THE IMPACT OF REPLACING RUN TRAINING WITH CROSS-TRAINING ON PERFORMANCE OF TRAINED RUNNERS

A Thesis
by
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Abstract

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Previous research has shown that runners who cross-train can maintain physiological parameters such as maximum oxygen consumption (VO2max) but has been equivocal about the ability to maintain competitive running performance while cross-training. In this study, a group of high school cross country runners (N=17, 12 male, 5 female) was tested immediately after their season on a treadmill for VO2max, lactate threshold, and running economy at sub-maximal speeds. They also performed a 3000-meter time trial on a track. Following the tests, the runners were randomly assigned to one of two cross-training groups, the first using elliptical exercise machines and the second using stationary bicycles, and given assigned workouts to replace all running. After five weeks of cross-training, the treadmill and performance tests were repeated. A control group of runners (N=9, 6 male, 3 female) completed the same tests but continued normal off-season run training in the interim. Post-study 3-km time trials were significantly slower than the pre-study for the groups using an elliptical trainer (47.7± 11.3 sec) and a stationary bike (42.7 ± 6.3 sec), while the subjects who continued running showed non-significant improvements (9.4 ± 8.3 sec). Differences between the elliptical trainer and stationary bike groups were not statistically significant. No significant changes were found in any group for VO2max or lactate threshold. Cross-training with either an elliptical trainer or a stationary bike maintained VO2max and lactate threshold as measured during treadmill running, but they did not preserve running performance level.

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Dedication

This work, like everything I do, is inspired and made possible by the support of Denise, Griffin, and Nathaniel. Thank you for your love, patience, and support.

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Foreword

Portions of this manuscript will be submitted to the National Strength and Conditioning Association's Journal of Strength and Conditioning Research. The references follow the style guidelines for authors specified by that journal.

1. INTRODUCTION

1.1 - Definition of cross-training

Cross-training is the use of one mode of exercise to prepare for a sport in which that mode is not a part of the competition; for example, a competitive swimmer who uses running as a part of training is cross-training. In sports which involve medium- and long-distance running, athletes often exhibit injuries related to the repetitive-impact nature of their sports. Cross-training has been widely discussed as a method for reducing impact stress and thus preventing such injuries. It is also used as a method of allowing injured athletes to maintain as much fitness and performance capability as possible when they must reduce or eliminate running during their recuperation period. Many different modalities of aerobic exercise have been proposed as cross-training modes for runners, including cycling, swimming, deep-water running, and fitness equipment such as stationary bicycles, stair-climbers, elliptical trainers, and cross-country ski machines (Nordic Track™). Different forms of resistance strength-training are also mentioned as cross-training for runners, but this research addresses only cross-training modes that primarily target the cardiovascular system.

1.2 - Motivation for research

The most cited studies of running and cross-training have investigated the response of various physiological measures to different modes of exercise. These studies generally agree that in acute exercise, subjects can achieve similar values on variables such as VO2max, heart rate, perceived effort, and blood lactate level, whether running or engaging in cross-training. Training studies, in which cross-training supplements or replaces running for a period of time, are more difficult. As a result, few studies have looked at the long-term, as opposed to acute, effects of cross-training compared to running. Research in which cross-training completely replaces running in experienced runners is even more rare.

Previous training studies on runners have shown very little difference between running and cross-training of comparable duration and intensity with regard to VO2max, the primary measure of aerobic fitness. These studies have also failed to show a significant difference in performance after cross-training, compared to running. However, in almost all cases, subjects who replaced running with cross-training saw declines in performance, which did not rise to the level of significance due to the small sample sizes of the studies. Most studies did not use competitive runners as subjects, reducing the relevance for those most interested in the performance effects of cross-training. No previous studies have completely replaced running with cross-training in trained, competitive runners.

To be of value for competitive runners and coaches, research must use subjects who are well-trained prior to the study. Training volumes and intensities must be maintained as similar to the pre-study levels as possible, since the runners are presumably already engaged in what they and/or their coaches consider to be optimal training. The study must be long enough to be relevant to injury-recovery protocols and to allow for detraining effects, if any, to appear. The number of subjects should also be large enough to allow for relatively small performance changes (<2%) to be statistically significant.

Among runners of a similar competitive level, running economy, or the energy cost of running at a given pace, is a greater predictor of performance than VO2max. Running economy has not been a dependent variable in previous cardiovascular cross-training studies. Running economy tends to improve with long-term training, an effect that may be due, at least in part, to changes in the muscle due to the repeated stretch-shorten cycle that occurs with each foot-strike. The lack of neuromuscular stimulus from running could negatively affect economy during cross training, which might account for performance changes not accompanied by changes in VO2max. In this research, running economy was measured directly at a variety of paces, as was stride length, a factor that affects running economy.

The question of what mode of cross-training to use is an important one for coaches and athletes. Cycling, whether on the road or a stationary bike, has long been a readily available mode of cross-training for runners and has been the most commonly studied mode of cross-training. Cycling engages the same primary muscles as running and allows for easy manipulation of intensity, yet the different body position and the fact that body weight does not have to be supported mean the muscles are not engaged in precisely the same way in cycling as in running. Elliptical training has emerged as an alternative form of cross-training which may have some advantages for runners. While using an elliptical trainer, the individual does have to support body weight during exercise, and the body position and movements more closely match those of running. No previous studies have looked at the long-term effects of elliptical exercise. No studies have compared the long-term training effects of multiple training modes using the same protocol.

1.3 - Significance of the Study

This research compared the long-term effects of two different cross-training methods on running performance and physiological measures related to running performance and used a group that continued run-training as controls. One training modality, the elliptical trainer, has not previously been studied as a long-term replacement for running. The subjects of the study were competitive runners immediately after the end of their cross country season. The fixed training protocol across three different modalities and the use of trained competitive runners as subjects helps make the results more generalizable to all competitive runners. The pre- and post-study measures of VO2max, blood lactate levels, and running economy help identify the specific mechanism through which any observed performance changes occur.

1.4 - Research Design

Subjects in this study were 27 competitive cross country runners at the high school and developmental college level. Immediately after the season, subjects completed five weeks of training using exclusively one of three assigned modes: running, stationary bike, or elliptical trainer. Lab tests and time trials were conducted for all subjects before and after the training portion of the study.

This research aimed to determine what differences, if any, occur in runners after training using either traditional running training, stationary bike, or elliptical trainer. Comparison was made both between different training modes and between pre-training and post-training results within a training mode. Variables studied were 3000-meter running time, VO2max, running economy and stride length at various speeds, and blood lactate response at various speeds.

It was hypothesized that the running group would maintain time trial performance, while the cross training groups would both get slower, with the cycle group having a greater magnitude drop in performance. It was further hypothesized that no groups would show significant changes in VO2max, but that the cross training groups would see reductions in running economy and/or increases in blood lactate levels at a given running pace, with the elliptical group again showing relatively better results than the cycle group.

2. SURVEY OF LITERATURE

In reviewing the literature, the emphasis has been placed on work which will most directly impact the question of how long-term cross-training might affect running performance. The discussion of physiological and biomechanical factors focuses on how those factors change in response to training, interruption of training, or differential responses to various modes of training. The discussion of cross-training research focuses on comparisons of acute and training response of performance-related variables to various training modes in comparison to running and on how similar the subject population and research protocols are to the proposed model involving full replacement of running in trained competitive runners.

2.1 - Measured Variables Affecting Running Performance

Three characteristics can be defined that explain most of the variability in performance in distance running events: maximal oxygen uptake (measured as the volume of oxygen consumed per minute per kilogram of body weight, and subsequently referred to as VO2Max); the pace or level of oxygen consumption that can be sustained without producing increases in blood lactate levels (lactate threshold, or LT); and the energy cost of running at a given pace (running economy, or RE). This section looks at work that explores what factors influence these variables, how each variable may contribute to running performance, and how the variables may be measured.

2.1.1 - Maximal Oxygen Uptake or VO2 Max

Oxygen is used to create energy aerobically. VO2max refers to the maximum amount of oxygen an individual is capable of using in a given time and is calculated by taking the amount of oxygen inhaled and subtracting the oxygen content of the exhaled air (6). In weight-bearing exercise, such as running, the energy cost of exercise is proportional to body mass; to allow comparison between individuals, the VO2max measurement is generally obtained by dividing oxygen consumption by body mass. The measurement of VO2max is used to quantify the capacity of the aerobic system. Aerobic energy production has fewer negative by-products which limit the duration of exercise; thus for endurance performance, one of the goals is to increase our ability to work aerobically.

Midgeley and McNaughton's (61) comprehensive review on training begins with the statement, "The maximal oxygen uptake (VO2max) has been suggested to be the single most important physiological capacity in determining endurance running performance." Training to enhance VO2max is the subject of numerous review articles and popular coaching material. A great deal of the theory of endurance training is based on the idea of training at the speed that corresponds with VO2max and at certain percentages of VO2max (26).

VO2max is potentially influenced by a variety of factors as oxygen makes its way from the environment all the way to the mitochondria in the muscles. The volume of oxygen consumed (VO2) is calculated by using the Fick equation, where Q equals Cardiac Output, CaO2 equals arterial oxygen content, and CvO2 equals venous oxygen content:

$$VO2 = Q\ (CaO2 - CvO2)$$

Cardiac output is the product of stroke volume (the volume of blood pumped with each beat) and heart rate. Arterial oxygen content is the amount of oxygen in the blood that is being delivered to the muscles, while venous oxygen content refers to the amount of oxygen in the blood that is returning to the heart and lungs. The difference in arterial and venous oxygen content is the amount of oxygen being taken up by the muscles (13).

As demonstrated by the Fick equation, VO2max is influenced by a variety of factors. The most prominent factors which could influence VO2max are: the amount of oxygen taken in from the environment by the lungs; the maximum heart rate and stroke volume in the heart; oxygen carrying capacity in the blood; ability to remove oxygen from the blood at the muscles; and capacity to consume the oxygen in the muscles (6). Improvement or degradation in one factor in the VO2max "chain" can lead to a similar change in VO2max itself, but the situation is not always so straightforward. Some factors are known to be more likely to be limiting factors on total VO2max. Changes in the limiting factors are more likely to lead directly to a change in VO2max, while changes in non-limiting factors may have no effect (6). It is also possible that two factors could see changes in opposite directions, with the effects cancelling each other out and no change in overall VO2max.

Oxygen Intake - Oxygen diffusion from the lungs to the blood is rarely considered a limiter of exercise in healthy individuals at sea level. For example, at high exercise intensities, the oxygen saturation in the blood is typically above 95% (72). This has been used as evidence that oxygen intake and transport from the lungs to the blood is not a limiting factor since saturation is near full (72). However, the phenomenon of exercise induced arterial hypoxemia occurs in many well trained endurance athletes (28). This drop in oxygen saturation in well trained individuals significantly impacts VO2max. Thus the relative importance of oxygen saturation to VO2max changes with training status (28).

A study by Powers et al. (72) showed the effect of oxygen availability can vary between highly trained and normal subjects. They tested VO2max while inhaling normal air and oxygen enriched air in both groups. In the normal group, VO2max was not significantly different while inhaling either air. In contrast, the highly trained group saw a significant increase in VO2max (from 70.1 to 74.7 ml/kg/min) when inhaling oxygen enriched air. This leads to the conclusion that oxygen intake plays a role in limiting VO2max in highly trained people but not in normal subjects, thus showing the impact of training status and endurance capacities. The meaning of these findings for the current study is unknown. The highly trained group in the Powers study was at a very high level of VO2max - the average was above the highest subject in the current study. There is also no data on how VO2max response to oxygen intake changes after alterations in training.

The degree to which oxygen is removed from the air and bound to hemoglobin (Hb) is dependent on the partial pressure of oxygen in the air and the affinity between oxygen and Hb (13). In a natural environment, partial pressure of oxygen in the air is almost entirely dependent on air pressure, which, in turn, is largely dependent on altitude. The affinity of Hb and oxygen is how strongly the components are attracted to each other, and is affected by temperature, pH, hydrogen ion concentration, and carbon dioxide concentration. This is a highly non-linear relationship with respect to partial pressure of oxygen. Because this pressure is much higher in inspired air than in blood at the muscles, the normal situation is of blood leaving the lungs at near 100% saturation and departing the muscles having given up most of its oxygen (13). Lower concentrations of oxygen in inspired air, such as seen at higher elevations, can result in lower saturations in blood leaving the heart. There is known to be significant individual variation in the relationship between oxygen pressure and Hb-oxygen affinity (i.e., some individuals exhibit “altitude effects” at much lower elevations than others), but no research was found suggesting a training response in the pressure-affinity relationship.

The current study was conducted at approximately 1000m altitude. Most individuals show no measurable change in oxygen saturation at this elevation, but a small number do. This could possibly affect any changes that might occur in oxygen intake capability due to fitness.

Cardiac Output - The heart’s cardiac output (Q) refers to the amount of blood that is pumped out of the heart each minute and is usually regarded as the major limiter of VO2max. Q is the product of heart rate (HR) and stroke volume (SV); so to increase Q, one of these factors would have to be increased. Maximal heart rate is a factor that does not change due to training, and perhaps even lowers slightly, while sub-maximal heart rate is lowered with training (13, 55). Offsetting this, endurance training leads to increase in SV at rest and all intensities.

The increase in SV occurs through increases in heart size and contractility (13). Size changes are reflected in end-diastolic volume (EDV), which is the amount of blood present at the end of the filling of the chambers of the heart. Contractility contributes to EDV by allowing greater stretch which allows more blood to enter the heart. Contractility also affects SV via the Frank Starling mechanism, which states the greater the stretch on the heart, the greater the subsequent contraction (13). This means that an increase in EDV, which would create a greater pre-stretch, would increase the subsequent ejection, or SV. Increasing EDV thus plays a central role in increasing SV.

In addition, endurance athletes have an increased ability to fill the heart rapidly at high intensities, which is important as at higher intensities, there is less time between heart beats for the heart to fill (55). Work by Levine et al. (56) showed that in endurance athletes, their increased SV was almost entirely a result of EDV increases due to enhanced elasticity of the heart.

Another mechanism that increases SV is an increase in blood volume. A study done by Krip et al. (48) manipulated blood volume in endurance trained and untrained individuals and studied its effect on cardiac function. They found that blood volume increases and decreases caused significant alterations in maximal diastolic filling rate, SV, and Q. These results demonstrate that an increase in blood volume, which is an effect of endurance training, improves SV and Q via enhanced diastolic filling.

Increases in heart rate near maximum heart rate can have negative consequences for oxygen delivery due to the rapid cycling that occurs in the heart and lungs. The heart may not have time to fully fill before each stroke (possibly reducing cardiac output) and diffusion time for oxygen in the lungs is greatly reduced because of how fast the blood moves through the oxygen exchange zone (potentially reducing oxygen saturation in the blood.). The body must balance multiple components of VO2max to achieve maximum oxygen delivery. Thus, in progressive exercise tests, subjects typically reach VO2max at a heart rate slightly below maximum; and then, they often see a slight drop-off in VO2 while heart rate climbs to a max in the final stages of the test. A similar situation could potentially exist at extreme altitudes where, despite increases in cardiac output, oxygen uptake would not increase due to diffusion limitations (80).

Oxygen in the Blood - Another major factor in oxygen transport is the oxygen carrying capacity of the blood itself. This is dependent on the red blood cell (RBC) mass and the concentration of Hb, which serves as the major carrier of oxygen in the blood. Red blood cells serve as the blood cells that carry oxygen, while Hb is an iron containing protein within red blood cells that binds with oxygen to transport it to the muscles. As discussed previously, the degree to which oxygen binds to Hb is dependent on the partial pressure of oxygen in the blood and the affinity between oxygen and Hb. While oxygen-Hb affinity is not generally considered a mechanism for changes in VO2max, the volume of blood and its make-up are major variables.

An increase in Hb would improve performance by allowing for an increased transport of oxygen to the muscles. Research has demonstrated this relationship by examining how reductions in Hb affect performance (16). For example, a reduction in Hb because of anemia has been shown to decrease VO2max (52). Interestingly, in a series of studies by Ekbolm et al. (30), Hb levels were reduced via withdrawal of blood, which produced an initial drop in Hb, VO2max, and endurance. After two weeks, VO2max returned to normal despite Hb and endurance performance still being reduced. This is one of many studies demonstrating the idea that VO2max and endurance performance cannot be considered synonymous.

On the other end of the spectrum, in studies artificially increasing Hb levels, VO2max and performance have been shown to increase (16). In one study by Buick et al. (14), eleven elite distance runners showed significant improvements in time to exhaustion and VO2max following a blood transfusion that increased Hb levels from 15.7 to 16.7 g*100 ml^{-1}. In a study on blood doping, which artificially increases Hb levels, improvements in VO2max have been between 4% and 9% (34, 35). When combined, these results show the impact that Hb levels have on VO2max.

With endurance training, blood volume is normally increased along with hematocrit (the volume percentage of red blood cells in the blood) and Hb. Blood volume can be increased by as much as 10% with training (21). The body seems to self regulate in creating an optimal hematocrit to allow for increased carrying capacity of the blood while also having adequate blood viscosity. It is not clear whether a high hematocrit with higher viscosity or a lower hematocrit with lower viscosity is better for endurance performance. Athletes using banned drugs, such as synthetic versions of erythropoietin (or EPO), to artificially boost red blood cell production, have performed well with dangerously high hematocrit levels (16). Conversely, some African runners have produced world-class performances with very low hematocrit and Hb levels that would normally suggest anemia.

Consumption of Oxygen at the Muscle - Oxygen diffuses out of the blood stream through the capillaries at the muscle cells. The level of capillarization determines how effectively this takes place. Capillary density increases with endurance training (9). In addition, capillary density has previously correlated with VO2max (6).

The ultimate target of oxygen is the mitochondria in the muscle cells, where aerobic energy generation takes place. To be transported across the muscle cell to the mitochondria, myoglobin is required. Myoglobin transports oxygen from the cell membrane of a muscle fiber to the mitochondria. Greater myoglobin concentrations allow for more oxygen transport to the mitochondria, potentially enhancing oxygen delivery and thus performance (13).

Oxygen is used in the mitochondria during the electron transport chain. Therefore the amount of mitochondria plays a large role in aerobic energy generation. In theory, the more mitochondria, the more oxygen utilization and extraction that can occur in the muscle. Mitochondrial enzymes function to aid the chemical reactions needed eventually to generate energy. However, many studies have shown that while mitochondrial enzymes increase significantly with training, the corresponding change in VO2max is much less. In one study, monitoring changes with training and detraining, mitochondrial capacity increased by 30% with training, while VO2max increased by only 19%, but during the detraining phase VO2max improvements lasted much longer than mitochondrial capacity increases (39). Mitochondria enzyme concentrations are much more likely to affect other factors in performance to a greater degree than VO2max, like lactate threshold and substrate utilization (5, 47).

It is generally assumed that use of energy (in the form of ATP) produced via oxygen in the mitochondria is not a limiting factor in VO2max (6). This is another way of saying that the muscles are always capable of consuming all aerobically produced energy or that oxygen can always be consumed as fast as it can be delivered.

Training Effects on VO2max & Correlation of VO2max with Performance - The effects of a season of endurance training on experienced high school-age runners was studied by Plank et al. (71). They tested nine male high school cross country runners, who had completed extensive pre-season training, both before and after their season for VO2max, RE at three paces, and blood lactate levels at different workloads. They correlated these measurements to end-of-season race performance. The runners showed small but significant improvement in their already high VO2max during the season. There were no changes in RE. The 5-km race time improved by an average of 31-seconds, but this improvement was not correlated with changes in VO2max. Actual race times from early and late season were used, and these are subject to a variety of uncontrolled influences such as weather and course conditions. There was a correlation between improvement in blood lactate levels and performance improvements. This confirms the widely noted finding that changes in VO2max are not the primary cause of performance improvement in experienced distance runners and that intramuscular changes that increase lactate buffering capacity may be an alternative explanation for faster times.

In another study showing that changes in performance are not necessarily correlated with changes in VO2max, McConnell and colleagues (59) reduced the volume and intensity of 10 well-conditioned male runners for a four-week period. During the four-week period, volume of training was reduced by 66%, and subjects completed all training at an easy effort, compared to 71% of training at a moderate or hard effort prior to the study. Testing at the end of the reduced-training period showed that VO2max was unchanged, but nine out of ten runners were slower for 5-km, and the average change of 12 seconds was significant. In lab testing, the runners showed higher blood lactate levels at the same pace and an increase in body fat percentage. The duration of the study was quite short; and in fact, any longer period with such a reduction in training would almost certainly show reductions in VO2max. RE was not studied.

Studies demonstrate improved performances without changes in VO2max (27). Also, studies show that VO2max can improve without changes in performance, which is seen in a study by Smith et al. (77) that showed improvements in VO2max by 5.0% without an improvement in performance over either 3,000m or 5,000m. In addition, in looking at long term changes in performance in elite athletes, changes in performance occur without subsequent changes in VO2max.

In highly trained athletes, many studies have shown that VO2max does not change, even with performance improvements. In one of the only studies done on a large group (*n* = 33) of elite runners, Legaz-Arrese et al. (54) tracked changes in VO2max across three years. Performance improved by an average of 1.77% in men and .69% in women, with VO2max remaining essentially unchanged (~76.56 vs. ~76.42 in men and ~70.31 vs. ~70.05 in women). This points to improved performance in elite runners without changes in VO2max. Furthermore, it has been shown that among homogenous groups, such as well trained runners, VO2max does not correlate well with performance and cannot be used to distinguish which runners are faster (54).

Further evidence can be seen in two case studies on elite runners. In a study on a female Olympic level runner, Jones (43) showed that while the athlete's 3,000-meter time improved by 46 seconds, her VO2max decreased from 72 ml/kg/min to 66 ml/kg/min. Another study by Jones (44), this one on the current women's marathon world record holder, found that while VO2max varied some based on the time of testing, it was essentially stable at 70 mL · kg–1 · min–1 from 1992 to 2003, despite the fact that both training volume and competitive performance increased greatly over the time period. The plateau in VO2max can even be seen in untrained individuals. Smith and Donnell (76) evaluated the changes in VO2max over a 36 week training period. VO2max substantially increased by 13.6%, but all of those gains were seen in the first 24 weeks of the study, with no further increases during the final 12 weeks. Similarly, in a study by Daniels et al. (27) in untrained subjects, VO2max increased during the first 4 weeks of training but did not increase after that even with a further increase of training, despite continued improvements in performance.

2.1.2 - Lactate Threshold, or LT

In exercise conducted at an intensity requiring more energy than the aerobic system can provide, anaerobic energy sources must make up the difference. Middle distance and even distance running events can have a significant anaerobic component. Due to this anaerobic component, certain products will accumulate in the body, potentially causing fatigue. Previous studies have demonstrated that an increase in H+, which is a proton that dissociates from lactate and would decrease the pH, may impair muscle contractility (58).

The previously accepted notion that lactate played a direct role in fatigue, essentially preventing continued contraction of the muscles, has been disproved. Nonetheless the acidosis concept of fatigue still has a great deal of validity (65). While lactate itself may not cause fatigue, it corresponds with other products in the body which may contribute to fatigue, thus lactate can still be used in studies as a marker of fatigue. For instance, as mentioned already, an increase in circulating blood lactate corresponds well with a decrease in pH and an increase in H+. An increase in H+ has been shown to reduce the shortening speed of a muscle fiber, while a reduction in pH impairs Ca2++ re-uptake in the sarcoplasmic reticulum and may inhibit phosphofructokinase (one of the rate-limiting enzymes of glycosis) (37, 13). In addition, a decrease in pH could stimulate pain receptors (13).

All of the aforementioned actions could potentially cause fatigue. While they are not directly caused by the presence of lactate, the level of lactate in the blood is strongly correlated with increased acidity, which is a cause or a marker of the substances causing those actions. The long tradition of focus on lactate, as well as the fact that tests for blood lactate levels are both well-established and simple, means that in the vast majority of the literature, lactate measures are used to represent the component of physiology and exercise performance related to acidity. The combined effect of these factors is generally referred to as the lactate threshold (26).

In this review, lactate threshold (LT) is defined as the fastest running speed at which blood lactate levels remain in a relative steady state. Or stated in another way, it is the fastest speed in which lactate production and clearance are in equilibrium. LT has been given many different definitions based on fixed lactate readings and on analysis of the shape of a lactate curve. Originally, LT was defined as a fixed lactate reading at 4.0 $mmol \cdot L^{-1}$, but more recent research has shown that lactate levels at LT can vary as much as 6 $mmol \cdot L^{-1}$, between 2 and 8 $mmol \cdot L^{-1}$ (8). Methods that depend on the shape of the lactate curve either look for a specific level of increase in lactate (such as 2 $mmol \cdot L^{-1}$ between consecutive measurements) or some degree of change in the slope of the curve.

In addition, LT can be expressed as a percentage of VO2max. In practice, this is generally done for an individual athlete, rather than used as a definition of LT. Lactate threshold can occur at a wide range of percentage of VO2max, even in trained individuals (13). As an example, if two trained runners both performed at a fixed intensity at 75% VO2max, one can be below his lactate threshold and one can be above. As a general rule, more trained endurance athletes do have a lactate threshold that occurs at a higher percentage of VO2max (27).

The lactate threshold is dependent on many factors relating to the production and clearance of lactate. This interaction is what governs the amount of lactate in the blood and ultimately the LT (10). It is important to note that blood lactate is measured when defining LT, not muscle lactate. That means that LT is dependent not only on how much lactate a muscle produces but also on how much lactate actually makes it into the blood stream. When lactate is produced, it can either stay in the muscle, travel to adjacent muscle fibers, move into the interstitial space between muscles, or travel to the blood stream.

The ability of the muscle to buffer the H+ ions could potentially delay fatigue. As mentioned above, a rise in H+ ion concentration causes many processes that could potentially lead to fatigue. In particular, its inhibitory effect on phosphofructokinase would impact ATP production through glycolysis. Training has been shown to increase buffering capacity in both recreational and well trained athletes (53). Furthermore, in one study, the buffering capacity of six elite cyclists was found to be significantly related to their performance in a 40-km time trial (81). This demonstrates the importance of dealing with by-products and buffering capacity when it comes to performance. Due to the impact of acidosis on energy production and performance, much of the coaching and scientific literature focuses on delaying this process. Of particular interest is the concept of the LT.

How much lactate travels to the blood is partially dependent on both the difference between lactate levels in the blood and muscle and on the lactate transporter activity, which will be covered later. Lactate appearance in the blood also depends on exercise intensity and the amount and type of muscle mass activated. Greater intensity means a greater reliance on glycolysis without as much aerobic respiration taking place. Also, the more intense an effort, the greater amount of fast twitch muscle fibers are recruited, which because of their characteristics, are more likely to produce lactate (13).

Many of the same factors thought to impact VO2max also affect LT. An increase in mitochondria allows for more pyruvate to be converted into acetyl-CoA and to enter the mitochondria. Because of these factors, the fiber type of the athlete and mitochondria concentration will help determine the amount of lactate produced and the LT. Not only does an increase in mitochondria size cause a decrease in lactate, but also an increase in mitochondrial enzymes decreases lactate as well (6). This is likely due to an increase in the pyruvate that is converted to Acetyl-CoA instead of lactate or to an increased capacity for lactate oxidation. Going beyond just changes in lactate concentration, several studies have established a relationship between mitochondrial enzyme activity and the LT (22). Lastly, a study on detraining found that the drop in LT that occurred closely mirrored the drop in mitochondrial enzyme activity (23). These results show the close relationship between lactate levels and mitochondrial enzyme levels.

On the other side of the equation is lactate removal, which occurs via several mechanisms. Within the muscle cell itself, lactate can be used as fuel by being taken up and oxidized by the mitochondria. Therefore, lactate can be consumed by the muscle fiber or it can be transported to adjacent fibers to be used. Additionally, it can be transported to interstitial spaces (the space surrounding/between muscle cells). In these instances, lactate produced in the muscle would not increase the blood lactate levels as it would either be consumed by the producing muscle or adjacent fibers, or it would be sent to interstitial spaces (13).

Lactate that makes it to the blood stream can be removed in several ways. Muscle fibers that are on the slow twitch side of the muscle fiber spectrum can act as consuming fibers that take the lactate from the blood and use it as an energy source. Muscle fibers that are not taxed to a high degree also are used to take up lactate from the blood stream. In addition, the heart, the brain and the liver all play an active role in clearing lactate from the blood. The heart and the brain use lactate as a fuel source, while the liver, through the Cori cycle, acts to convert lactate to pyruvate and then ultimately the fuel source glucose (13).

This process has been termed the lactate shuttle, in which lactate is produced in a muscle then sent through the blood stream, where it can be taken up and used as a fuel source by muscle fibers or other tissues and organs

Muscle fiber type plays a role in lactate production and ultimately LT. Fast twitch muscle fibers are more likely to produce lactate due to the individual characteristics of the fiber that make it prefer glycolysis, such as having a larger amount of glycolytic enzymes (11). In addition, having fewer mitochondria, less myoglobin, and greater lactate dehydrogenase activity creates an environment where the pyruvate is more likely to become lactate. Conversely, for slow twitch fibers, mitochondria concentration plays a role in enhancing the LT (10).

The best way to measure LT is a subject of debate (10). Because lactate measurement requires a blood sample, by necessity, data points will be much more sparse than is the case with VO2max. Identifying a precise point where lactate exceeds a defined level, or where the increase in lactate exceeds a certain rate, is not possible in a practical setting. Traditionally, the lactate test has consisted of a series of approximately five minute steps that gradually increase in pace, with the goal of reaching a lactate steady state before the end of the step. However, research is unclear on what the best testing method is, and if using a step test, how long each step should be and how much velocity should be increased with each step. This has led some researchers to suggest long stages of up to 20 minutes (10). This is not practical in most research settings; and in most cases, it would not produce valid results as fatigue would interfere with the completion of the protocol.

In evaluating how LT may change in response to training, there are two opposing forces that mainly act upon the lactate curve. These opposing forces are the aerobic and anaerobic capacity (66). Aerobic capacity is essentially how well the aerobic system functions to minimize lactate levels. In essence, anaerobic capacity refers to the maximum amount of pyruvate that can be produced. An increase in glycolytic capacity by improvements such as increases in glycolytic enzymes is one example.

The theory is that maximum pyruvate production impacts the LT because if more pyruvate is produced without a change in the amount that can be turned into acetyl-CoA (i.e., increased aerobic ability), then more pyruvate automatically gets converted to lactate (13). Therefore, a change in LT can occur without any change in aerobic abilities. These two factors interact to produce the lactate curve. An increase in anaerobic capacity would shift the curve to the left (meaning more lactate produced at each speed), while an increase in aerobic capacity would shift the curve to the right (meaning less lactate produced at each speed). Under this model, an increase in lactate production is not necessarily correlated with impaired endurance performance. It could be a response to training that allows athletes to tolerate higher levels of lactate.

2.1.3 – Running Economy

The last of the traditional “big three” physiological parameters for running performance is running economy (RE). RE is the measurement used to classify total efficiency in research. The measurement uses oxygen intake to represent energy use and is commonly defined by how much oxygen it takes to cover a given distance at a fixed speed (73). RE significantly correlates with performance and has been used in conjunction with other factors as a model to explain running performance. In a study on well trained runners (average VO2max of 72), Conley and Krahenbuhl (20) showed that RE could explain 65% of the variation in race performance among the group of 12 runners.

RE is a measure of gross efficiency, meaning that it is the result of both internal and external components, so that mechanical, neural, and metabolic efficiency play a role. Biomechanical efficiency refers to the mechanical cost of running and includes such factors as energy storage and how wasteful a movement pattern is. Neural efficiency can be defined as an improvement in the communication between the nervous system and the muscles themselves. Lastly, metabolic efficiency refers to factors that impact the production of energy for the muscles to use, such as fuel source or oxygen delivery. These three types of efficiencies combine to create total efficiency (73).

Saunders et al. (73) provide a good review of the literature on running economy. They list a number of studies that showed the intra-subject variability in sub-maximal RE in laboratory conditions to be 1.5-4.5%, with the mean at the lower end of the range, indicating that RE measures can be assumed to have good validity. Evidence is given that RE accounts for more of the variance in performance among trained runners than does VO2max. The authors list strength training (along with altitude training) as a major area of intervention to improve RE that has been studied. They also note that most studies demonstrating improvements in RE used untrained or moderately trained subjects.

Biomechanical Efficiency - There are several mechanisms that improve biomechanical efficiency, one of the most important being the stretch-shortening cycle (SSC). The SSC occurs when a muscle is actively stretched and then is immediately contracted. During the pre-stretch portion, energy is stored in the series elastic components of the muscle, and then, the energy is released during the contraction part. Essentially it is a spring like mechanism with storage and release of energy greater than contraction alone. The amount of elastic energy return is dependent on several factors, including the length and speed of the stretch, the stiffness of the muscle, and the time between the stretch and the subsequent contraction (73).

In general, a stiffer muscle will store more energy than a compliant muscle, although there is likely an optimal stiffness. In addition, the longer the delay between the stretch and the subsequent contraction, the more energy dissipates. Therefore, the SSC works best when a stiff muscle is rapidly stretched and contracted with little time in between. A good example of this is the calf muscle upon landing and subsequent toe off during running or the extension of the hip while sprinting. Evidence of the impact of the SSC on RE can be seen by the fact that muscle stiffness strongly correlates with RE (25).

The stiffness of the muscle-tendon unit is dependent on several factors, including active characteristics such as the muscle concentric/eccentric contraction state and passive characteristics such as the length and condition of the muscle, tendon, and fascia during impact. Demonstrating the impact of muscle stiffness, Kyrolainen et al. (49) found that stiffer muscles surrounding the ankle and knee created an increased SSC response, which resulted in greater force applied during the subsequent toe-off. The keys for obtaining optimal stiffness and energy return are to put the body in optimal position upon impact, training the muscle and tendon to be able to absorb and utilize the forces, and training to pre-activate the muscles.

Pre-activation of the muscles before landing is a way to actively manipulate stiffness of the system, resulting in greater storage of elastic energy. Dalleau et al. (25) demonstrated this in showing that the energy cost of running was related to the stiffness of the lower leg. Pre-activation occurs as the muscles in the lower leg prepare for impact. This is done to adjust for the impact forces, essentially acting as an internal cushioning mechanism, and decrease the stress caused by muscular vibration.

A study by Ker et al. (46) found that the Achilles tendon stores 35% of its kinetic energy, while tendons that are in the arch of the foot store 17%. It has been estimated that without the two aforementioned mechanisms of storage and release of elastic energy, the VO2 required would be 30-40% higher (73). To properly utilize these elastic mechanisms, the body has to be in optimal position biomechanically, and the tendons have to be trained to utilize the forces. Rapid movements, such as sprinting or plyometric training, will train the tendons to be able to utilize the energy better.

Additionally, the use of these elastic energy systems depends greatly on a person's biomechanics. Running in a certain way will elicit a greater elastic storage and return as it will put the muscles and tendons in a better position to be able to store and use energy. For example, forefoot running (or barefoot running) has been shown to improve RE when compared to heel striking with shoes (78).

There are several biomechanical characteristics that impact the efficiency of the running gait. One factor is the individual stride length. Since speed is equal to stride length multiplied by stride rate, optimizing and manipulating those variables is of importance. In a study on fatigue during a marathon, it was found that RE decreased in the later stages of the marathon partly due to a decrease in stride length (38). This leads to the question of whether manipulating stride parameters can optimize RE. Evidence has shown that runners are most efficient at their self-selected stride lengths and that when made to run with shorter or faster stride lengths, RE was worse (17).

It should be noted in the Cavanagh study (17) that not all runners self selected their optimal stride length. In another study, researchers found that twenty percent of their subjects selected stride lengths that resulted in an elevated RE (64). It is of interest that all of these subjects were overstriders. Similarly, in the Cavanagh study, of the 10 subjects who did not select optimal stride lengths, seven were overstriders. Overstriding occurs when the initial footstrike occurs in front of the runner's center of gravity, resulting in ground reaction forces acting opposite the direction of running. A study by Kyrolainen et al. (49) found that increased braking force, which would occur in overstriding, results in a decreased RE. It has been hypothesized that overstriding results in a reduction in the ability to use stored elastic energy. It appears that, for a given runner and running speed, optimum stride length functions based on a U-shaped curve, where too short or too long a stride length results in increased VO2 consumption (64).

In addition to stride parameters such as length and frequency, vertical oscillation contributes to RE. Excess vertical oscillation decreases RE and is one of the factors that helps explain why long distance runners are typically more economical at slower paces than middle distance runners are (73). In fact, several studies have found that runners are more efficient at running velocities at which they frequently train (45).

Whether a runner should use a heel strike or a midfoot/forefoot strike is often debated and can play a role in biomechanical efficiency. Cavanagh and Williams (17) suggested that a heel strike is more economical due to decreased muscle activation required to provide cushioning, because heal strikers let the shoe do the cushioning. However, it has not been established if the muscles used to alter cushioning play a role in fatigue during a race. Also, as previously mentioned, a forefoot strike potentially utilizes elastic storage and return to a much higher degree than a heel strike, thus negating the muscle activation consequences. Research by Ardigo et al. (3) backed up the benefits of a forefoot strike, showing that a forefoot strike results in a shorter ground contact time and time of acceleration, both beneficial adaptations. Given these facts, forefoot or midfoot strike are likely to be more economical, especially at faster speeds, which require rapid force production and short ground contact times, such as middle distance events, or even distance events at the elite level.

It is likely that there will be individual differences in regards to foot strike, but forefoot striking may be more efficient mechanically, and perhaps, more importantly, may be needed for the increased force production coupled with a short ground contact time that is seen in faster running (49). Additionally, forefoot striking allows for greater use of elastic energy storage and return from both the Achilles tendon and the arch of the foot. Similarly, Lieberman et al. (57) also found that a forefoot strike allowed for more conversion of translational energy into rotational energy.

Neuromuscular Efficiency - In addition to the various components that impact mechanical and metabolic efficiency, neuromuscular characteristics need to be taken into consideration. This efficiency can be broken into two categories, factors which improve the neural signaling and motor programming of the running motion and those that improve the muscle force production itself. Although it is often not considered one, running is a skill, just like hitting a baseball or swinging a golf club. As the movement is practiced, the body becomes more efficient by refining the motor program, learning exactly what muscles to recruit, what ones to inhibit, and the exact number of muscle fibers needed. It is through this refinement that the movement becomes better coordinated and efficient. Research has demonstrated these claims, consistently showing that repeated practice results in improved muscle fiber recruitment and movement control (12). The resulting decrease in VO2 required to run at a given pace will, other factors being equal, by definition increase RE because of the inverse relationship between RE and VO2 consumption..

Neuromuscular efficiency can also be seen through muscle activation studies comparing untrained with moderately- or well-trained individuals. In a study done comparing cyclists, differences in muscle recruitment were found. Novice cyclists showed greater variability in muscle recruitment between pedals, more variations of recruitment between each individual, more muscle co-activation, and longer muscle activation periods than well trained cyclists (18). These results point to the idea that training can improve neuromuscular characteristics.

A study of elite middle-distance runners (50) looked at the relationship between muscle structure and RE. Ten runners completed treadmill tests that determined running economy at different speeds, and then they had biopsies in the vastus lateralis (thigh) that determined muscle fiber-type and activity of muscle enzymes. No correlations were found between enzyme activity and RE, but higher levels of fast-twitch muscle fibers were associated with higher RE. Although the physiological characteristics of muscle are significantly determined by genetics, the relative expression of slow- and fast-twitch fibers can be altered through strength-training. This suggests that strength-training may be able to improve RE.

Metabolic Efficiency - It is also possible that glycogen depletion could play a role in fatigue in shorter races. While glycogen depletion is usually thought of in terms of long duration exercise where total glycogen depletion is a problem, it can occur at a local muscular level. Glycogen breakdown occurs within each working muscle fiber, in addition to some total body glycogen breakdown stimulated by hormones. It cannot be transported from fiber to fiber, except when converted to lactate, transferred, and then reconverted to glycogen. Given this, glycogen depletion can occur in individual fibers before total glycogen depletion occurs, and the selective depletion depends on the intensity of the activity and the use of that fiber (1). Therefore, it can play a role in fatigue in much shorter events.

With glycogen depletion of a muscle fiber, that fiber can no longer perform work at the same intensity (13). When some fibers in a motor unit have been glycogen-depleted, there are fewer total fibers to cycle in and do work, potentially causing fatigue due to the increased demand put on the other fibers. This can be seen in animal models that show, after partial glycogen depletion, anaerobic performance was impaired (51). Research done by Jacobs et al. (41) showed the specificity of glycogen depletion when they compared a group that almost exclusively depleted ST fiber glycogen with one that partially depleted both ST and FT fibers. In the ST only group, maximum strength was not impaired but muscular endurance was. In the FT and ST depleted group, maximum strength was impaired as well, presumably because of the glycogen depletion in the FT muscle fibers.

Due to the way RE is commonly measured, which fuel substrate serves as the energy source will affect the measurement. RE is commonly calculated by dividing the rate of oxygen uptake by running speed. VO2 is used because, when measured at a speed using almost entirely aerobic energy sources, it represents the amount of ATP used. However, the common measurement does not take into account that the energy equivalent of oxygen depends on which substrate is used. Fats, carbohydrates, and proteins all provide a different amount of energy per liter of oxygen (13).

Strength Training and RE - The current study addresses the effect of various modes of aerobic training, and thus avoids introducing new strength training. However, numerous studies have found that strength training can lead to improvements in RE. This could provide indirect evidence for how RE might decline with the cessation of running, even when VO2max is maintained through cross-training, if the ground reaction forces in running result in gains in RE via the same mechanisms as the gains found through strength training.

In a study involving 12 moderately trained female runners, Johnston et al. (42) maintained pre-study endurance training in both control and experimental groups while adding three days per week strength training in the experimental group only. This obviously has the effect of increasing the training volume for the experimental but not the control group. The strength-training workouts involved upper- and lower-body exercises similar to the National Strength & Conditioning Association (NSCA) recommendations for distance runners (4). After 10 weeks of training, there were no changes in VO2max or body composition in either group, but the strength-training group showed an improvement in RE. There were no tests for running performance.

In a nine-week study of 14 competitive cyclists, Bastiaans et al. (7) held training volume constant between two groups but replaced 37% of the total volume of endurance training in the experimental group with explosive strength training. Short-duration (sprint) performance declined in the control group but was maintained in the explosive strength training group. Neither group showed changes in time trial or max workload. While this study dealt with cyclists rather than runners, the results imply that explosive strength training allows for maintained endurance performance with a reduced endurance training load and for better sprint performance with a constant total volume of training.

Paavolainen et al. (67, 68, 69) studied the effects of nine weeks of explosive strength training on 18 moderately-trained distance runners. Total training volume was kept constant in both experimental and control groups, but 32% of training volume in the experimental group and 3% of training volume in the control group was replaced with explosive strength-training. Subjects were tested before and after the training for VO2max, 5-kilometer time (5K), RE, maximal anaerobic running velocity (VMART), and maximal 20-meter speed (V20). Among the experimental group, 5K, R, VMART, and V20 all showed significant improvements, while no change was observed in VO2max. In the control group, VO2max showed significant improvement, V20 decreased significantly, and no changes were seen in 5K, RE, or VMART. Pooling the data showed a significant correlation of changes in 5K with RE and VMART. This study provides further support for the theory that improvements in VO2max are neither necessary nor sufficient for improvements in distance running performance. It offers a possible explanation for this decoupling in suggesting that explosive strength training can bring about improvements in RE, maximal velocity, and maximal sustained anaerobic velocity. Any or all of these factors can lead to improvements in distance running performance.

A study by Mikkola, et al. (62) provides evidence of changes brought about by explosive strength-training in conjunction with distance running. Twenty-five distance runners, aged 16-18, trained for eight weeks, with the control group continuing their usual endurance training. The experimental group maintained the same total volume of training but replaced 19% of the volume with explosive strength-training. In the experimental group but not the control group, leg extension forces increased and were accompanied by faster neural activation, more rapid force increases, and performance improvements in maximal anaerobic speed and 30m sprint speed. The control group showed greater increases in thickness of the quadriceps femoris muscle. Neither group showed changes in VO2max, RE, or maximal aerobic speed. No test was conducted for running performance. This is one of the largest studies in the field, and sample population characteristics are quite similar to those in this proposed study.

Measurement of RE - As mentioned previously, one problem with RE is that it can be measured and expressed in several different ways. There are two ways to report VO2 using running speed. One is to express it in terms of the VO2 at an absolute speed, while the other is to express it as VO2 divided by speed. These methods both rely on the idea that below a certain speed (around LT), the oxygen cost is independent of speed, but Vickers (79) demonstrated that this is not the case. When measuring economy at an absolute speed, runners will be running at vastly different relative intensities that will change several factors. Biomechanical factors such as ground contact time, ground reaction forces, stride length, and stride frequency are all speed dependent. One individual at six minute mile pace may need a very low percentage of their max force development, while another runner might need a much larger percentage, thus changing ground contact times. That is but one example of how speed affects biomechanics. In addition, substrate use would be vastly different among groups of individuals at an absolute speed. Since races are of a given distance, expressing RE as the oxygen cost per unit of distance seems to make more sense, but it still neglects the effect substrate use has on VO2.

One last way that RE is reported is caloric cost. In this measurement, the respiratory exchange ratio is used to calculate the caloric equivalent of VO2, which can be used to determine the amount of energy used per unit of distance. A study by Fletcher et al. (31)

compared RE expressed as VO2/distance and caloric unit cost. They stated that the traditional way of measuring RE appeared to be flawed for several of the reasons discussed earlier and for the practical reason that faster runners tended to have the worst economy, which makes little logical sense. In their study, Fletcher et al. (31) found that the better runners had a lower energy cost of running (better economy) and that RE expressed as caloric unit cost was much more sensitive to changes in speed. One of the interesting findings was that RE using the VO2 measurement showed that RE was independent of speed. The caloric unit cost showed that RE got worse as speed increased, which would be the expected outcome as when speed increases reliance on carbohydrate (which provides less energy than fat for a given amount of oxygen consumption) also increases. This debate on how to measure RE demonstrates that we have a long way to go in understanding efficiency. It also makes one question the conclusions based on studies looking at what improves RE.

One other problem with measuring RE is whether to use gross or net VO2. Gross VO2 refers to the total oxygen consumption, while net VO2 refers to the total oxygen consumption minus the resting value. It has been hypothesized that net VO2 would better reflect active energy usage and correct for a speed-related bias that is present when measuring RE as VO2/speed (79).

2.2 - Cross-Training

Cross-training is the use of one mode of exercise to prepare for a sport in which that mode is not a part of the competition. By this definition, virtually any athlete who takes part in weight-lifting is cross-training. Running could be considered cross-training for almost all sports outside the realm of track and triathlon. For the purposes of distance running, and this research study, cross-training is defined as non-running activities that mimic at least some the physiological effects, and particularly the aerobic effects, of run training. Although strength-training is often used a means of preparing for distance running, and clearly fits some definitions of cross-training, it is not directly considered in this work.

Among the most frequently considered forms of aerobic cross-training for running are cycling (on road bikes, mountain bikes, or indoors on stationary bikes or cycle ergometers); swimming; deep-water running, in which the athlete mimics the running motion in a pool, generally while wearing some type of floatation aid; rowing or rowing machines; and a variety of aerobic exercise equipment such as elliptical trainers or stair-climbers. In evaluating these various training modes, we are interested in the responses they elicit in terms of VO2max, heart rate, perceived effort, LT, and neuromuscular effects. We are particularly interested in how these responses compare to the same measurements during run training, and how the results of a long course of training using a particular training mode compares to the same training completed via running.

2.2.1 - Acute Effects of Cross-Training

Studies on cycling consistently show lower VO2 at the same heart rate and lactate concentration, indicating that the two exercises do not have precisely the same metabolic effects. Schneider et al. (74) looked at a group of highly trained male triathletes (mean VO2max > 70 ml/kg/min), who are presumably experienced and extensively trained in both running and cycling. They found laboratory VO2max to be 6.8 percent lower during cycling than for treadmill running; but in both modalities the measurements were comparable to reported values for elite single-sport athletes. They also found ventilatory threshold (Tvent) to occur at 67 percent of VO2max in cycling and 72 percent of VO2max in running (when compared to the VO2max for the respective exercise mode). The cycling Tvent was comparable to reported levels in competitive cyclists, while the running Tvent was lower than reported levels in elite runners. The researchers speculated that cross-training adaptations enhance oxygen uptake values across modalities but that anaerobic threshold adaptations occur primarily in specific muscle groups being trained.

Cycling differs from running in the amount of muscle mass used, types of movements, and the fact that the athlete does not have to support his body weight. The elliptical trainer does require support of body weight and was specifically designed to mimic closely the running action. A study of elliptical trainer use by cardiac patients showed that HR and VO2 do have the same relationships, when compared to treadmill walking (75). Specifically, in cardiac rehabilitation patients, the study found that at two given prescribed rate of perceived exertion (RPE) values, the patients showed significantly higher VO2 and heart rate while using an elliptical trainer compared to treadmill walking. The relationship between VO2 and HR was essentially identical across both modalities and both RPE levels. In another study, Crommett et al. (24) found that there were no significant differences between treadmill running and elliptical trainer exercise among college students exercising at self-selected intensity.

Another study by Mercer et al (60) comparing elliptical trainer use to treadmill running in trained subjects had similar findings, with treadmill VO2max of 53.0 ml/kg/min (±7.7) and elliptical trainer VO2max of 51.6 ml/kg/min (± 10.7) . The Mercer study also found that both HR and RPE correlate with VO2 in the same manner whether using a treadmill or an elliptical trainer. They concluded that no adjustments in target heart rate are needed in transitioning from a treadmill to an elliptical trainer. A third study found overall RPE had the same relationship to HR in treadmill running or in elliptical trainer exercise, but the elliptical trainer exercise produced a higher RPE for the legs alone (36).

In contrast to these findings, Abrantes et al. (2) compared treadmill running to elliptical trainer, stationary bike, and rowing ergometer. Subjects undertook three bouts of exercise calibrated to induce heart rates of 60-65%, 70-75%, and 80-85% of maximum HR. Averaging results of all three bouts, the study found that TM for a given HR running produced the highest VO2 and respiratory exchange ratio (RER), while the elliptical trainer produced the lowest VO2 and RER (2).

A study on VO2 by trained runners during deep water running examined the effect of familiarity with the training mode (33). Runners who never used deep water running, or who only did low-intensity deep water running (below LT), had a VO2max 15-20% lower in the water than on a treadmill. Runners who regularly did more intense deep water running sessions had VO2max differences of 4-10%. These latter results correlate with other studies showing that during water immersion exercise, heart rate is 5-10% lower at the same work intensity, suggesting runners familiar with deep water running can reach the same intensity of workout (19).

2.2.2 - *Long-Term (Training) Effects of Cross-Training*

There is very little information about the complete replacement of running with another form of exercise for an extended period of time. One study replaced running with deep water running for four weeks in a group of moderately trained subjects (15). No significant changes were seen in 5k performance (19:02 vs 19:09), VO2max (63.4 vs 62.2), LT running velocity (249.1 m/min vs 253.6 m/min) or running economy at a fixed percentage of pre-study VO2max velocity. This study suffered several limitations as it did not use a running control group; the training involved a significant increase in intensity; and the duration was short.

Hoffmann et al. (40) studied the effects of assigning a group of untrained college men to complete nine weeks of either run training or cycle training. Training initially consisted of 45 minutes, four days per week at 75 percent of maximum heart rate (MHR), and later increased to 80-85 percent MHR, with two days per week of interval training at above 90 percent MHR. All subjects were tested for VO2max and ventilatory threshold (VT) on both treadmill running and cycle ergometer both before and after the training. As might be expected given the extensive training by untrained subjects, both groups saw significant increases in VO2max on both modalities. Interestingly, there were no significant differences between the two modalities for either group in the magnitude of VO2max improvement (i.e., improvement in VO2max was not dependent on whether a subject trained for the exercise mode being tested.) Ventilitory response differed, as both groups had improvements in VT for the mode in which they trained for but not for the other mode. The authors concluded that there is a dissociation of VO2max and VT specific to training.

An analysis of 40 weeks of training of four elite triathletes was used to determine mathematically the transfer of training effects between different exercise modes (63). The authors used official splits from the legs of triathlon competition, as well as 30-minute treadmill run distance and 5x400 meter swim time to measure performance. Training stimulus was measured using exercise time and heart rate. Three first-order transfer mathematical functions were developed to model the relationship between training and results, with parameters set to minimize the sum of residual squared error. The authors found significant transfer effects in both directions between running and cycling, while determining that swimming was a highly specific activity that neither gained nor provided benefits from/to running and cycling.

Some studies have examined the effect of adding cross-training to existing running training. One study looked at the effect of adding swimming to a running program versus adding an equal amount of running or maintaining the same training (32). In the eight week training program, subjects supplementing training increased volume by 10% per week. Running performance was measured with a 3.2-km time trial. Significant improvements were seen in the extra running (-26.4 sec) and swimming (-13.2 sec) groups, while the control group had a non-significant 5.4 sec improvement. Treadmill VO2max or velocity at VO2max did not improve for any group, but the extra running group had a significant increase in the velocity associated with a blood lactate of 4 $mmol \cdot L^{-1}$. Lab tests were also completed on an arm crank exercise machine, and the swim group alone showed improvements in VO2max and VO2 at 4 $mmol \cdot L^{-1}$ lactate. The increment in training here was quite small, but the results support the principle of specificity, which states that training most specific to the desired activity will produce the best results.

Another study augmented run training for 10 days with an 80% increase in total volume, either with cycling or additional running (70). The additional training took the form of a second daily workout of equal length to the primary workout on eight out of ten days. This was a cross-over design with all subjects completing both modes of augmented training, with 30 days normal training leading off the study and a 14-day rest period with a 20% reduction in training preceding each increased training period. RE and lactate level at submaximal pace and 5K time on a treadmill were assessed the day before and the day after each 10-day increase in training. No performance differences between the two protocols were seen in a 5K run, but the cycle training resulted in slightly lower RE at the fixed submaximal running velocity. Both modes saw post-training reductions in lactate levels at submaximal pace and increases in foot impact shock. It should be noted that the 80% increase in training used here is very large, but the duration of each training phase is shorter than the time shown in other studies to produce significant changes in performance or in any physiological variable (1, 4, 9).

The only longitudinal study comparing elliptical training to running used untrained female subjects training three days per week, which predictably showed all modes of training improved fitness (29). The 12-week study also included a stair-climbing group, and initially, it had the subjects train for 30 minutes at 75 percent MHR before progressing to 40 minutes at 85 percent MHR. Pre- and post-tests for VO2max were completed on a cycle ergometer (cycling was not a training modality used in the study), and there were no differences between groups in amount of improvement. The only training-specific test was a sub-maximal fixed-load test, in which all groups showed similar reduction in HR over the course of the study. No effort was made to determine cross-over effects of training to different exercise modalities.

A study with highly-trained female runners replaced half of running training with cycling and did maintain a full-running control group (82). This study found no significant changes in either group over a six-week period after the conclusion of the competitive season. However, training volume was not constant between the groups as the volume (in minutes/day) of cycle training was double that for running training. Also, due to small group sizes (N= 11 total for two groups), the level of significance in performance change was quite large. In fact, every subject and control got slower over the course of the study, and the average change for cyclists was 32 seconds over 3000 meters versus 9 seconds for controls.

This points out a frequent problem in published studies, where performance changes that would be considered extremely significant by competitive athletes do not rise to the level of statistical significance due to small subject populations. Experimental designs and data presentation differed too much to allow a true meta-analysis, but of all the studies reviewed for this research that replaced (rather than supplemented) some or all of running training, none showed an average improvement in running performance post-study.

3. METHODS

3.1 - Subjects

A total of 30 runners (19 male, 11 female) from local cross country teams were recruited as subjects at the conclusion of the 2006 fall season. Subjects were required to have completed at least one season of competitive distance running; to have a minimum of 10 consecutive weeks of training prior to entering the study; to have no injury limits on participation in competition in the last three weeks of the season; and to have completed a 5000-meter cross country race faster than 23:00 for males or 27:00 for females. The subjects included two developmental level college runners, who were non-varsity athletes with personal best 5000-meter times slower than those of the fastest high school subjects.

3.2 - Pre-Study Testing

All aspects of the study were submitted to and approved by the Appalachian State University Institutional Review Board. In the first week after the conclusion of their competitive season, subjects reported to the Human Performance Lab for measurement and testing. Height, weight, and body fat percentage (via three-site skinfold measure) were taken. Subjects then completed a ten-minute treadmill warm-up run before undergoing a graded exercise test on a treadmill.

In determining the paces to use to complete the treadmill test, the following procedure was used: The subject's best 5-km race time was converted to a decimal value in minutes, and this value was divided into 5000 to obtain a pace in meters per minute. This value was converted to miles per hour (by multiplying by $60 \cdot min \cdot hr^{-1}$ and dividing by $1609.3 \cdot m \cdot mile^{-1}$) to allow for easy computation of treadmill paces. The actual treadmill pace was determined by multiplying the race by a pre-determined percentage and rounding to the nearest one-tenth of a mile per hour (the precision of the treadmill control).

Stage	1	2	3	4	5	6
Pace (% of 5k best)	75	90	97.5	105	112.5	112.5
Incline	1%	1%	1%	1%	1%	5%

Table 3.1 - Treadmill Test Pace and Incline, per Stage

The first two stages of the treadmill test were four minutes each, run at paces equal to 75% and 90%, respectively, of the subject's best 5-km race pace. During the final 90 seconds of these stages, stride length was measured by determining the time required for 30 strides. Two separate research assistants each used a stopwatch to measure the time while counting 30 consecutive footfalls of the same foot. The results were averaged, and this time, along with the treadmill speed, was used to calculate distance travelled in 30 strides, and simple division produced the stride length.

Beginning with the third stage, each stage lasted two minutes. Treadmill speed for the third stage was 97.5% of 5-km race pace, and increased by 7.5% of race pace in each subsequent stage until the subject was unable to continue. If a subject completed the fifth stage (112.5% of race pace), the speed would be held constant and the treadmill grade increased by four percent per stage for subsequent stages. During the treadmill tests subjects were urged to continue for as long as they could and encouraged about their performance during the test. During the latter stages of the test, subjects were asked to indicate via handsignal when they believed they could continue for one more minute and were instructed to visualize finishing a race and encouraged to complete the current or next stage of the test.

A rate of perceived exertion (RPE) scale was described to the subjects prior to the test. In the last fifteen seconds of each stage, subjects were asked to indicate their current RPE by pointing to the appropriate level on a poster-sized chart held in front of them. They were also asked immediately after the test to indicate their RPE level at the time they stopped running.

Respiratory data including oxygen consumption (VO2) and expired CO2 were recorded every 15 seconds using the Fitmate Pro from Cosmed. VO2 for stages 1 and 2 was determined by taking the last seven readings (i.e., beginning 90 seconds before the end of the stage), discarding the highest and lowest reading, and averaging the remaining values. The same process was used on later stages with the last four VO2 readings (i.e., beginning 45 seconds before the end of the stage). Heart rate for each stage was calculated using the same processing of averaging the central values from the latter part of the stage.

RE on each stage was defined as the measured VO2 for that stage divided by the running speed. Note that the running speeds on each stage were fixed for a given subject in the pre- and post-study testing. Thus VO2 is the only parameter that could produce intra-subject pre/post variation in running economy.

Blood lactate levels were measured for each pace with samples taken in the final 30 seconds of the stage. Blood was taken via finger-stick and collected in capillary tubes while the subject continued to run at the given pace. The blood was immediately diluted 1:3 with a lysing buffer by adding 25 ml of drawn blood to vials previously filled with 50 ml of buffer.

The vials were labeled by subject and test stage and frozen for later analysis. Lactate levels were measured using the YSI Lactate analyzer.

A 3000-meter time trial was run on a 300-meter indoor track 1-3 days after the treadmill tests. Subjects were grouped with others of similar ability and/or assigned non-subject pacers to help insure a maximum effort. Three separate trials were run for subjects of different ability levels, with all subjects in a given trial generally having best 5000-meter race times within a three-minute range. Splits were called out after each lap, and subjects were additionally told at half-way of their approximate mile pace. All tests were repeated at the conclusion of the training period, with subjects following the same protocol as used in their initial tests.

3.3 - Training

After completion of the preliminary testing, subjects were assigned to training mode (elliptical trainer, cycling, or running) to use as their sole mode of aerobic exercise for five weeks of training. Subjects who volunteered for cross-training were initially assigned to clusters based on sex and previous running performance. Using best 5-kilometer race time as the performance criteria, both the males and females were split into two groups: “faster” and “slower” runners. This gave four clusters, and within each cluster, half the subjects were assigned to stationary bike training and half to elliptical exercise training based on random numbers assigned from the Excel spreadsheet program. The control group was not randomly assigned.

Subjects in all three groups (control, cycle, elliptical) were given workout prescriptions based on their typical volume of training during the cross country season. Subjects who typically ran six or seven days a week during the season were instructed to train six days per week. Subjects who typically only ran five days per week during the season were instructed to train five days per week. The duration of daily workouts for each individual was based on typical in-season running and was specified within a ten-minute range. The minimum daily training range was 35-45 minutes, and the maximum was 50-60 minutes. The exception was one weekly “long day,” in which subjects were instructed to train for 10-15 minutes longer than their usual daily workout. A sample weekly training schedule is shown in Table 3.2. Note that the day-to-day schedule is intended to be representative of the training completed, but subjects were free to choose which days to complete various types of training.

	Lowest Training Volume	**Highest Training Volume**
Mon	35-45 min @ moderate effort	50-60 min @ moderate effort
Tues	40 min with sprints	50 min with sprints
Weds	rest	50-60 min - moderate effort
Thurs	35-45 min @ moderate effort	50-60 min @ moderate effort
Fri	45 min with 4 x 4 min tempo	55 min with 5 x 5 min tempo
Sat	45-55 min @ moderate effort	60-70 min @ moderate effort
Sun	rest	Rest

Table 3.2 - Sample Training Schedule for Low- and High-Volume Subjects

Most daily workouts were prescribed at a “moderate” effort. Subjects were given several cues to gauge this effort level. The first was an effort comparable to regular daily practices (not races or interval workouts) during cross country season. The second was a RPE equal to that which they described when their heart rate reached 165 during the treadmill test. (This number was determined by finding 75 percent of maximum heart rate reserve, assuming a resting heart rate of 60 and a maximum heart rate of 200.) The final effort cue was to train at the hardest effort that still allowed them comfortably to maintain a conversation.

Two days per week were exceptions to the moderate effort workouts described above. The first was a “sprint” day. On this day, subjects would warm up at the usual intensity for ten to fifteen minutes. After this, they would do ten repetitions of fifteen seconds at a maximal effort, with each sprint followed by an easy-effort recovery of 105 seconds. (Sprints started at two-minute intervals.) Cross-training subjects were instructed to increase the level or resistance of their machine during sprints, in addition to increasing the cadence, in order achieve a maximal effort.

The second day of more intense training was a “tempo” day, designed to help subjects maintain their lactate threshold fitness. Subjects would again warm up at the usual intensity for ten to minutes. After this, subjects did four or five repetitions of four to five minutes each at lactate threshold effort, with two minutes easy recovery effort after each hard effort. Subjects were again given cues for appropriate intensity. The first was effort similar to 5-kilometer racing (for subjects with best race times of over 20 minutes), or slightly less intense than race effort (for subjects with best race times under 20 minutes).

Subjects maintained training logs indicating the duration and type of training they completed each day. The logs also asked subjects to indicate any other type of exercise training or intense activity in which they participated. Subjects were asked not to participate in any type of strength-training, other than optionally continuing body-weight circuit exercises if they had been doing such exercise during the cross country season.

Training logs were turned in weekly. To be included in the study results, subjects were required to complete a minimum of 22 training sessions during the five-week period and could not have more than one week with fewer than four training sessions.

3.4 - Post-Training Testing

After completion of the training period, subjects repeated the treadmill and time trial testing. The treadmill test was done first. Each subject used the same individual protocol for changing speed and grade that was used in the pre-study test. Subjects were given ten minutes of warmup running on the treadmill prior to being fitted with the equipment for the actual tests. No other running was done prior to the tests after the cross-training period ended.

The 3000-meter time trial was done for each subject two to three days after the treadmill testing. Cross-training subjects were instructed not to run between the treadmill testing and the time trial but were allowed to continue cross-training at a moderate intensity level if they so desired. The time trial was done on the same indoor track as the pre-study time trial. Subjects were again accompanied by non-subject pacers to encourage them to maintain their best pace. All time-trials before and after the study were performed between 4:30 and 5:30 p.m. All treadmill testing both before and after the study was performed between 4:30 and 7:30 p.m. These times matched the typical late-afternoon workout schedule that the subjects used during the cross country season prior to the study.

3.5 – Statistical Analyses

Descriptive statistics (mean ± standard deviation) were reported for all dependent variables. The SPSS statistical analysis program (version 14.0; SPSS, Inc, Chicago, IL) was used for data analysis. A repeated measures two-tailed Welch's *t*-test was used to evaluate the significance of within-group changes during training. An independent samples two-tailed Welch's *t*-test was used to evaluate the significance of differences between groups. Statistical significance was assumed at the $p \leq 0.05$ level.

4. RESULTS

The most important results are the times in the 3000-meter time trial conducted before and after the five week training period. This was the measure used for running performance, and the results demonstrate that performance declined significantly for the cross-training regroups during the course of the study. Figure 4.1 on page 49 shows the pre- and post-study average times for each group in the 3000 meter time trial. The elliptical training group had pre-study time of 748.7 sec (± 24.7 sec) and post-study time of 796.5 sec (± 28.7 sec). The cycle training group had a pre-study time of 728.8 sec (± 21.1 sec) and post-study time of 771.6 (± 25.7 sec). The running group had a pre-study time of 697.4 sec (± 30.7 sec) and post-study time of 687.8 sec (± 27.8 sec).

Three of the original subjects in the cycle training group were excluded from compilation of results (see *Notes on research subjects* at the end of this chapter). These were three of the slowest subjects, and this resulted in the cycle group having faster pre- and post-test time trial results than the elliptical group, even though the cross-training subjects were sub-divided by pace and sex prior to randomization. As described previously, the control group was recruited separately and had faster average race times than the experimental subjects. However, none of the between group differences in pre-study 3000-meter time were statistically significant.

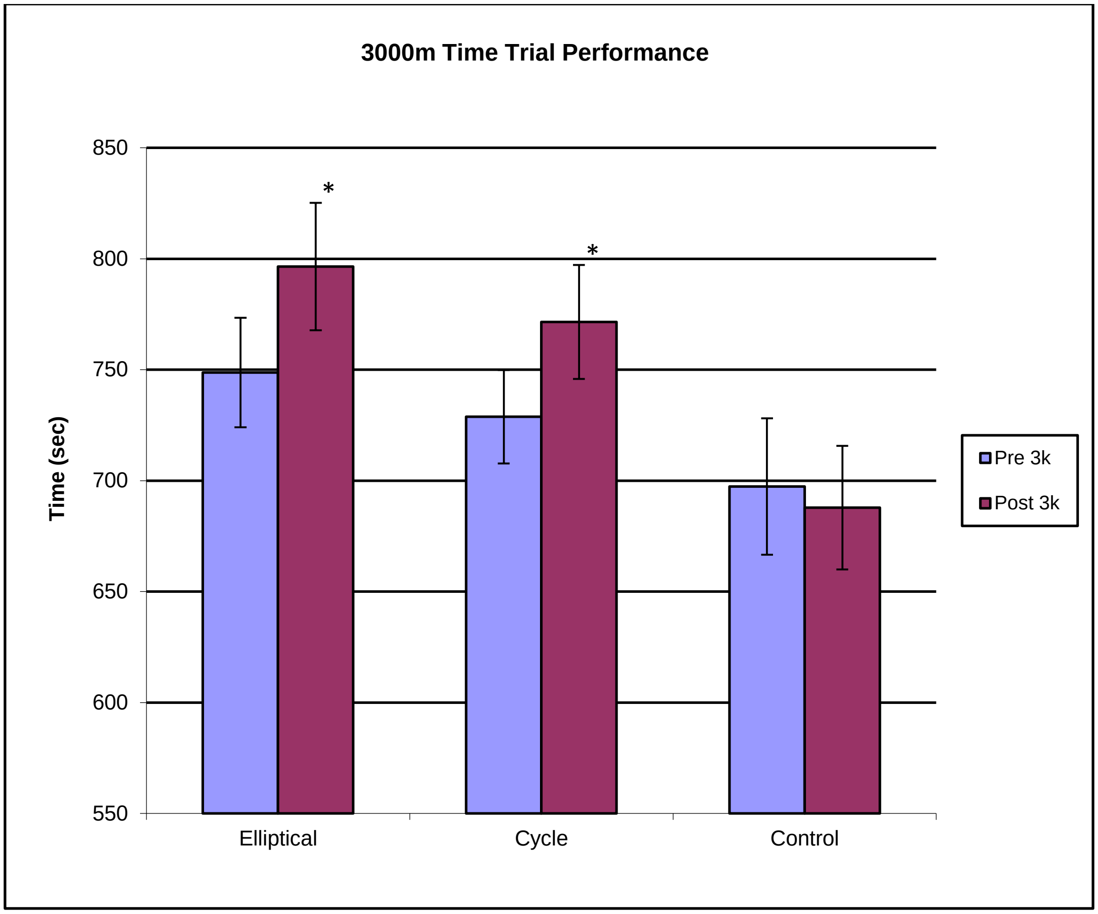

Figure 4.1 – Mean 3000-meter Time Trial Result, Pre- and Post-Training
Data presented as mean ± standard error of measurement
* - significantly different from pre-test ($p < 0.001$)

The change between the pre- and post-training 3000-meter time trial is shown in Figure 4.2 on page 50. The elliptical training group was slower, on average, by 47.9 sec (± 11.3 sec). The cycle training group was slower on average by 42.8 sec (± 6.3 sec). The control group was faster on average by 9.6 sec (± 8.3 sec). The combined average for the two cross training groups was slower by 45.7 sec (± 7.0 sec).

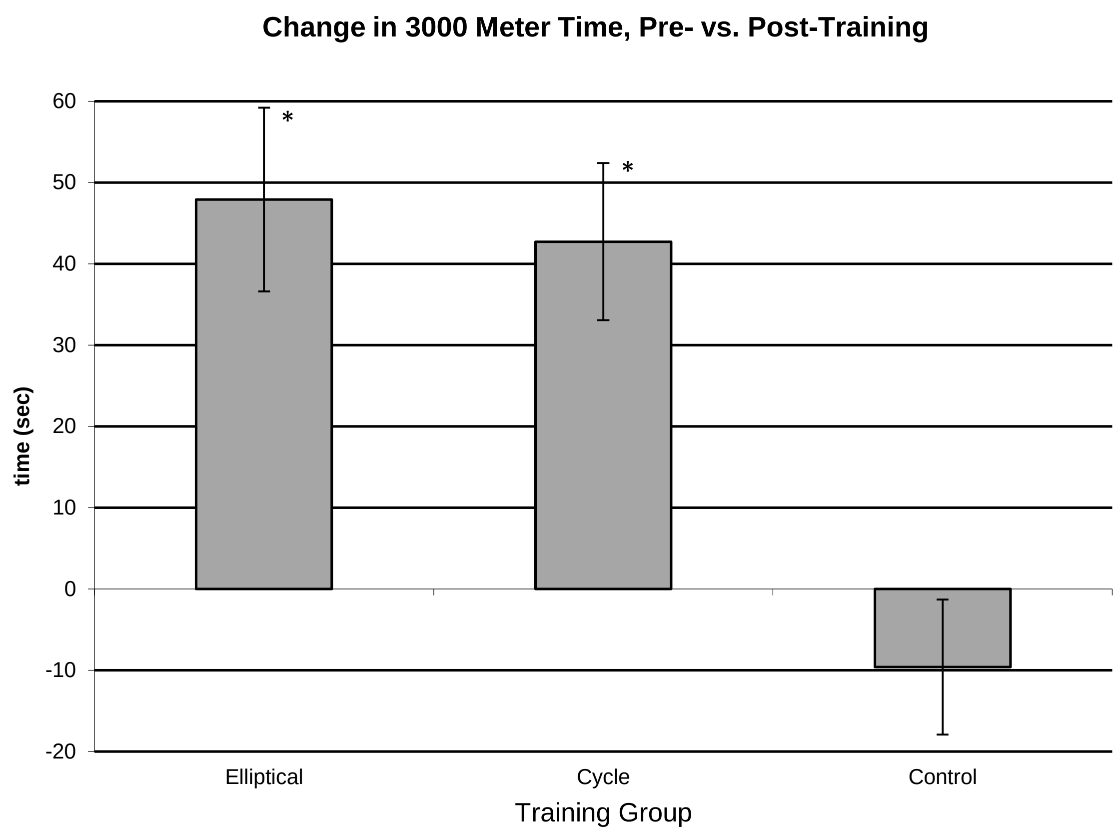

Figure 4.2 - Changes in 3000-meter Time Trial, Pre-Training vs. Post-Training
Data presented as mean ± standard error of measurement
* - significantly different from control ($p < 0.001$)

The change in performance for both cross-training groups was statistically significant at a level of $p < 0.001$. The change in performance for the control group was not significant ($p = 0.29$). Comparing changes between groups, the difference between both cross-training groups and the control group was significant at a level of $p < 0.001$. The difference between the elliptical training group and the cycle training group was not significant ($p = 0.71$).

Running economy was defined for a given pace as the VO2 consumption at that pace. This definition does not allow for direct comparison of running economy at different paces. Since pace on each stage was individualized for subject, it is not meaningful to calculate an average running economy for any group on any stage. However, each subject ran at the same series of paces during the pre- and post-training treadmill tests. Thus it is valid to calculate an individual change in running economy for each stage of the treadmill test, and group means for the change in economy can be compared. Figure 4.3 shows the change in running economy for each group for the first three stages of the treadmill test.

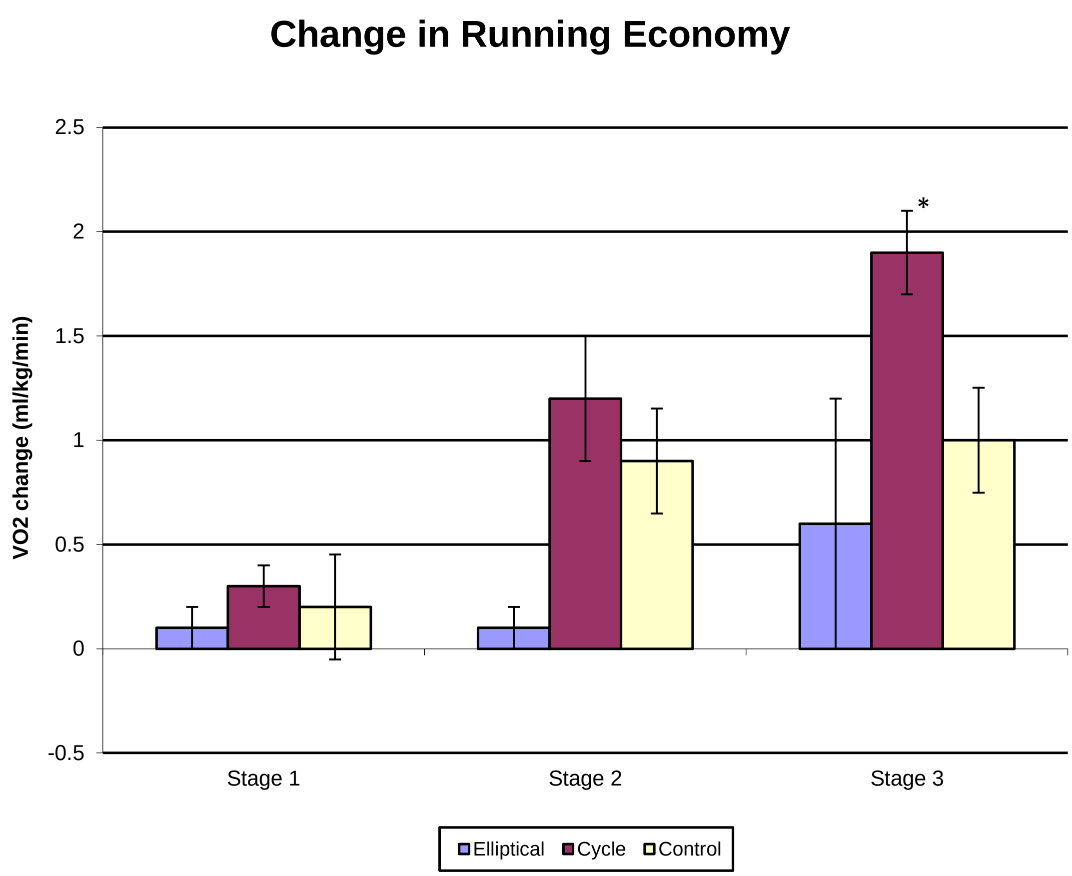

Figure 4.3 - Changes in Running Economy, Pre-Training vs. Post-Training
Data presented as mean ± standard error of measurement
* - significantly different from pre-training value ($p < 0.05$)

For all three training groups, the average change in running economy was very small at 75% of 5000-meter race pace (< 0.5 ml/kg/min); and in each case, the standard error was larger than the average change. There were no significant changes between pre- and post-training tests and no significant differences between groups ($p > 0.8$ for all group pairings).

Changes in running economy for stage two (90% of 5000-meter race pace) were negative (higher VO2) for all groups and larger for the cycle training group (0.9 ml/kg/min). For both the cycle training and control group changes were comparable to the standard error; but again, there were no significant differences between groups or in any group pre- and post-training.

On the third stage (97.5% of 5000-meter race pace), the magnitude of decrease in running economy was greater for all three groups. The change was greatest in the cycle training group (1.4 ml/kg/min), and this was statistically significant ($p < 0.05$). The changes did not rise to the level of statistical significance for the elliptical or control groups ($p = 0.47$ and $p = 0.19$). Because all groups saw decreases in running economy, there were no significant differences between groups.

Stride length was measured in the first and second stages of each treadmill test. As with running economy, stride length will be specific to individual runners and correlated with the particular paces they ran on each stage. There is no meaning to average of stride length across groups for a particular stage. Again, though, it is valid to calculate an individual change in stride length for each stage of the treadmill test, and group means for the change in stride length can be compared. Figure 4.4 on page 53 shows the change in stride length for each group for the first two stages of the treadmill test.

Stride length increased post-training, compared to the pre-training test, for all three groups on each of the first two stages of the treadmill test. The changes on stage one for the cycle training group (0.08m ± 0.04m) and the control group (0.06m ± 0.02m) were statistically significant ($p < 0.05$), while the change in the elliptical training group (0.01m ± 0.02m) was not significant. In stage 2, the increase for the control group was identical

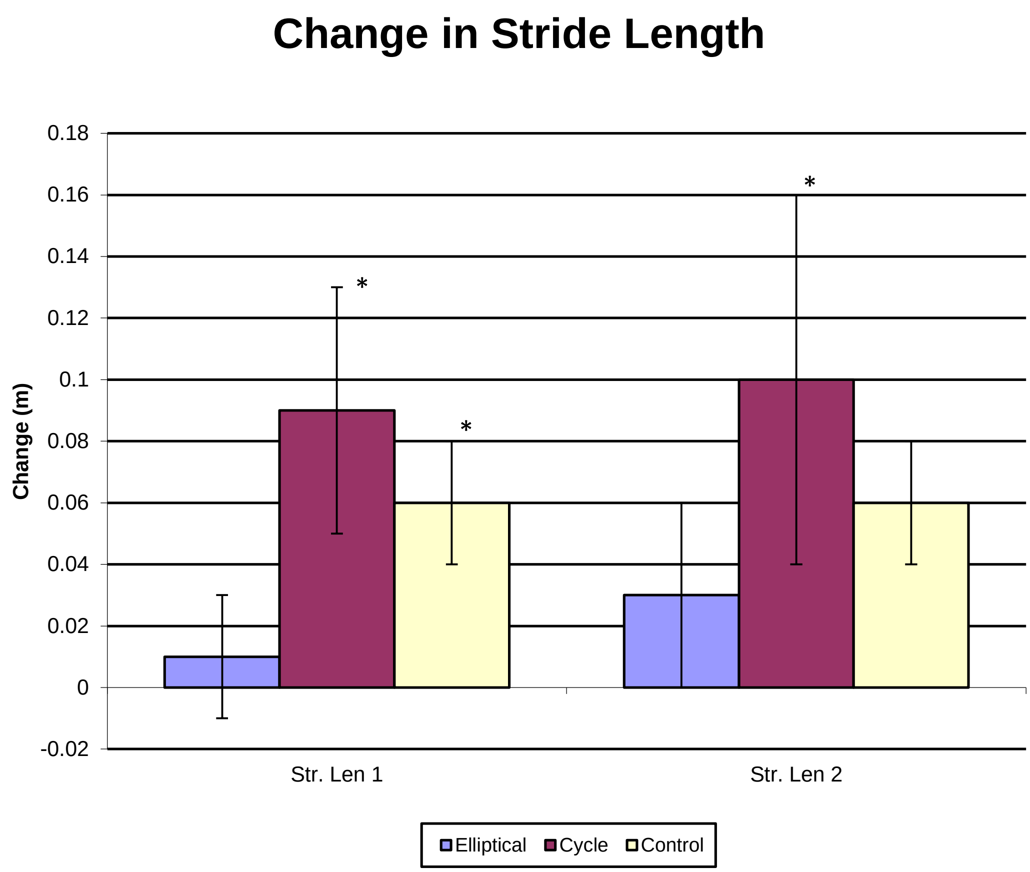

Figure 4.4 - Changes in Stride Length, Pre-Training vs. Post-Training
Data presented as mean ± standard error of measurement
* - significantly different from pre-training value ($p < 0.05$)

(0.06m ± 0.02m) and again was statistically significant ($p < 0.05$). The largest average increase was again in the cycle training group (0.07m ± 0.06m), but the greater variance and smaller group size meant the change was not statistically significant ($p = 0.22$). The increase in stride length on the second stage for the elliptical training group (0.03m ± 0.03m) was again not significant.

None of the differences in stride length change between groups were statistically significant. The closest results came to significance were on stage one in which the difference between the elliptical training and cycle training groups was significant at the level *p* = 0.13 and the difference between the elliptical training and control groups was significant at the level *p* = 0.14. All between-group comparisons of stride length changes on stage two produced *p* values greater than 0.4. There were no significant correlations between changes in stride length and changes in running economy for any group on any stage of the treadmill tests.

Laboratory measurements for VO2max and blood lactate levels for each stage are shown in Table 4.1. There were no significant changes between pre- and post-training measurements for any of the three groups on any of the measures. There were no significant between-group differences in the amount of change that occurred between the pre- and post-training tests for any of the measures.

	Elliptical Training	Cycle Training	Control (Running)
VO2 max ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.8 ± 0.9	-0.6 ± 1.3	-0.2 ± 0.6
Stage 1 [La] (mmol)	-0.3 ± 1.4	0.3 ± 1.3	0.0 ± 0.4
Stage 2 [La] (mmol)	-2.3 ± 1.2	-0.9 ± 1.4	1.2 ± 1.2
Stage 3 [La] (mmol)	2.4 ± 1.9	4.3 ± 3.4	0.4 ± 1.3
Stage 4 [La] (mmol)	1.0 ± 1.3	0.8 ± 2.4	0.7 ± 0.8

Table 4.1 - Changes in Metabolic Measures, Pre-Training vs. Post-Training
Data presented as mean ± standard deviation

For all three groups the changes in VO2max over the course of the training period were less than the standard error. The average change in VO2max across all subjects in all groups was exactly zero.

Stage 1 lactate levels were essentially unchanged in all groups, with an average change never more than 0.3 mmol for any group and the standard error several times the mean change. Stage 2 mean lactate changes were larger for all groups, but were negative for both cross training groups and positive for the control group. None of the stage 2 changes was significant. Stage 3 shows a trend toward larger increases in lactate level for both cross-training groups but not in the control group. This might suggest that cross-training subjects were reaching their lactate threshold at an earlier pace, but the changes were not significant ($p > 0.2$).

Measuring change in lactate levels requires a subject to complete the stage of interest in both the pre- and post-training tests. Only 12 subjects completed stage four on both tests, and 11 of 27 subjects failed to complete stage three on at least one test. This increased the threshold for significance on those stages. On stage four the changes were positive, and of greater magnitude than on the first stage, for every group. However, for every group the standard error was greater than the change in lactate, and no change reached statistical significance. In both cross-training groups the increase in lactate was smaller than that seen on stage three.

Table 4.2 presents descriptive data on the 27 subjects who completed the study and were included in the data. No groups showed significant changes in body weight, height, or body mass index. There was a significant change in body fat percentage ($p < 0.05$) in the stationary bike group during post-testing compared to pre-testing. However, the elliptical and control groups also showed increases ($p > 0.05$) in body fat percentage, so there was not a significant difference between groups on the change in body fat percentage. The changes in body fat percentage did not correlate significantly with changes in performance or running economy.

	Elliptical Training	Cycle Training	Control (Running)
Sex	6m, 4f	6m, 1f	6m, 3f
Age (years)	15.4 ± 0.3	16.5 ± 0.3	17.4 ± 0.5
Weight (kg)	57.3 ± 3.0	60.6 ± 2.2	62.6 ± 2.4
Height (m)	1.67 ± 0.02	1.72 ± 0.03	1.72 ± 0.03
Body Fat (%)	11.3 ± 1.6	9.9 ± 0.9	11.0 ± 1.9
Body Mass Index	20.3 ± 0.6	20.4 ± 0.5	21.2 ± 0.6
VO2 Max ($ml \cdot kg^{-1} \cdot min^{-1}$)	57.0 ± 2.4	59.2 ± 2.1	60.0 ± 1.8
5-km best (sec)	1240 ± 27	1212 ± 42	1147 ± 41

Table 4.2 - Subject Characteristics
Data presented as mean ± standard error of measurement
All values are from pre-study testing

Three female subjects originally assigned to the cycle training group were ultimately not included in the results (see *Notes* below for discussion of this). It appears that the cycle training group is taller, heavier, faster, has a higher average VO2max and a lower average body fat percentage. However, after controlling for sex makeup of the groups, there were no differences in the cross-training groups.

As previously discussed, all subjects volunteering to forgo running were assigned to either the cycle training or the elliptical training group. The running control group was recruited separately, and as a result was significantly different from the other groups ($p < 0.05$) in terms of age, VO2max, and 5-km best time.

Notes on the research subjects: Two subjects, one assigned to the cycle group and one assigned to the control group, participated in the initial testing but did not take part in any of the follow up testing. No data from these subjects was included in any of the results presented here.

Data for two subjects were excluded from all calculations, after it was determined the subjects were not at a sufficient competitive level prior to the beginning of the study and did not meet the criteria for inclusion. Both subjects were 14 year-old females with no running experience prior to the just-completed cross country season, and both had best 5k times at least 225 seconds slower than any of the other subjects. Both subjects were assigned to the cycle training group. Both improved their time trial performance substantially (57.8 and 19.2 seconds). Upon reviewing the data it was determined that this reflected the general improvement in fitness that moderately-trained subjects will show regardless of training modality, and that inclusion of these subjects would reduce the applicability of the results to competitive runners.

Removing the two slowest subjects did not ultimately cause a change in the major findings of the study, although it did impact the strength of the findings. With the two subjects included, average change in 3000 meter performance for the cycle group was 21.7 sec (± 10.2 sec). The change is significant ($p < 0.05$), compared to significance $p < 0.001$ with the subjects excluded. In comparing the change in 3000-meter time to that of the control group, the cycle group with the slower subjects included was significantly worse ($p = 0.047$) compared to $p < 0.001$ with the subjects excluded. In comparing the change in 3000-

meter time to that of the elliptical group, the cycle group with the slower subjects included was not significantly better ($p = 0.205$) compared to $p = 0.707$ with the subjects excluded.

All four of the subjects who were not ultimately included in the data were females, three in the cycle group and one in the control group. All three groups initially had 10 subjects, six males and four females. After excluding subjects that did not meet study criteria or complete the study, the cycle group had six males and one female, and the control group had six males and one female.

The researchers considered discarding but ultimately included one female elliptical training subject. This subject displayed low level of motivation and the supervising coaches believed her follow-up time trial did not represent a serious effort. She was over two minutes slower than her original time and ran the entire distance near a teammate who was significantly slower during the season and during the pre-study time trial. Her inclusion alone resulted in an 11-second addition to the change in average time trial performance for the elliptical training group. This caused the average change in performance of the elliptical group to be worse than the cycle group.

Despite the large drop in performance by this individual, the difference in performance change in the two groups was not statistically significant whether the subject was included or excluded. Also, the elliptical group showed a change in time trial performance that was significantly worse than the control group even if this subject was excluded from the results. As the inclusion of this subject did not affect the significance of changes in the major variables of interest, and there were no objective criteria other than performance changes which would disqualify the subject from participation, this subject was included in the final results.

5. DISCUSSION

5.1 – Running Performance

The results confirmed the major hypothesis that subjects following a cross-training protocol would have reduced running performance compared to subjects who continued to run during the five-week training period. The average cross-training subject was 40 seconds slower for the 3000 meter time trial post-training, while the running subjects averaged a nine second improvement. For both cross-training groups, the change in time trial performance was significant ($p < 0.01$) compared to the control group, and the post-training results were slower than the pre-training results by a significant amount ($p < 0.01$).

Previous studies have not shown significant differences between cross-training and running training over periods ranging from four to eight weeks. As discussed in Chapter 2, these studies contained flaws that raise questions how well the results would predict the actual results if competitive runners switched their training to a non-running mode for an extended period. Almost all of the studies used subjects that were at best moderately trained and experienced in competitive running; pre-study performance measures for 3000- or 5000-meter showed subjects that would not be varsity level on even mediocre high school teams. Cross-training protocols often resulted in a significant increase in total volume of training, an option that would generally not be available for a competitive runner.

Viewed as a whole, the previous literature on cross-training does suggest the important findings of the current study. Even though all the reviewed studies failed to find a significant difference in performance between cross-training and running groups, in every single case, the cross-training groups had worse post-training results than the running groups. The power of the studies was limited by small sample sizes, but taken as a whole, the literature certainly allows for speculation in the same direction as this study's conclusion that running training is superior to cross-training, if the goal is to run fast. It is also true that over a distance of 3000 meters (a race distance also commonly used as a research performance measure), a 20-second difference would generally be considered competitively significant, even though that time amount was not statistically significant in the reviewed studies.

This result also matches the experience and intuition of the wide body of professional running coaches. The motivation for this research was the question of how to deal with the situation of a highly fit runner affected by a mid-season injury (such as a stress fracture or tendonitis) that might allow for a return by the championship meet but precludes normal training for a period of time. This is a relatively common situation, and experienced coaches would disagree with the past literature and say that it is extremely rare for an athlete in this situation to maintain his or her position relative to those who continue normal running.

The magnitude of the difference between cross-training and running groups (approximately 45 seconds for each cross-training mode) is very discouraging to someone contemplating cross-training as a method for maintaining running ability during a forced interruption of training. Several factors do suggest that the real-world prospects for the injured athletes might be somewhat more optimistic.

First, the protocol involved a complete lack of running for the approximately 40 day period between the two time trials, other than the post-training treadmill test 2-3 days prior to the second time trial. In reality, a runner hoping to compete after a break due to injury would probably not face such a total restriction. As described in chapter four, and soon to be discussed further, VO2max was maintained in all training modes. Performance differences were presumably related to running-specific adaptations affecting running economy or lactate response. Even a small amount of running, as one would gain from returning 7-10 days prior to competition, or by doing one running workout per week during the cross-training phase, would probably greatly attenuate the losses due to cross-training. If the schedule allowed for a return two or more weeks prior to the goal competition, the aerobic benefits of the cross-training could allow the athlete quickly to make up much of the lost ground.

Secondly, the motivation for training was completely different in this study compared to an injured runner aiming to return for a specific competition. Subjects in this research had just completed a competitive cross country season. Both cross-training and control subjects potentially had a lower motivation for intense training due to the lack of impending competitions. It is quite possible that the cross-trainers, who were using an unfamiliar exercise mode without any benchmarks such as pace to guide them, may have been further below in-season training intensities. An athlete using cross-training to prepare for an important upcoming competition might more closely match the efforts of someone who continued running.

Finally, this research focused on aerobic training methods and their effects and deliberately avoided introducing strength-training into the training protocol. However, numerous studies have shown significant effects from various types of strength-training on running economy and/or distance running performance. Given that the aspects of running performance believed to be influenced by strength-training are exactly the aspects that are potentially vulnerable to decay during non-running periods, it is a reasonable to speculate that this might be an ideal supplement to aerobic cross-training for an athlete trying to maintain race fitness. No studies have looked at this particular combination, but the results for various training studies in isolation suggest combining aerobic cross-training with lower-body strength-training as a recommendation for runners trying to maintain fitness across a break from running.

It was hypothesized that elliptical training mimicked running more closely than did cycling and thus would produce better results in time trial and in running economy. This did not prove to be the case. The post-training time trial performance of the elliptical group was slightly worse than for the cycle group, though not significantly so. It is possible that with larger group sizes or more strict control of training sessions, there might be results that allowed for a specific recommendation towards one mode of cross-training.

Regardless of what findings might be uncovered with further study of cross-training modes, these results seem to state clearly that the difference in results between cross-training methods is dwarfed by the differences between cross-training and continuing with normal run training. In some instances, an injury may dictate the choice of cross-training method. An athlete may have a strong preference for a particular cross-training mode, or one mode of cross-training may be more accessible, and thus the choice of mode could produce better compliance with the training schedule. In the absence of further results tipping the scales toward a particular cross-training mode, any of these factors would be sufficient reason for choosing one mode over another.

5.2 – Factors contributing to performance

Data on running economy at various paces does not conclusively explain the changes in performance for cross-trainers. A reduction in running economy at a given pace would cause VO2 to be higher at that pace. Cycling did show statistically worse running economy on stage 3 in the post-training test, compared to pre-training. But there were not statistically meaningful differences between groups, as all groups showed slight decreases in economy on stages two and three. (A majority of subjects in all groups failed to complete stage four in one or both treadmill tests, so those data are less useful in assessing effects of training.) The only significant change seen in running economy at any point was in the bike group, where RE declined pre- vs. post in stage three.

Two points should be made here. First, the elliptical and control group saw almost the same mean change in RE stage three, but the change did not reach significance. More important, by stage three anaerobic energy sources were contributing significantly to the workload for most subjects. Changes in VO2 for stage three and beyond may not accurately describe the change in work output to maintain the given pace. Stages one and two were designed to keep the subjects at predominantly aerobic intensities for long enough to allow VO2 to stabilize, and in these stages there were no significant differences either pre- vs. post-training or between groups.

Looking at specific mechanical contributors to running economy, a shorter stride length (higher stride frequency) is often associated with better running economy at a given pace. The cycling group had a statistically longer stride on stage one post-training, and the control group had a longer stride post-training after stages one and two. In this case, there was not a statistical correlation between longer stride and economy. As noted in Chapter 2, much of what is called "running economy" is the product of internal neuromuscular factors that are not amenable to direct measurement in a treadmill test.

There were no significant changes in VO2max, either between groups or within a group between pre- and post-training tests. This is in line with previous work that has consistently shown that VO2max is maintained over time regardless of the type of training, and that VO2max effects are transferrable across a variety of training modes. There is some question, with the current study and others, whether the time course of training is long enough to demonstrate conclusive results about VO2max changes, since even complete cessation of training for at least two weeks does not cause a change in VO2max.

The fact that significant changes in performance were not accompanied by changes in VO2max confirms many previous results that showed little correlation between VO2max and performance among runners of similar ability or for an individual runner over time. The implications of this are that maintaining VO2max may be a necessary but not a sufficient condition for maintaining running performance and that any regular and significant aerobic stimulus will maintain VO2max for five weeks or more. In determining optimal training during a non-running period, emphasis should be given to the impact on characteristics other than VO2max, such as lactate response and biomechanical efficiency during the competitive activity.

Body fat was significantly increased post-training in the cycle training group, and slightly smaller (non-significant) increases in body fat were seen in the other groups as well. Differences between groups were not significant, and there was no significant correlation between body fat changes and changes in performance or running economy. Given the large number of variables measured in the study, it is possible this outcome is a statistical artifact. However, the timing of the study (post-season, mid-November through December) does make it plausible that diet, lifestyle, or training changes led to a body fat increase. Although this was not significantly related to any performance measures, higher body fat is associated with lower VO2max and poorer running results. In a real-world cross-training situation, it would be advisable to monitor body composition to be sure in-season levels of body fat are being maintained.

5.3 - Confounding factors

A number of factors related to the subjects and the conduct of their training in the study could possibly be confounding factors in the results. It is difficult for some people to recreate the motivation for training that they have during a competitive season. Because the study took place after the end of the cross country season, subjects in any of the groups may have been less intense in their workouts than they were prior to the study. It is possible this effect could be greater in subjects who were cross-training because they were not engaging in their normal form of training. It is difficult to speculate how motivation in these subjects would compare to that of an injured athlete engaging in cross-training specifically to retain competitive fitness.

Because the study was both after the competitive season, and at the end of the calendar year, subjects may have had changes in lifestyle outside of training, particularly diet and sleep. This could have been directly responsible for the observed change in body fat percentage, and may have indirectly affected some other measures. No attempt was made in the data collection to track diet, sleep, or psychological factors like motivation.

Subjects turned in weekly training logs, but worked out on their own and were responsible for monitoring their own training. It is possible that some subjects may have overstated the number or duration of workouts. Desired intensity for the workouts was described subjectively, and subjects selected their own intensity for each workout. Some subjects may not have achieved desired levels that matched those of workouts during the cross country season.

Recruiting a sufficient number of trained runners who were willing to give up running for five weeks was the limiting factor on the size of the subject population. As a result, all volunteers who were willing to forgo running were assigned to one of the two cross-training groups. A separate group of runners was recruited, using the same eligibility standards, to be controls. The running control group was significantly older, more experienced, and faster than the cross-training groups. It is possible that any of those variables was correlated with the variables of interest in a way that directly affected the results of the study. It is also possible that the differences resulted in the control group having better compliance with the training protocol or higher motivation for the training and the follow-up time trial.

Some of the measured data are more susceptible to error and have a greater chance of confounding results given the relatively small size for each group. For a given subject, blood lactate values at each stage require a precisely measured quantity of both blood and lysing buffer. These quantities must be measured accurately in both pre- and post-testing, meaning four volumes must be correct to produce a valid measure of change in blood lactate level. Human error here could be a cause of the lack of any significant changes in blood lactate levels in any group. During the body fat measurements, three sites are measured in both pre- and post-testing, with a low-precision caliper. It is possible this accounts for the surprising finding of significant increase in body fat in the bike group. However, there were some increases seen in every group and the previously noted factors of post-season or end-of-year lifestyle changes are reasonable explanations for this result.

Per-stage physiological data from the treadmill tests makes the presumption that the subjects had reached a steady-state for the measured parameters by the final 30 seconds of each stage. The length of stages followed protocols seen in many other studies, but by necessity, the need to reach steady-state before increasing intensity is weighed against the need to reach maximum intensity before the subject begins to suffer from accumulated fatigue. Analysis of data, particularly the shorter term data on heart rate and VO2, does support the idea that subjects generally reached steady state on each stage. Nonetheless, some measurements may not represent true steady state values.

Some subjects failed to complete the third stage in one treadmill test, either pre- or post-training. A majority of subjects in all groups failed to complete stage four in at least one test. Because data from both the pre- and post-tests are necessary for comparisons, results from the third and fourth stages are based on a smaller group of subjects, and the threshold for statistical significance is higher. Some significant changes in blood lactate level in the later stages may have been missed for this reason. Both the elliptical and cycle group had much higher mean stage three changes in blood lactate than the control group, but the differences did not rise to the level of significance.

There is the potential that learning effects impacted the post-training results on the treadmill test and/or the time trial. No subjects had prior experience with a graded exercise test, and may have benefited in the second test from greater familiarity with the protocol or testing equipment. Some subjects had little or no experience with treadmill running, and may have improved their treadmill running skill. There were no results that would reflect these effects, but it is possible that learning effects offset similar or larger changes in the opposite direction. Most subjects had little or no experience racing on an indoor track, and some had little or no experience at the 3000 meter distance. Some may have benefitted in the second time trial from familiarity with the event or better knowledge of pacing. Again, the results do not show such effects but they may have partially offset even larger changes in the opposite direction.

5.4 - Directions for Future Research

Modifications to the current study could be made to strengthen the results or better investigate the areas of interest. Much of this would involve improving the subject pool. Although the subjects were at a high running level compared to most previous work, there was still a great deal of variation in running ability and experience. In addition, it would be good to have enough willing subjects to have true random assignment between research and control groups.

Requiring a minimum of 15 months experience (two seasons of cross country or track with continuous training in the interim) and setting minimum standards of 18:00 5000 meters for males and 21:30 5000 meters for females (approximately varsity level for a good high school team) would reduce subject variation and make it more likely that all subjects would maintain a high level of motivation during training. As a practical matter, such a study might have to be conducted over multiple time periods to ensure enough subjects were available.

Training intensity was an uncontrolled variable in this research. Monitoring of training, such as having subjects use recording heart monitors for all workouts, would allow for comparison of the actual workloads each subject completed during training. Having all training sessions conducted under supervision, with RPE evaluated during or immediately after each workout, would ensure compliance with the training protocol and provide further ability to compare workloads. Time constraints limited the training period to five weeks, but six to eight weeks would more closely match the course of changes of variables shown in some other work, and also match the recovery period often seen for injuries such as stress fractures.

The protocol for the treadmill tests could potentially be modified to increase confidence that all subjects reach steady state on each stage, and that subjects complete a minimum number of stages. Each stage could be increased by one minute, and the paces might be adjusted downward at each stage. The improvements in the subject pool suggested above would contribute to this, as more experienced and faster runners could reliably complete a longer test without having fatigue become a limiting factor. An entirely separate area of inquiry that relates to this would be the responses of trained subjects at a variety of percentages of 5000-meter race pace, to determine if particular percentages are especially critical to include in a protocol, and how closely spaced stages must be to provide valid results.

As running economy seems like the most likely contributor to changes in running performance due to cross-training, further research in that area would be valuable. Analysis of the correlation between both running economy and VO2max and running performance would allow a better understanding of these effects. Race performance is subject to great variation from many factors, but because these measurements only require a single lab test, it would be feasible to measure a larger number of subjects, and to repeat test on individual subjects across multiple seasons.

This suggests additional areas of inquiry into the long-term course of RE within individuals. The literature review does not show any longitudinal studies on the effect of age, years of experience, or long-term training on RE. The most relevant data comes from case studies showing changes in performance and VO2max over time with elite athletes, generally showing a plateau in VO2max or improvements that are substantially smaller than the degree of performance improvement. This is suggestive of ongoing increases in RE, but specific measures of RE are not described.

One issue with studying RE is how to define it. It is possible to define RE negatively as “everything affecting running performance that is not how much oxygen you can consume (VO2max) and how high a percentage of that VO2max you can sustain without seeing big increases in lactate (LT).” In this study we go even further and simply define RE as the steady state VO2 required to maintain a particular pace. This requires confirmation or assumption that the pace is slow enough that anaerobic sources are not significant contributors to maintaining speed. This means that strictly using VO2 to evaluate RE limits the evaluation to speeds slower than race pace, and perhaps misses important factors in RE that will be present during competition.

The field needs further work to develop other measures or definitions of running economy. This study looked a specific mechanical component, stride length, that contributes to RE, but many internal factors also affect RE and different methods are needed to evaluate them. Tests that allow assessment of RE at race speeds will also contribute greatly to our understanding of how the various components of running performance impact the final results.

Strength-training is a mode of cross-training that needs to be evaluated in a manner similar to that used in this research. Previous work on the effects of strength-training on running economy or performance suffer from the same flaws that most previous work on cross-training had, namely that the subject populations were not trained competitive runners, and the training protocols often involved significant increases in overall training.

There are numerous possible areas for investigation in a training study with competitive runners. Repeating the current study with an additional strength-training component would evaluate interaction effects between cross-training and strength-training. A program adding strength-training, compared to a control group adding a similar volume of run training, would isolate the impacts of strength-training versus the generic effects of any additional training volume. Similar work could be done comparing different strength-training protocols, such as explosive or plyometric training vs. a control group adding a traditional muscular endurance training program. There are many possibilities in combining various run-training or cross-training protocols with different strength-training programs to evaluate how various combinations interact.

This work has made a valuable contribution by providing the first statistically significant finding confirming the widely held belief among coaches that running is critical to maintaining race performance, even when other forms of training can maintain physiological markers of fitness. The results also demonstrate that VO2max can be maintained equally well over a five-week period whether training via running, elliptical trainer exercise, or stationary bike. Given the slower times recorded post-training by the cross-training subjects, it is clear that additional exercise such as strength-training must be considered if running performance is to be maintained. Future research should investigate whether strength training can reduce or eliminate the performance losses associated with substituting cross-training for running, and investigate the effects of strength-training on RE in trained competitive runners in a way that holds training volumes constant across study groups.

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APPENDIX A – PARENT INFORMED CONSENT FORM

Department of Health, Leisure and Exercise Science Appalachian State University

PARENTAL CONSENT FORM

The Effects of Cross Training on Distance Running Fitness and Performance

Your child is invited to be in a research study about how different types of training effect distance runners. Your child was selected as a possible participant because of his/her current participation in high school cross country. We ask that you read this form and ask any questions you may have before agreeing to have your child in the study.

Description

This study examines whether there are changes in physical measures or performance time in a simulated race when runners train using exercise other than running, commonly called cross-training. This type of training is sometime used by runners as a replacement for running, either because they wish to vary their type of training or because injury prevents them from running. Participants in the study will train for approximately six weeks using one of three assigned modes of training: running, elliptical machine exercise, or stationary bike exercise. The frequency, duration, and intensity of the training will be similar to their current cross country training. Before and after the study, participants will take part in a graded exercise test on a treadmill, in which they run at gradually increasing intensities until they indicate they wish to stop. Before and after the study, participants will also take part in a 3000-meter time trial, which is a simulated race on a track.

Risks

The techniques used in this study pose a possible slight risk to your child. These risks are described below.

<u>Exercise Treadmill Test</u>

With the performance of a graded exercise test in which the heart, lungs, and blood vessels are required to work very hard, the risk of heart attack, stroke, and sudden death are increased. However, these problems are not likely because your child is young. These problems are less likely in cardiovascularly fit individuals such as children who have just completed a cross country season. The overall risk of sudden death during or after exercise in young athletes is less one per year for every 100,000 participants. Problems with your child's heart from birth may also become known when this type of test is performed. But because your child was examined by a doctor before beginning sport participation, this is less likely to happen. If any problems are noted upon testing, you and your child's doctor will be informed. Other problems that happen with treadmill testing include minor muscle strains in the legs and possibly cuts and bruises from falling off the treadmill. We will watch your child very closely to make sure this does not occur. Faculty and students participating in the test will be CPR and First Aid certified and an AED (Automated External Defibrillator) machine is available if needed.

<u>Finger-stick Blood Draws</u>

Approximately 6-8 finger sticks blood draws will be performed during each of the two treadmill tests. The risk of finger stick blood draws includes the possibility of the collector, or analyzers contracting blood borne diseases such as hepatitis or HIV. Chances of infection are minimal and all precautionary measures to minimize these occurrences will be taken. The risk of blood-borne infection exposure to your child is much lower than the risk to the collector and analyzers. In order to minimize all risks the testing staff will be completely trained to deal with these risks. The process of performing a finger stick may produce minor bruising that lasts for 1-3 days. Your child will feel a little sting when the needle pricks the finger but this will only last a few seconds. We will wipe the finger with alcohol and place a Band-aid over the puncture site to reduce the chance of infection.

<u>3000-meter Run Trial</u>

This test is to determine your child's best effort time for a 3000-meter run. It will be conducted on an indoor track at Appalachian State University. The risks associated with this test are the same as those associated with any other distance running race, and as those described above for the exercise treadmill test. Your child will be encouraged to perform their best during the time trial, but will not be coercively induced to exceed their own tolerance for discomfort.

<u>Exercise Training</u>

The training associated with this study has the same minor risks associated with all exercise. Because your child is accustomed to regular endurance exercise, their risk of heart problems or muscular or skeletal injuries is reduced. Your child will be asked to exercise at an intensity and for a duration that is similar to their regular training schedule from cross country. Following this schedule will lower your child's risk of injury or illness. If your child is in the run training group, there may be risks associated with the location where the running takes place. This includes the risk of bone or joint injuries due to falls or twisted joints, possible injury by vehicle if running on roads, and environmental risks due to extreme heat, cold, or lightning. We will provide advice on how runners can reduce these risks as much as possible. If your child is in a cross-training group, their training will take place inside a fitness center. In addition to general exercise risks, there is a slight risk of injury from falling off the exercise equipment or from equipment malfunction. These risks are minimized by fitness center maintenance and the presence of staff to instruct your child on the proper use of the equipment. The staff is trained to respond to any injuries that occur. If you have access to home exercise equipment that is appropriate to your child's assigned mode of training, you may allow your child to use this equipment in lieu of going to the fitness center. In this case, you assume responsibility for ensuring that the equipment is safe and functioning properly, that your child knows how to use it, and that your child is properly supervised during the exercise.

Benefits

Exercise Test Results

Your child will receive results from exercise testing at the beginning and end of the study. These tests normally cost $100-$150 and will be done free of charge. The data from these tests can be valuable to coaches in designing better training for athletes and monitoring the results of past training.

Personalized Exercise Training Program

Your child will be provided with an individualized exercise program designed based on their reported cross country training and the results of their exercise testing at the beginning of the study. Weekly monitoring of training progress will be provided, with more frequent consultation available if desired.

Cross-Training Opportunity

Subjects assigned to the cross-training groups will be provided with free access to training facilities. This has a value of $10-25 per month. Cross-training has been identified as a possible method of reducing impact-stress related injuries and maintaining exercise motivation in runners.

Improved Knowledge of Cross-Training

The results of this study will expand the knowledge of how different forms of cross-training affect fitness and performance in competitive runners. This will allow coaches and athletes in the future to better plan training.

Compensation for Injury

No funds have been set aside to cover the costs of physical injury or illness resulting from this study. Immediate first aid will be provided onsite free of charge if a physical injury occurs during training or testing. You understand that long-term medical costs will not be covered by Appalachian State University.

Confidentiality

The records of this study will be kept private. All data will be tabulated using subject identification numbers rather than names. No personal identifying information will be included in any published results of this study. Consent forms will be kept securely along with results for five years after the completion of this study, and all information will be destroyed at the end of this period.

Volunatary Consent / Right to Withdraw

Your decision whether or not to have your child participate will not affect your current of future relations with Appalachian State University, your child's current school, or any sports team at that school. Participation in this study is not a a condition for membership on any school or club sports team. If you decide to allow your child to participate, you are free to withdraw your child at any time without affecting your relationship with Appalachian State University or your child's current school or sports team. Furthermore, your child may also choose to discontinue participation at any time. The researcher conducting this study is David Honea. The faculty mentor for this study is Dr. Chuck Dumke. You may ask them any questions you have now. If you have any questions later, you may contact Mr. Honea at (828)264-4207. You may contact Dr. Dumke at (828)265-8652. If you have further questions about your rights as a research participant, you may contact Robert Johnson, Appalachian State University IRB administrator at (828)262-2120.

My questions concerning this study have been answered to my satisfaction. I hereby give voluntary consent for my child to participate in this study. I certify that I have been given a copy of this consent form.

Name of Child _________________________

Signature of Parent/Guardian__________________________ Date _____________

Signature of Researcher_______________________________ Date _____________

APPENDIX B – MINOR SUBJECT ASSENT FORM

Children's Assent Form

Running / Cross Training Study

We are asking if you are willing to be in our cross-training study to see how different types of training may affect runners. Because you are currently running high school cross country, we are asking if you want to be in a study. A study like this will be most valuable to scientists, coaches, and runners if the participants are all trained, competitive runners. Elliptical exercise machines and stationary bikes are two types of cross-training that may help runners. We will not know how effective these types of training are until after the study.

Study Description

If you agree to be in this study, you will come to our lab to run on a treadmill right after your cross country season ends. In this test we will gradually make the treadmill faster until you tell us you want to stop. You will probably be tired, like at the end of a medium-length race, after this test. While you are on the treadmill we will measure your heart beat and breathing, and use a finger-stick needle to take a little bit of blood several times. This will probably sting a little bit. A few days after the treadmill test, you will run in a 3000-meter race on an indoor track with several other runners in the study.

After the treadmill test and the race, we will ask you to train using just one type of training for about six weeks. You may be assigned to elliptical machine training, stationary bike training, or running. You will not be able to choose which type of training you do; it will be randomly assigned to you. You will train about like you do during cross country season: four to six days a week, usually 40 to 60 minutes each day, at a variety of paces. We will tell you how much training to do and how hard to do it, but you can chose which days of the week, what time, and where to do it.

At the end of the six-week training period, you will return to ASU two more times, to repeat the treadmill test and the 3000-meter race. These will be done in exactly the same way the first tests were done.

Risks and Benefits of the Study

The risks of the testing we will do in this study, and the training we ask you to do, are about the same as with most hard exercise, like the kind you do in cross country practice. You may feel very tired, lightheaded, have muscle cramps, or feel sick to your stomach sometimes. You could fall and get cuts or bruises, twist an ankle or knee, pull a muscle, or have some kind of injury from doing more exercise than your body can handle. None of these risks will be worse during our study than when you exercise with on your own or with your team. We will try to help you reduce the risks of injury. There is a slight risk during exercise of much more serious problems, such as heart attack or stroke, that occasionally even cause sudden death. These things might happen because of problems with your heart that have been with you since birth but that no one knows about. Because you were examined by a doctor before you started cross country, and have trained for a whole season before starting this study, these problems are less likely. Serious health problems during exercise are less likely in young people, and in people who are already in good shape.

You may not enjoy your assigned type of training as much as running. Your race times may not be as good right after the study as if you had spent the same amount of time on running training. This may impact you if you want to compete in indoor track. Since the study will be finished in December, there will probably not be any impact on your performance next year in outdoor track or cross country.

One benefit of the study is that cross-training may reduce your chances of injury or provide you with a mental break at the end of the season. Whether you are assigned to cross-training or running, we will give you a training schedule designed especially for you, based on your cross country training and the results of your tests. This may help you do a better job staying in shape in the off-season. The treadmill tests will provide very valuable information about how your body responds to running, and if you share this with your coach it may help in planning your future training. Normally people would pay up to $300 for these tests and a personally designed training plan, but you will not pay anything for any part of this study. When the study is done, we will know more about how cross-training affects runners, and this could help everyone in the sport in the future.

Signing here means that you have read this paper or had it read to you and that you are willing to be in this study. If you don't want to be in this study, don't sign. If you sign this form but later change your mind, you can drop out of the study at any time. Remember, being in this study is up to you, and no one will be mad at you if you don't sign this or even if you change your mind later.
You can ask any questions that you have about this study. Signing here means that you have had a chance to ask any questions you want and have had your questions answered. If you have a question later that you didn't think of now, you can ask us next time, or you can have your parents call Mr. Honea at (828) 264-4207 or Dr. Dumke at (828) 265-8652.

Signature of Participant ____________________ Date _____________

Signature of Investigator ____________________ Date ____________

APPENDIX C – LABORATORY TEST DATA COLLECTION FORM

Treadmill Testing – Post-Test

Subject #: ____________

Name:____________________________ Date: _______________ Time:_________

Height:_____ Weight:__________ Skinfold: Trial 1 Trial 2 Trial 3

Thigh _____ _____ ______

BMI: ______ Ab/Superilliac _____ _____ ______

Chest/Arm _____ _____ ______

BF% ______

Best 5k pace:__________ Fitmate #:_______

Running economy: Four minute stages. After 2:30 at given pace to reach steady state, record VO2 values every 15 seconds. Record time for 30 strides beginning ~2:30 into stage. Record HR and RPE at end of stage.

Grade = 1.0%		Grade = 1.0%	
Stage 1 – 75% = _____		Stage 2 – 90% = _______	
VO2@ 2:30__________		6:30__________	
2:45__________	30 stride time:	6:45__________	30 stride time:
3:00__________	________ sec	7:00__________	________ sec
3:15__________	________ sec	7:15__________	________ sec
3:30__________		7:30__________	
3:45__________	RPE:_____	7:45__________	RPE:___
4:00__________	HR:______	8:00__________	HR:____
	[La]:____		[La]:_____

VO2max: Two minute stages. Record VO2 at 1:30, 1:45, and 2:00 of each stage. Record HR and RPE at end of stage.

	Stage 3	*Stage 4*	*Stage 5*	*Stage 6*	*Stage 7*	*Stage 8*
Grade	1%	1%	1%	5%	9%	13%
Pace	97.5% =	105%=	112.5%=	112.5%=	112.5%=	112.5%=
VO2	9:30-	11:30-	13:30-	15:30-	17:30-	19:30-
	9:45-	11:45-	13:45-	15:45-	17:45-	19:45-
	10:00-	12:00-	14:00-	16:00-	18:00-	20:00-
RPE						
HR						
[La]						

Time at termination: ___________

Notes:____

____

APPENDIX D – SUBJECT INSTRUCTIONS

Instructions for Elliptical Cross-Training

Training Period: Friday, November 10 through Wednesday, December 13. You may get one or two extra days at the end, depending on when your follow-up testing is scheduled. The time trial at the end will be on Monday, December 18.

How Often?: You should aim to do 5-6 days of training per week. The suggested minimum number of workouts for the whole study is 23 in five weeks. Since you may miss some days (for example, at Thanksgiving), you should always try to get at least five days during normal weeks.

How Long?: All workouts should be at least 40 minutes, and the average workout should be similar to the average run you did in cross country. You should not go over 60 minutes, unless you want to do one longer workout a week up to 70 minutes to simulate a long run.

Types of Workouts: Do one day of "tempo" training and one day with short "sprints" each week. The other days should all be continuous pace workouts. You will get a workout sheet with individual recommendations, including heart rate ranges, next week. Here are general guidelines everyone can use.

- Tempo – After 10-15 minutes of warmup, go at an effort that is about like a 5k race or a little easier for four minutes, with two minutes recovery. You will need to raise both your RPM's and the Level on the elliptical machine for the hard parts, and lower it for the easy parts. (For example, you might do 85 RPM on level 5 for the tempo, and 75 RPM on Level 2 for the recovery. The level can vary a lot depending on the machine you are using.) You should do this four or five times. At the end, cool down for 8-10 minutes.
- Sprints – After 15-20 minutes warmup, set the elliptical machine to a higher level and go as fast as you can for 15 seconds. Then put the machine back to a low level and go at an easy pace for 1:45 seconds. Do this 10 times (you will start one "sprint" every two minutes.) Cool down for 5-10 minutes after the last one.
- Warmup/Cooldown – This is done on the elliptical machine too, at an easy pace.
- Continuous – Go at an effort like a regular cross country practice for 40-60 minutes. You can start with a lower level and gradually increase over the first ten minutes to your normal level (for example, if you want to use level 4, you can do level 2 for the first five minutes, level 3 for the next five minutes, and then level 4 the rest of the time.)

Using Elliptical Machines: These machines can vary a lot. Most have handles to work the arms as well – choose this kind if available. On some you can vary the grade (steepness) and level; on others you only change the level. The level has a bigger impact on how hard you work; the grade mainly changes which parts of your legs do the work. Levels can vary a LOT on different machines – some only go 1-10, while others have up to 25 levels. Level 5 can be pretty hard on one type of machine and very easy on another – try to get used to one kind of machine so you will know if you are working harder or easier on a given day.

Many machines will tell you how much work you are doing, either in Watts or Calories/hr. This measurement can also vary a lot between two different kinds of machines – the same effort may show up as 700 Cal/hr on one machine and 1000 Cal/hr on another. Again, if you get used to the machines you use, you'll start to recognize what different levels of work mean.

If you have little or no experience with cross training, the effort the first few times may feel a lot harder than the amount of work you are actually doing. If you notice after a week or so that the same level now feels a lot easier, you should increase it.

Keeping Track of Your Training: Use the log sheet to record when you workout, how long, and what kind of workout you do each day. We collect them weekly. Please note anything unusual or things that affected your training (such as, you got sick or hurt.)

Other Training: Please don't run! Running across the field in PE, or a church league basketball game, is o.k., but no regular running. Don't start lifting weights or doing any other kind of new strength training. You can, and are encouraged to, continue doing any type of abs or core exercise training that we have done in practice.

Questions?: If you have any kinds of questions about cross training, including the best settings for different types of workouts, contact Coach Honea. You can reach him by email at marathondave@mindspring.com or by phone at 264-4207.

Use of the Wellness Center

If you do not have a membership: I am giving them a list of your names. They have a card they will give you on your first visit that you will show each time you go. There will also be a sign-in sheet at the desk in the fitness center that you will need to sign each time you go.

If you already have a membership: You just go in like you regularly do.

FOR EVERYONE:

It is critical that people in this study not overwhelm the facility during busy times, especially 4:00-6:00pm on weekdays. No more than two people in the study should be using a given type of equipment at one time during these time periods on Mon-Wed-Fri, and no more than three people in the study should be using the same type of equipment at the same time on Tues-Thurs. Anyone who can plan to do workouts on the weekend, or before or after the 4-6pm time period, will help ease the crowding.

Please remember this is a facility with people from the whole community, not a student center. Representing Watauga High well is critical to maintaining our access to the center.

Use of ASU Facilities

If you have an AppCard with family fitness center access, you are entitled to use these facilities. Still, we need to be aware of the effect that several people trying to do the same thing at the same time could have on other users. Just like at the Wellness Center, 4:00-6:00pm on weekdays tends to be their busiest time, although Friday is usually much less busy.

- If numerous people are trying to use the same type of equipment at one time, try to make use of all three fitness centers (Quinn, Mt. Mitchell on the top floor of the student center, and the new SRC). All three have both bikes and elliptical trainers.
- Try not to have large groups all showing up together to start a workout. This can cause a backlog, since it means that several pieces of equipment will all be taken up at the same time. (Normally, even when the gym is full someone will be leaving every few minutes. If you all start at exactly the same time, none of that group of machines will come open in the next 45 minutes.)

Please try to remember that your behavior represents our whole team and school – don't do anything that calls attention to us in a negative way.

Instructions for Stationary Bike Cross-Training

Training Period: Friday, November 10 through Wednesday, December 13. You may get one or two extra days at the end, depending on when your follow-up testing is scheduled. The time trial at the end will be on Monday, December 18.

How Often?: You should aim to do 5-6 days of training per week. The suggested minimum number of workouts for the whole study is 23 in five weeks. Since you may miss some days (for example, at Thanksgiving), you should always try to get at least five days during normal weeks.

How Long?: All workouts should be at least 40 minutes, and the average workout should be similar to the average run you did in cross country. You should not go over 60 minutes, unless you want to do one longer workout a week up to 70 minutes to simulate a long run.

Types of Workouts: Do one day of "tempo" training and one day with short "sprints" each week. The other days should all be continuous pace workouts. You will get a workout sheet with individual recommendations, including heart rate ranges, next week. Here are general guidelines everyone can use.

- Tempo – After 10-15 minutes of warmup, go at an effort that is about like a 5k race or a little easier for four minutes, with two minutes recovery. You will need to raise both your RPM's and the Level on the bike for the hard parts, and lower it for the easy parts. (For example, you might do 85-90 RPM on level 5 for the tempo, and 75 RPM on Level 2 for the recovery. The level can vary a lot depending on the bike you are using.) You should do this four or five times. At the end, cool down for 8-10 minutes. If you do a hard spin class, it would probably count as your tempo workout for that week.
- Sprints – After 15-20 minutes warmup, set the bike to a higher level and go as fast as you can for 15 seconds. Then set the bike back to a low level and go at an easy pace for 1:45 seconds. Do this 10 times (you will start one "sprint" every two minutes.) Cool down for 5-10 minutes after the last one.
- Warmup/Cooldown – This is done on the bike too, at an easy pace.
- Continuous – Go at an effort like a regular cross country practice for 40-60 minutes. You can start with a lower level and gradually increase over the first ten minutes to your normal level (for example, if you want to use level 4, you can do level 2 for the first five minutes, level 3 for the next five minutes, and then level 4 the rest of the time.)

Using Stationary Bikes: There are three basic types – upright, recumbent (seats with backs), and spin. Upright and recumbent are very similar. The spin class bikes are different, and you should probably only use a spin class as your hard tempo workout for the week. Generally you can adjust the level (like changing gears on a regular bike) to change how hard you are working at a given pedal RPM. Levels can vary a LOT on different bike – some only go 1-10, while others have up to 25 levels. Level 5 can be pretty hard on one type of bike and very easy on another – try to get used to one kind of bike so you will know if you are working harder or easier on a given day.

Many machines will tell you how much work you are doing, either in Watts or Calories/hr. This measurement can also vary a lot between two different kinds of bikes – the same effort may show up as 500 Cal/hr on one bike and 700 Cal/hr on another. Again, if you get used to the bikes you use, you'll start to recognize what different levels of work mean.

If you have little or no experience with cross training, the effort the first few times may feel a lot harder than the amount of work you are actually doing. If you notice after a week or so that the same level now feels a lot easier, you should increase it.

Keeping Track of Your Training: Use the log sheet to record when you workout, how long, and what kind of workout you do each day. We collect them weekly. Please note anything unusual or things that affected your training (such as, you got sick or hurt.)

Other Training: Please don't run! Running across the field in PE, or a church league basketball game, is o.k., but no regular running. Don't start lifting weights or doing any other kind of new strength training. You can, and are encouraged to, continue doing any type of abs or core exercise training that we have done in practice.

Questions?: If you have any kinds of questions about cross training, including the best settings for different types of workouts, contact Coach Honea. You can reach him by email at marathondave@mindspring.com or by phone at 264-4207.

Vita

David Morris Honea was born in Cocoa Beach, Florida, to Thomas and Sherry Honea. He graduated from Enka High School in North Carolina in June 1987. The following autumn, he enrolled at North Carolina State University to study electrical engineering. In May 1992, he graduated summa cum laude with a Bachelor of Science degree and was a valedictorian of the university. He competed in track and cross country for North Carolina State University and was an NCAA all-American in cross country and Atlantic Coast Conference champion at 10,000 meters in track. He was awarded the NCAA Walter Byers Post-Graduate Scholarship as the nation's top graduating male student athlete in 1992.

Mr. Honea was awarded a National Science Foundation graduate fellowship in 1992 and enrolled in graduate school in electrical engineering at North Carolina State University. He was awarded the Masters of Science degree in May 1994. He continued research in computer engineering in the Center for Advanced Computing and Communication at North Carolina State University, publishing four conference papers in the field of computer vision.

Mr. Honea is a USA Track & Field Level II coach in the areas of Endurance, Jumps, and Combined Events and is a USA Track & Field certified coaching instructor. From 1995 to 2001, he was an assistant coach for cross country and track and field at North Carolina State University. He is currently a math at instructor at Wilkes Early College in Wilkesboro, N.C. and coaches cross country and track at Watauga High School in Boone, N.C. He resides in Boone with his wife and two sons.