mass effect on VO_2 of somewhere in the range of 1.5 to 1.7%. The observed change in VO_2 of 2% in the current study falls above this expected range and may be further explained by the speed of the running trials.

Previous running economy studies have maintained a constant speed for all participants. There is however, no defined speed for measuring running economy, potentially making comparisons between studies more difficult. The range of speeds used within various running economy studies has been reported between 167 and 250 $m \cdot min^{-1}$ (Cole et al., 2006, Cunningham, 1990, Dallam et al., 2005, Plank et al., 2005 and Thomson et al., 1999). The runners in the current study completed the running economy trials running at a range of 234 to 308 $m \cdot min^{-1}$ (M= 282.3 ± 18.6 $m \cdot min^{-1}$) and only one runner had a predicted speed at maximal lactate steady state under 250 $m \cdot min^{-1}$. Instead of controlling for speed between subjects, potentially resulting in differences in relative intensity, the current study incorporated control of relative intensity (by predicting maximal lactate steady state as 85% VO_{2max}), in an attempt to allow each athlete to reach higher relative intensities that may be more representative of what they experience in competitive settings (Almarwaey et al., 2004). The current study may therefore support the observations that the mass effect of footwear may be more apparent at higher speeds (Frederick, 1984).

Subject specific changes in VO_2 in the current study may in part be explained by potential differences in shoe sole material as the shoe models were not identical between trials. While the average change in VO_2 was 2% between shoe conditions, the change in VO_2 between the SHOE and FLAT conditions in the current study fell between -0.29% (lower VO_2 for SHOE) and 5.42% (lower VO_2 for FLAT). Nigg et al. (2003) found subject specific changes of up to 2% when comparing shoes of identical mass (within 6g of each other) but with different sole material. They were unable to identify any significant group characteristics, but emphasized that 'fine tuning' of sole material is most likely specific to each individual and may not elicit significant group effects. Thus it seems plausible that part of the subject specific variation may be due to how each runner's body responded to the differences in sole material composition. Based partly on these studies, shoe mass effects are believed to account for the majority of changes in VO_2 when manipulating footwear (Divert et al., 2008, Frederick, 1984 and Nigg et al. 2003).

When researchers investigated the effect of a 10 week training program on beginner runners and running mechanics, there were several biomechanical variables that changed in conjunction with RE (Moore et al., 2012). This observation that beginner runners naturally develop their running gait as they become more economical runners provides important insight into the role of biomechanics on running economy. Future investigations into these biomechanical traits in runners as a result of footwear manipulation may shed some light on the VO_2 response to footwear manipulation and it's magnitude in individual runners.

There were no significant correlations found in the current study between the general anthropometric measurements (height and weight) taken and the magnitude of change in VO_2. If oxygen consumption is influenced primarily by the mass of the shoe, then an understanding of intra-individual variations in VO_2 with footwear manipulation may require further investigations into specific anthropometric measurements (limb length and weight) and mechanical alterations of running form (Divert et al., 2003).

Practical Application

With previous research suggesting that improved running economy may increase sustainable running speed, the findings of this study become of great interest to runners and coaches looking to improve running performance (Burkett et al., 1985, Hanson et al., 2011 and Perl et al., 2012). Burkett et al. (1985) suggested that every 1% increase in VO_2 may lead to a 2.94 $m \cdot min^{-1}$ decrease in sustainable running speed. When considering the results from the current study, the observed decrease in VO_2 of 2% when wearing the FLAT would suggest an increase in sustainable running speed by 5.88 $m \cdot min^{-1}$. The mean 5000 m race times for the participants in the current study was approximately 17:30 (min:sec). This equates to an average running speed of 285.7 $m \cdot min^{-1}$. Thus, an athlete capable of running a 17:30 (min:sec) 5000 m race in the Mizuno Wave Universe may be able to maintain an average running speed of 291.6 $m \cdot min^{-1}$ through proper footwear manipulation. This could drastically lower their 5000 m race time from 17:30 to 17:09 (min:sec).

Conclusions and Recommendations

For Further Study

While the aim of the current study was to compare VO_2 responses between the Mizuno Wave Elixir 6™ standard running shoe (SHOE) and the Mizuno Wave Universe 4™ racing flat (FLAT) while running at maximal lactate steady state in male adolescent runners, further study into footwear manipulation and running performance in both adults and adolescents could potentially provide information regarding actual transfers of laboratory data to race performance measures.

The current study involved 6 minute running trials while running on a treadmill. While the speed was relatively high (85% VO_{2max}) for each participant there are some clear limitations to the application of the findings. The shoes used for the running economy trials were different models. Future studies investigating the weight effect of footwear on running performance may choose a protocol more similar to the one used by Martin (1985) in which he simply attached extra mass to the foot. This has the potential to minimize non-weight effects. However, the potential for alteration in the structure and sole material of the shoe remains as this design applies a variable that may influence how the shoe responds to the extra mass.

In order to easily control running speed the participants ran on a treadmill while each trial lasted 6 minutes, with only the final 2 minutes being used to calculate VO_2. Both the running surface and running time are different than many of the conditions in which the participants find themselves in during competition.

Literature suggesting that running surface may influence running speed through changes in ground contact time and stride length supports further investigations of footwear manipulation and running economy on varying running surfaces (McMahon and Greene, 1979). The amount of time spent running in competitive 5,000 m races and the presence of fatigue in these intense bouts may also provide opportunities for further research as fatigue is associated with decrements in running economy (Xu and Montgomery, 1995 and Burgess and Lambert, 2010). Additional investigation into the effect of fatigue on the VO_2 response to footwear manipulation may allow for further application of laboratory measures to competitive settings. Studies investigating possible biomechanical alterations and the magnitude of the VO_2 response with footwear manipulation may provide a more detailed explanation of the effect of footwear on running economy and performance.

The main observation of the current study was that running economy was better in the Mizuno Wave Universe 4™ than in the Mizuno Wave Elixir 6™. While this improvement in running economy within the adolescent population is most likely due to differences in mass between the shoe models a running economy protocol directly comparing the VO_2 response to footwear manipulation between adolescent and adult runners remains necessary and may provide a means to relate these findings to those found in adult studies.

There is need for studies involving performance tests in order to more effectively associate improvements in running economy through footwear manipulation with faster race times. Also, while the current study found no significant correlations between general anthropometric measurements (height and weight) and magnitude of change in VO_2, future research investigating specific anthropometrical measurements (limb length and weight) or biomechanical characteristics may aid in the understanding of intra-individual variation in VO_2 with footwear manipulation.

Appendix A

Participant	Age (yrs)	Height (in)	Weight (lbs)	Body Fat (%)	5000m Time (min)	VO_{2max} Time (min)	VO_{2max}*	Trial Speed (m·min^{-1})	Shoe VO_2*	Flat VO_2*	Shoe RPE (OMNI)	Flat RPE (OMNI)
1	17	68	154	15.4	18.95	12	68.6	274	62.8	61.3	7	6
2	17	75	154	10.1	16.48	14	70.6	283	55.1	53.8	3	2
3	15	69	145	9.9	17.52	14.17	74.9	301	65.7	65	6	6
4	17	74	166.5	13.3	17.3	10.6	59.1	234	49.7	49.1	7	7
5	17	71	143	13	16.65	14.17	75.7	304	59.1	55.9	6	5
6	15	66	113	9.4	17.23	12.83	74.6	300	65.9	63.8	6	6
7	17	66	133	8.9	18.42	11.5	72	289	66.1	65.5	6	5
8	15	70	134	11.4	16.95	14.6	76	306	72.3	69.3	6	7
9	17	70	129	4.9	17.32	14.5	73.3	294	62.2	61.6	6	5
10	17	71	158	13.2	17.6	12.17	65.4	260	51.4	50.3	6	2
11	16	70	146	7.6	18.17	14.5	76.5	308	70.5	68.9	6	4
12	17	69	147.5	13.4	18.85	10.5	64	255	57.2	55.4	6	5
13	16	71	143	6.1	16.83	13	70	280	62.3	62.4	6	3
14	17	70	149	11.1	16.8	11.5	69.4	277	61.4	59.3	6	6
15	14	68	120	8.1	17.25	14.5	73.2	294	65.4	65.2	6	7
16	16	66	117	7.9	16.98	12	68.3	273	59.1	58.2	6	5
17	15	74	158	10.4	17.27	12.33	68.4	273	58.8	58.9	6	6
18	16	69	130	6.1	18.47	10.66	71	284	67.9	68.1	6	7
19	17	61	150	10.1	18.6	11.33	68.9	275	63.4	61.3	6	6
20	17	71	138	12	16.78	13	71.3	286	66.5	65.5	6	5
MEAN	16.25	69.45	141.4	10.115	17.521	12.693	70.56	282.5	62.14	60.94	5.95	5.25
STDV	0.96	3.20	14.48	2.80	0.77	1.43	4.36	18.63	5.87	5.83	0.75	1.51

*VO_{2max} and VO_2 reported in ml•kg^{-1}•min^{-1}

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Education:
Bachelor of Science, Exercise Science, 2008
Brigham Young University

Teaching Experience:
UNLV Graduate Assistant
•Kinesiology 175: Physical Activity and Health Fall 2011, 2012
and Spring 2012
.
•Kinesiology 491L : Exercise Physiology Laboratory Summer 2012

CSN College of Southern Nevada
•Biology 121 : Human Nutrition Spring 2013

•Biology 189L: Fundamentals of Life Science Spring 2013

•Biology 223L : Human Anatomy and Physiology I Spring 2013

•Biology 224L : Human Anatomy and Physiology II Spring 2013

RESEARCH EXPERIENCE
Graduate Assistant
·Cosmed BODPOD
·Hydrostatic Weighing Tank
·Orca Metabolic Cart
·Moxus Metabolic Cart

Student Reviewer: **International Journal of Exercise Science**
2012: Effects of Exercise Sequence in Resistance-Training on Strength, Speed, and Agility in High School Football Players. (In Progress)

Abstracts
•2012 ACSM Annual Meeting Abstracts
Hafen, P., Bremner, C., Garcia, J., Girouard, T., Golding, L.A. (FACSM), Harris, S., Jarrett, M., Shaheen, H., Trocio, K. and Santo, T. Fitness Level of

Professional Hockey Players. *Medicine & Science in Sports & Exercise* 44 (5) supplement: S404, 2012.

Trocio, K., Chavez, C., Garcia, J., Golding, L.A. (FACSM), Goldman, J., Hafen, P., Hannston, A., Harris, S., Jarrett, M., Shaheen, H., Stalker, G. and Santo, T. Reliability and Validity of The HPI Caliper And Body Composition Formula. *Medicine & Science in Sports & Exercise* 44(4) supplement: S594, 2012.

•2012 SWACSM Meeting Abstract

Jarrett, M., Hafen, P., Moschella, K., Barkley, J. (FACSM), Dufek, J.S. (FACSM), Navalta, J., Tandy, R., and Santo, T. Interactive Video Gaming: Beneficial to Health or Just Fun? (In Progress)

GRANT AWARDS

University of Nevada, Las Vegas Graduate and Professional Student Award - $700 equipment grant 06/12

COACHING BACKGROUND

- USA Track and Field Level I Coach
- Certified Personal Trainer – National Strength and Conditioning Association (NSCA)
- Certified Strength and Conditioning Specialist (CSCS) – NSCA

Head Varsity Men's/Women's Cross-Country Coach

Adelson Educational Campus, Las Vegas, NV **2011-2012**

Coronado High School, Henderson, NV **2012-2013**

Thesis Title: EFFECT OF RACING FLATS ON RUNNING ECONOMY IN MALE ADOLESCENT RUNNERS

Thesis Examination Committee:

Chair, Antonio S. Santo, Ph. D. R.D.N., C.S.S.D.
Committee Member, Janet Dufek , Ph. D.
Committee Member, Lawrence Golding, Ph. D.
Committee Member, John Mercer, Ph. D
Committee Member, Merrill Landers, Ph.D