

Plyometric Training, Running Economy, and Marathon Running

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Dedication

This thesis is dedicated to my kids, Leila and Zaviyar, who remind me daily about the beauty of curiosity and learning.

Abstract

Plyometric training (PLYO) has been shown to improve running economy (RE) and performance in distance races up to 5-km in competitive runners. Core training (CORE) is widely practiced by distance runners, though there is little evidence for its efficacy in improving performance or preventing injury. **Purpose:** The purpose of this study was to examine the effect of a weekly PLYO or CORE training session on a population of recreational marathon runners. Sprint and jump performance, distance running performance, and training variables were assessed. In addition, different approaches to quantifying RE were examined. Competitive (COMP) and recreational (REC) runners were compared, and RE variables were used to model marathon performance. **Methods:** The PLYO and CORE study was a 12-week randomized controlled trial using pre- and post-tests to assess sprint, jump and distance running performance variables. Training log data during an 8-week run-in period (RI) and a 13-week marathon training period (MT) were analyzed to assess training variables. The RE study employed a cross-sectional design, utilizing race or time trial results, a 30-min submaximal treadmill run, and marathon results to compare COMP to REC runners, as well as examining factors predicting marathon performance within the two groups. **Results:** Sprint performance improved from baseline with PLYO training. Jump performance was maintained with PLYO training while it decreased in the CORE group. No differences were found in training experience variables between PLYO, CORE and a no additional training (CON) group, though limited evidence suggests a potential benefit

of PLYO training. While CORE and/or CON groups increased from the RI to the MT period in rate of perceived exertion, soreness, and days missed due to injury, the PLYO group did not change. In addition, pre-marathon creatine kinase (CK) levels were lower in PLYO than CORE runners, and post-marathon CK levels trended toward lower as well.

Assessment of RE factors found that correcting O_2 utilization for velocity is important in capturing differences between COMP and REC runners, with COMP runners using less O_2 per km. This measure was a significant predictor of marathon performance, reported as difference from predicted finish time based off races or time trials of 2-mi to 10-km.

Within groups, the use of allometric scaling was important in using RE to model marathon performance. **Conclusion:** Implementation of PLYO training in a population of recreational marathoners can improve sprint and maintain jump performance, but the benefits do not transfer to distance running performance, including RE. Other benefits to health and training variables may be seen, and may be more important to this population. Running economy is an important predictor of marathon performance. Competitive runners are more economical than REC runners, and more economical runners perform better in the marathon, relative to their shorter distance performances.

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CHAPTER 1: Introduction

Background

Participation in road races, including 26.2 mile marathons, has reached new heights of popularity. The U.S. boasts over 500,000 marathon finishers per year, up from 25,000 in 1976, and today's runners take substantially more time, on average, to complete the marathon (Running USA, 2013). This trend indicates a shift toward a more recreational, rather than competitive population. While today's marathon runners are either less fit or less competitive than previous generations, the fascination with the factors related to finish time remains strong. In addition, the question of best training practices related to health and well-being have become perhaps even more important, as many marathon participants, especially less experienced runners, cite health benefits as a reason for marathon participation (Ogles & Masters, 2003).

Importance of the study

Plyometric training (PLYO) has many positive outcomes related to improved muscle and neuromuscular function: lower limb strength, power and speed (Markovic & Mikulic, 2010). In addition, explosive speed (or maximal velocity sprint) training has been shown to produce beneficial neuro-muscular adaptations (Ross, Leveritt, & Riek, 2001). Plyometric training has been shown to improve running economy (RE) and performance in races of up to 5-km, and muscle power in competitive runners

(Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999; Ramirez-Campillo et al., 2014; Saunders et al., 2006; Spurrs, Spurrs, Murphy, & Watsford, 2003). Recreational runners may improve RE with a relatively low intensity and volume PLYO training program (Turner, Owings, & Schwane, 2003). The impact of PLYO or sprint training on recreational runners has not been studied extensively. However, it is plausible that the improvements in power and efficiency in the running stride could potentially benefit recreational runners in a number of ways as well.

Plyometrics is one of a number of interventions that may improve RE. Few studies have examined RE at a range of paces in order to ascertain the intensity and methodological approach that is most useful in using RE to predict running performance at different distances. Most research has only reported RE in relatively simple terms of oxygen utilization at a pre-determined, standardized pace. The scientific literature suggests that there may be more meaningful ways of characterizing RE, including the use of allometric scaling (e.g., ml/kg^{0.75}/min). Calculating oxygen utilization per km of distance run may allow for a better comparison of heterogeneous populations. In addition, other metabolic factors such as respiratory-exchange ratio (RER) and RER variability may shed light on the physiological response to sub-maximal exercise.

Other health benefits may be derived from some forms of high-intensity training. Long term exposure to PLYO training has been shown to increase bone mass in children and pre-menopausal women (Markovic & Mikulic, 2010), and higher intensity forms of training are effective in maintaining muscle mass, an important indicator of health in

aging populations (Koopman & Van Loon, 2009). The health implications are important to consider for a general fitness population such as recreational runners, regardless of whether it has any bearing on athletic performance.

Injury during marathon training and racing are quite common (Fredericson & Misra, 2007; Maughan & Miller, 1983; Satterthwaite, Larmer, Gardiner, & Norton, 1996). For a recreational population, any training beyond the baseline required to successfully complete the event should be evaluated to ensure that the benefits of the added training do not come at a cost of an increased rate of injury or other negative health consequences. The question of interest addressed by this study is whether PLYO and speed training can be beneficial, either in terms of performance or health outcomes, when done concurrently with marathon training in a recreational population.

Summary and objectives

Plyometric and explosive speed training has been shown to improve RE and, in some cases distance running performance. No studies have examined PLYO training for marathon runners, yet the improvements in RE seen in other studies suggest a possible benefit for the marathon.

Marathon performance is a multi-faceted and complex topic. The growing population of runners engaged in longer events such as half marathons and marathons demands a renewed and more nuanced inquiry into the important factors in marathon performance. Today's marathon runners are on average slower than the average runner

of 30 years ago, but many are motivated to attain certain levels of performance (Ogles & Masters, 2003). At the same time, health and wellness are increasingly important motivations for those engaged in long distance running, so injury rates, training factors such as soreness and rate of perceived exertion (RPE), and muscle damage are important variables that should be reported with respect to specific training practices.

This research will address the following objectives:

- 1) Examine the effects of a PLYO training protocol on sprint and jump performance, and distance running performance at distances ranging from 2 miles to a 26.2 mile marathon.
- 2) Evaluate the effect of a PLYO training protocol on injury rates, soreness, readiness to run, RPE, and muscle damage during training and after the completion of a marathon.
- 3) Model the relationship between RE and marathon performance, utilizing a definition of RE that allows for the examination of a variety of metabolic factors rather than strictly focusing on oxygen utilization at a pre-specified pace.

Significance

Previous studies on PLYO training for distance runners have primarily focused on competitive, male populations, and have done little to assess the health and training experience of these subjects. This study may be the first to look at this type of

intervention for recreational marathon runners. Further, it will attempt to assess the effects of the intervention not only in terms of performance, but also with respect to the health and training variables.

CHAPTER 2: Review of Literature

Predictors of Marathon Performance

Historical Background

Timed athletic events over precisely measured courses represent an opportunity to examine the relationships between various physiological measures and performance in the field, particularly in running, cycling, swimming and skiing events. Given the simplicity and lack of technical challenge presented in the testing process, it comes as no surprise that running has been studied extensively. A wide range of predictors of running performance have been studied. Predictors include a variety of lab-based exercise testing measures, anthropomorphic characteristics, and performance measures at various distances.

The early work of A.V. Hill identified a relationship between oxygen utilization and running speed, and established the concept of VO_{2MAX} and the interest in maximal rates of oxygen consumption and CO_2 elimination during exercise (Hill & Lupton, 1922). Saltin and Astrand tested the Swedish National team (and a few other athletes, including a Kenyan runner) in a number of sports and concluded from their results that maximal oxygen uptake is the most important factor in determining success in endurance events (1967). This conclusion was based on the finding that champion-level skiers and various other endurance athletes had the highest VO_{2MAX} values, with the

World Champion skier attaining the highest. In addition to its contribution to endurance exercise performance, VO_{2MAX} has been identified as an important factor in reducing cardiovascular disease risk, surpassing even physical activity level (McMurray, Ainsworth, Harrell, Griggs, & Williams, 1998). While the importance of VO_{2MAX} values in endurance exercise capacity and health have clearly been established, much recent work in sport performance has focused on attaining a more nuanced and sport-specific view of modeling performance. Marathon running has increased dramatically in popularity. In the United States alone, there are approximately a half-million marathon finishers each year, up from 25,000 in 1976 (Running USA, 2013). Since the 1970s, the study of sport performance has increased dramatically, emerging from early roots in medicine and general health (Hale, 2008).

Laboratory-Based and Anthropomorphic Predictors

VO_{2MAX} and lactate threshold (and the associated velocities) are commonly held to be the most reliable laboratory-based predictors of distance running performance (Joyner & Coyle, 2008). In the world of exercise testing, VO_{2MAX} remains the most widely recognized and utilized model of understanding endurance sport performance (Noakes, 2000). Champion performers tend to have VO_{2MAX} values much higher than either sedentary population or recreational athletes (Joyner & Coyle, 2008). In distance running, VO_{2MAX} has a high correlation with finish time in a range of race distances shorter than the marathon. Research in the early 1970s found a -0.91 correlation between VO_{2MAX} and finish time in a 10-mile road race (Costill, Thomason, & Roberts,

1973). At an almost equivalent distance, 16-km, recent research found an almost equal correlation of -0.902 between VO_{2MAX} and finish time (McLaughlin, Howley, Bassett Jr., Thompson, & Fitzhugh, 2010). The correlation between 2-mile time trial finish time and VO_{2MAX} has been reported to be -0.91 in men, and a -0.89 correlation in women (Mello, Murphy, & Vogel, 1988). In races between two and 10 miles, consistently high correlations between VO_{2MAX} and finish time have been established.

The study of a world record holding marathon runner challenged the notion that VO_{2MAX} can explain marathon performance (Costill, Branam, Eddy, & Sparks, 1971). The athlete, D.C. (widely recognized to be Derek Clayton, easily identified by the world record time cited in the publication), had a VO_{2MAX} of 69, which is certainly higher than average, but is considerably lower than many athletes unable to run anywhere near as fast as Clayton (Costill et al., 1971). In the relatively homogeneous group of 27 highly trained male marathon runners, no relationship ($r = 0.08$) was found between VO_{2MAX} and marathon finish time (Costill et al., 1971). Other studies have demonstrated that among relatively homogeneous groups, VO_{2MAX} and performance are not strongly correlated (Noakes, Myburgh, & Schall, 1990).

Lactate threshold (LT), or the workload at which blood lactate increases dramatically, has been identified as another key physiological factor in determining distance running performance (Faude, Kindermann, & Meyer, 2009; Joyner & Coyle, 2008; McGehee, Tanner, & Houmard, 2005; McLaughlin et al., 2010; Stallknecht, Vissing, & Galbo, 1998; Tanaka & Matsuura, 1984). However, caution must be taken in

differentiating and interpreting the results, as different definitions, methods, and protocols have been used, and there has been no consensus on the most meaningful definition and method of determining LT (Faude et al., 2009; Newell, 2007). These inconsistencies may influence the strength of association between lactate threshold and running performance.

Confusion may arise from an evolving understanding of the role that lactate plays, not as a toxic by-product of anaerobic metabolism, but as both a product and a fuel source during exercise (Brooks, Brown, Sicurello, & Butz, 1999). Despite a more nuanced view of the role of lactate during exercise at the cellular level, LT remains a valuable concept in predicting performance and establishing training intensities (Faude et al., 2009; McGehee et al., 2005; McLaughlin et al., 2010). For an individual, there is a minimal exercise intensity at which a substantial, readily identifiable rise in circulating plasma lactate occurs, and it is apparent that this rise is associated with a corresponding increase in energy expenditure and is reflective of non-sustainable metabolic changes occurring within the working muscles (Faude et al., 2009; McGehee et al., 2005).

Regardless of the precise terminology and definitions employed, the literature does suggest that plasma lactate concentration at specified paces does serve as an important indicator of running ability, and can be used in combination with other factors to predict race performance (Faude et al., 2009; Stallknecht et al., 1998). Given the understanding of lactate's role in aerobic metabolism, it can even be argued that the LT reflects the oxidative capacity of the working muscle (Joyner & Coyle, 2008).

Three distinct thresholds have been defined, with the aerobic threshold (AT) defined as the exercise intensity where lactate rises above baseline values, and the anaerobic threshold (AnT) defined as the exercise intensity beyond which lactate rises exponentially (Faude et al., 2009). The third threshold has been defined as the onset of blood lactate (OBLA), which is standardized to the exercise intensity associated with a rise in blood lactate to 4.0 mmol (Tanaka & Matsuura, 1984). Though the terms are often used interchangeably, a study comparing the velocity at anaerobic threshold (V_{AT}) and velocity at onset of blood lactate (V_{OBLA}) found a significant difference between the two, and resulting differing relationships between threshold and marathon performance (Tanaka & Matsuura, 1984). The researchers noted that V_{AT} (defined as the point at which lactate increases from the initial level) had a stronger relationship with marathon performance than V_{OBLA} , and that V_{AT} closely approximated marathon race pace (K. Tanaka & Matsuura, 1984). In another study, velocity at LT, defined as the velocity at which lactate increased above baseline levels, was a better predictor of 3-kilometer time-trial performance than any other measure, including V_{OBLA} (4.0 mmol) (Grant, Craig, Wilson, & Aitchison, 1997).

The AnT typically corresponds with a level of blood lactate lower than the standard 4.0 mmol/L that has been defined as the OBLA. Anaerobic threshold has been defined as somewhere between 2.0 and 4.0 mmol/L, though the true range in individuals may be closer to 2.0 to 10.0, with the average being around 3.0 mmol/L (Borch, Ingjer, Larsen, & Tomten, 1993; Faude et al., 2009; Noakes, 2003; Stallknecht et

al., 1998). As a reflection of this more flexible, individual-specific definition of LT, alternative terminology has been proposed. The speed at which the LT occurs has been referred to as the maximal lactate steady state (MLSS) (Faude et al., 2009). It has also been defined as the maximal steady state workload (MSSW) (Borch et al., 1993). A meta-analysis of 32 studies examining the relationship between LT and endurance exercise performance suggested the use of MLSS may be a more useful definition of an individual's LT than a pre-established setpoint such as 2.0, 3.0 or 4.0 mmol/L (Faude et al., 2009).

Measurement of plasma blood lactate requires a lactate analyzer and capillary blood sampling (McGehee et al., 2005). The velocities associated with various ventilatory markers, including V_E (expired minute ventilation), V_E / V_{CO_2} (ventilatory equivalent of carbon dioxide), and V_E / V_{O_2} (ventilatory equivalent of oxygen) have also been used to determine endurance capacity and changes in training status (Anderson & Rhodes, 1989; Meyer, Lucia, Earnest, & Kindermann, 2004; Wyatt, 1999). Referred to broadly as the ventilatory threshold (VT), these markers have been shown in some studies to be associated with LT (Faude et al., 2009). While VT may actually be easier to determine in a laboratory setting, given the prevalence of metabolic testing on gas exchange systems, the relative lack of data examining the relationship between VT and endurance exercise performance presents a limiting factor (Faude et al., 2009). However, VT as defined by the point on the V_E slope where the line increases disproportionately has been significantly associated with LT through meta-analysis

(Wyatt, 1999). Whether the relationship between the two is causal or incidental remains a point of controversy, but the products of increased lactate production and metabolism, CO₂ and hydrogen ions, most likely stimulate increased ventilation (Wyatt, 1999).

Some studies have shown improvements in running performance in races of similar distance after a training intervention despite finding no change in VO₂ MAX or lactate threshold (Paavolainen et al., 1999; Spurrs et al., 2003; Saunders et al., 2006). These changes have largely been attributed to improved running economy (RE). Running economy has widely been recognized as a third key, laboratory-based measure that can be utilized to predict running performance (Joyner & Coyle, 2008; McLaughlin et al., 2010).

Anthropometric measures may enhance a model for predicting time-trial or race finish time, but have produced inconsistent results. In males, body weight, percent body fat, and height-to-weight ratio were significantly related to two-mile time-trial finish time ($p < 0.05$) (Mello et al., 1988). However, the sample size for women in this study was much smaller for women than men ($n = 17$ for women, and $n = 44$ for men), which could account for the lack of a statistically significant relationship in women. In one study of recreational runners, gender, height, weight and percent body fat were all related to 10k finish time, though the relationships, which ranged from $r = 0.47$ to 0.63 , were not as strong as a number of other factors (Sinnott, Berg, Latin, & Noble, 2001). A study comparing three groups of 10-km runners by performance level (defined as elite,

good, and average), found statistically significant differences between the groups in both anthropomorphic and training variables (Bale, Bradbury, & Colley, 1986). The elite and good groups weighed less than the average group, and were higher in ponderal index, meaning they had greater height to weight ratio than the average group (Bale et al., 1986). In skinfold and body composition values derived from skinfold measures, all three groups were different, with the elite group having the lowest total skinfold measures, percent body fat, and absolute fat, followed by the good group, with the highest values coming from the average group (Bale et al., 1986). Not surprisingly, the elite group also trained more (both in miles and training sessions per week), had been training longer, and did more fast running and interval training (Bale et al., 1986).

Specific to the marathon, among a relatively homogeneous group of elite marathoners, significant relationship between skinfold (body fat) measures was found in women, but not men (Arrese, Izquierdo, & Serveto Galindo, 2005). This finding runs contrary to the Mello study, but that may again be a relic of sample size rather than an actual sex difference. Among recreational male marathoners, ponderal index was related to marathon finish time, though again the relationship was much less robust than other factors, such as fastest 10k time and training pace (McKelvie, Valliant, & Asu, 1985).

Morphology of the heart, in particular left ventricular telediastolic diameter, appears to be important in predicting performance in elite male marathoners, but not

elite females (Arrese et al., 2005). The same study found that serum ferritin is an important predictor of marathon finish time for elite women, but not men.

Among athletes of similar competitive level, Noakes argued that RE and/or muscle power are more closely correlated with differences in performance than $VO_{2\text{MAX}}$ and LT (Noakes, 1988). This conclusion is based on a non-systematic review of previous research, so must be interpreted with caution. However, the idea that $VO_{2\text{MAX}}$ and LT alone cannot explain running performance has been important in opening the door to look more closely at the importance of muscle-related factors in distance running.

Peak velocity during a maximal anaerobic running test (V_{MART}) correlates with race times for sprinters, middle distance, and 5-km runners (Paavolainen et al., 1999; Rusko, Nummela, & Mero, 1993; Rusko, 1996). While this test of maximal velocity has not been studied with respect to marathon runners, there is physiological plausibility that the relationship may extend to races longer than 5-km. A study of 18 well-trained male distance runners found significant relationships between MART VO_2 gain (the ability to produce power above the $VO_{2\text{MAX}}$) and RE, and also between 5k velocity and average EMG of 5 leg muscles during ground contact 3k into the 5k race (Nummela et al., 2006). This suggests that the neuromuscular factors captured by the V_{MART} test may be related to resistance to muscular fatigue (Nummela et al., 2006). One could speculate that the delayed onset of fatigue seen in faster 5k runners may also be beneficial for runners competing at longer distances such as the marathon. Peak treadmill running velocity, or the fastest pace sustained for at least one minute during a

VO_{2MAX} test, was identified as the best laboratory-based predictor of running performance for all distances modeled (10k, half marathon, marathon and 90km ultramarathon), with correlations ranging from $r = -0.83$ to -0.93 (Noakes et al., 1990).

Field-Based Predictors

Outside of the laboratory, race finish time at other distances have been found to be the best predictor of race performance, better even than peak treadmill running velocity (Noakes et al., 1990). The notion that recent running performance is the best predictor of future running performance, even at different distances, may seem like an obvious conclusion, but this study does provide important validation of this commonly accepted idea. Several researchers (including Daniels & Gilbert, Davies & Thompson, Mercier, Leger, & Desjardins, Gardner & Purdy, and Osler) have produced extrapolations to predict expected finish times in races based on finish times in races of different distances (Noakes, 2003). These values tie various performances to a predicted or reference VO_{2MAX}. Noakes points out that these values are simply a proxy for resistance to fatigue, and rather than an athlete's actual VO_{2MAX} (Noakes, 2003).

A multiple regression analysis of various training, anthropomorphic, and personality variables identified best 10k time as the strongest correlate ($r = 0.687$) of marathon finish time, followed by self-reported training pace ($r = 0.546$) (McKelvie et al., 1985). Two-mile and half- marathon time trials were the strongest predictors of marathon finish time in college-aged novice marathoners (Lundstrom, Ingraham, & Rhodes, 2012). The relationship between performances also appears to extend to

events that are longer in distance than the marathon. In a study that assessed anthropometric and training variables, no significant associations were found with 24-hour run distance, except for personal best marathon and personal best 24-hour run times (Knechtle, Wirth, Knechtle, Zimmermann, & Kohler, 2009). A similar study on male 100-km runners found that training volume and best marathon time were significantly associated with 100-km finish time, while previous 100-km time and anthropomorphic factors were not significantly related (Knechtle, Wirth, Knechtle, & Rosemann, 2010).

An area of research that has been explored less extensively is that of anaerobic field testing and distance running performance. A study of the relationship between 10-km race finish time and a battery of anaerobic tests found statistically significant relationships between 10-km time and 50-m sprint time, 300-m sprint time, squat jump height, countermovement jump height and plyometric leap distance (Sinnott et al., 2001). Squat jump power and countermovement jump power, which were calculated using the Lewis equation, were also significantly related to 10-km time, though not as strongly as jump height for the two different jumps (Sinnott et al., 2001). Many of these variables were strongly related to each other, so a forward stepwise multiple regression was performed to create a model to explain the variance within the total group, within men, and within women. Overall, plyometric leap distance was the strongest predictor ($r = -0.86$) and the inclusion of 300-m sprint time explained additional variance. The analysis of the men in the study identified plyometric leap distance as the strongest predictor ($r = -0.778$) and that the addition of body weight to the regression explained

additional variance. Among the women, 300-m sprint time was the strongest predictor, and as with the men, the model was enhanced by the addition of body weight.

Plyometric leap test, as described in this study, consists of a series of alternate leg bounds for distance, a test that is elsewhere referred to as a bound test (Spurrs et al., 2003).

While anaerobic field testing may provide useful information not captured by submaximal testing, not all results have proven statistically significant. In well-trained male distance runners, 20-m sprint time (with a 15-m acceleration zone) was not significantly associated with 5-km time trial time, while laboratory based anaerobic testing did achieve statistical significance (Nummela et al., 2006; Sinnett et al., 2001).

Summary

Training for and running a race, and the marathon in particular, presents a variety of challenges, and the numerous variables involved make predicting performance as much an art as a science. VO_{2MAX} and lactate threshold have been identified as important laboratory-based factors that can predict marathon performance. Running economy, which will be discussed below, appears to be a critical factor in predicting race performance of runners who are similar in VO_{2MAX} and LT. Other factors such as performance in anaerobic tests and anthropometry can likely enhance a model for predicting marathon performance. Field-based testing such as time-trials at other race distances and previous race performance are the strongest predictors of race finish time, but they shed little light on the mechanisms for performance and instead

confirm only that running performance in the past predicts running performance in the future. Anaerobic field testing may be somewhat immune to this criticism, and should be explored more thoroughly in future research.

Running Economy and Related Submaximal Measures

Introduction

Running economy (RE) is quantified as the oxygen required by an individual to run at a specific submaximal pace (Saunders, Pyne, Telford, & Hawley, 2004b). It is typically assessed using treadmill testing and a metabolic cart to measure oxygen utilization. Running economy is typically expressed as VO_2 , with mL/kg/min being the standard unit of measure. Some studies report RE in meters covered per ml/kg (Turner et al., 2003) or ml/kg/km (Foster & Lucia, 2007). While calculating VO_2 per kg of body mass is common, research indicates that the relationship between body mass and oxygen cost do not increase proportionately, and thus body mass should be scaled allometrically (Berg, 2003; Bergh, Sjodin, Forsberg, & Svedenhag, 1991; Helgerud, 1994; Saunders, Pyne, Telford, & Hawley, 2004a; Storen, Helgerud, & Hoff, 2011).

The consensus from available research suggest raising body mass to a power of between 0.66 and 0.75 as an appropriate corrective measure to account for the allometric relationship between body mass and oxygen cost of running. Studies on RE have high test-retest reliability (1.5-5.0%) among a range of populations (Armstrong & Costill, 1985; Pereira & Freedson, 1997; Saunders et al., 2004a). Typical error can be

reduced by ensuring that proper controls are taken to standardize time of testing, testing equipment, nutritional status, recent training, environmental conditions, footwear, and other potential confounding variables (Pereira & Freedson, 1997; Saunders et al., 2004a).

Respiratory exchange ratio (RER) during submaximal exercise is a reliable indicator of the ratio of fat to carbohydrate that is being utilized for energy by the exercising athlete (Coyle, 1995; Hawley & Spargo, 2007; Jeukendrup & Wallis, 2005). While it falls outside the scope of the traditional definition of RE, RER at a submaximal pace reflects metabolic economy, as glycogen is spared by those who burn fat at a higher proportion. Elite male and female distance runners have been shown to better utilize fat during exercise than less trained individuals, which allows them to spare glycogen and thereby increase endurance capacity (Hawley & Spargo, 2007). This may be a particularly important factor in events like the marathon, where glycogen depletion can be a limiting factor to performance (Saunders et al., 2004b). Increased fat metabolism likely occurs due to adaptations at the cellular level within the working muscle, such as increased mitochondrial density, and increased levels of mitochondrial oxidative enzymes such as succinate dehydrogenase (SDH) and citrate synthase (CS). Muscle triglyceride content and utilization has been shown to increase with training, which may allow the endurance-trained athlete to rely more heavily upon lipid metabolism than their untrained counterparts (Goodpaster, He, Watkins, & Kelley, 2001; Hurley et al., 1986).

It is possible to integrate RER into analysis of RE. When comparing the traditional oxygen cost model with an energy cost model, researchers found that the energy cost model was more sensitive to changes in pace than the traditional oxygen cost model (Fletcher, Esau, & MacIntosh, 2009). After calculating the energy requirement (in kcals/kg/km) of running at three submaximal paces, they found statistically significant differences in the energy cost of running between each of the three paces, whereas the oxygen cost model yielded no statistically significant differences between the paces.

Breathe-by-breathe RER variability (RER VAR) has recently been explored as a potential means of assessing aerobic fitness, and possibly metabolic flexibility. While this remains a relatively new area of research, there is evidence that training increases sample entropy scores of RER VAR in both adolescent female soccer players and novice college aged marathoners (Biltz et al., 2011; Brown, 2013). No assessment of RER VAR at a range of paces has been published, nor has RER VAR been examined as a possible predictor of running performance.

It is well accepted that RE is an important aspect of distance running performance, as a more economical runner can do the same amount of work with less energy utilization (Saunders et al., 2004b), though the quantification of this is disputed. Improvement in RE has been proposed to allow the runner to cover a greater distance without experiencing as much fatigue (Joyner & Coyle, 2008). The importance of RE in marathon performance was illustrated in a case study of Derek Clayton, who held the world record in the marathon at the time he was tested (Costill et al., 1971). In this

study, marathon performance quotient (MPQ) was defined as $\%VO_{2MAX}$ at marathon pace divided by $\%VO_{2MAX}$ at a standardized submaximal pace, in this case 10 miles per hour. The highest MPQ was attained by Clayton (1.27) when compared to other highly trained male marathon runners (0.97). The researchers are quick to point out, however, that this is not a predictive tool, but rather an index of the contributions of $\%VO_{2MAX}$ at marathon pace, VO_{2MAX} , and RE.

A number of methods and approaches improving RE have been examined. Footwear, environmental conditions, and other external factors can also impact RE. Approaches and theories on interventions to improve RE are wide-ranging, likely due to the fact that it is determined by an assortment of mechanisms, including biomechanical, metabolic, and other physiological factors.

Components of Running Economy

The factors affecting RE can be divided into the following categories: training, environment, physiology, biomechanics, and anthropometry (Saunders et al., 2004b). Bonacci, Chapman, Blanch, and Vicenzino discuss neuromuscular adaptations and their effect on RE (2009). Noakes identifies stride pattern and running technique, the elastic properties of muscle and tendon, biomechanics, age, fatigue, fitness and training, gender and race, clothing and shoes, and environment as factors that may affect RE (2003). Foster and Lucia emphasize the anatomical basis for differences in RE, particularly between the dominant East African runners and their European and North American counterparts (2007). Brooks, Fahey, and Baldwin state that improvements in

running efficiency may come from superior mitochondrial respiratory capacity or a more efficient running style, though they state that RE is not a good predictor of performance, and its role is not well understood (2005).

Training status affects RE. Numerous studies have demonstrated that trained individuals are more economical than untrained subjects (Saunders et al., 2004b). This may be due to improvements in efficiency of the chain of oxygen delivery and utilization within the working muscles or improved neuromuscular properties of the individual which result in more economical running mechanics (Saunders et al., 2004b). The idea that running improves an individual's economy is somewhat intuitive, and is an expression of the principle of specificity of training (Brooks et al., 2005). It also explains the why younger runners are less economical, as they are likely to have less lifetime training volume and less practice at refining the running stride (Noakes, 2003). Runners most likely acquire an optimal stride length and cadence over time through self-monitoring and subtle adjustments in order to minimize effort at a given workload (Cavanagh & Williams, 1982).

Environmental factors change the energy cost of running. Running surface, wind, altitude, and hills can all affect RE (Noakes, 2003). It is possible that there may be some individual variation in the degree to which these factors affect an individual's RE, which may in turn explain some of the variation in how an individual performs in different environmental conditions (Noakes, 2003).

Physiological factors that affect RE include heart rate, body temperature, ventilation, and lactate levels (Saunders et al., 2004b). A slight increase in body temperature improves economy, but beyond a mildly elevated body temperature the inverse is true, and the over-heated runner becomes less economical. Increased heart rate, ventilation and levels of blood lactate correspond with higher energy cost of running and decreased economy. These physiological factors are all related to cardiovascular fitness, and adaptations to endurance training can lead to decreased cost of running at a given workload (Brooks et al., 2005).

A variety of biomechanical and kinematic factors play a role in determining RE (Anderson, 1996). One aspect of this category is the improved efficiency of movement due to improved neuromuscular patterns discussed above with respect to habitual training (Brooks et al., 2005). Some of the other biomechanical factors include stride length, low vertical oscillation, a more acute knee angle during the swing phase of the stride, greater angular velocity during foot plant, reduced arm motion and effective use of stored, elastic energy (Anderson, 1996).

There may be a relationship between RE and musculo-tendinous stiffness. This is supported by a recent study that found a correlation between changes in RE and triceps surae tendon stiffness (Fletcher, Esau, & MacIntosh, 2010). A previous study utilizing a spring mass model found a significant inverse relationship between leg stiffness and the oxygen cost of running ($r = -0.80$) (Dalleau, Belli, Bourdin, & Lacour, 1998).

Ground contact time has been suggested as a variable that is related to the oxygen cost of running (Paavolainen et al., 1999). However, another study observed no relationship between 5k performance and ground contact time, but rather a relationship between stride length and 5k performance (Nummela et al., 2006). A recent study reported that the sum of running stride peak forces was inversely related to the oxygen cost of running ($r = -0.66$) in a group of 11 elite male runners (Storen et al., 2011). Measurements were taken at a velocity of 15 km/hr, which was below the velocity of lactate threshold for these runners. Running stride peak forces were characterized as the sum of horizontal and vertical peak forces. The sum of peak forces was also significantly inversely related to 3-km race time ($r = -0.71$). The researchers assert that their results demonstrate the importance of minimizing vertical movements and horizontal braking force to improve running economy and running performance. A study on biomechanics and RE in trained male and female distance runners supports the importance of minimizing horizontal breaking force (Kyrolainen, Belli, & Komi, 2001). The researchers were unable to isolate any biomechanical factors to explain differences in RE, with the exception of average horizontal breaking force.

Anthropometric characteristics have some impact on RE, though perhaps not in ways that the observer of the sport may expect. Body weight has been shown to be inversely related to oxygen cost of running, as measured in ml/kg (Pate, Macera, Bailey, Bartoli, & Powell, 1992; Saunders et al., 2004b; Williams & Cavanagh, 1987). This finding has been theorized to be the result of the non-linear relationship between weight and

energy cost required for running, as discussed with respect to literature on allometric scaling of VO_2 (Bergh et al., 1991; Helgerud, 1994; Saunders et al., 2004b; Storen et al., 2011). As previously discussed, body mass can be raised to a power of between 0.66 and 0.75 to more accurately reflect the actual oxygen cost of movement across a range of subject body masses. While energy cost per kilogram may go down with weight gain, the gross energy expenditure will increase due to the increased body mass (Saunders et al., 2004b).

Other anthropometric characteristics, such as leg length and height, do not play a clear-cut role in RE. However, distribution of body mass, and in particular leg mass, has been suggested as an important determinant of RE (Myers & Steudel, 1985). Having a higher proportion of leg mass proximal to the center of mass (thigh, hamstring) versus distal from the center of mass (the calf) is advantageous to distance running and promotes a more economical stride (Myers & Steudel, 1985). This argument is based on the lever physics of moving the legs through the range of motion required by running.

The concept of distribution of mass naturally leads to questions about footwear and shoe choice. It can be expected that heavier clothing will impair RE, as the extra ounces do nothing to make the individual more economical, and may even contribute additional wind resistance (Noakes, 2003). Locating those additional ounces of clothing at the end of a limb can be expected to further compromise RE, as the distal location will require greater effort to move the extra weight (Myers & Steudel, 1985). Wearing heavier shoes has indeed been shown to increase the energy cost of running, if the

shoes are otherwise identical in type and material (Catlin & Dressendorfer, 1979). Taken to the logical extreme, this would suggest that barefoot running would be the most economical footwear option.

A study that compared barefoot versus shod runners found that runners wearing shoes exhibited greater leg stiffness, perhaps in response to the fact that the shoes have cushioning properties that allow the leg to comfortably land in a rear-foot strike (Bishop, Fiolkowski, Conrad, Brunt, & Horodyski, 2006). The researchers suggest that the legs adjust to footwear and running surface to maintain a fairly constant stiffness of impact that is optimal for effective running. The study did not assess RE in barefoot versus shod runners.

In another study on the kinematics of barefoot running, researchers examined foot-strike patterns in five groups: barefoot US runners, shod US runners, barefoot Kenyan runners, shod Kenyan runners, and Kenyan runners who had grown up barefoot, but had recently begun wearing running shoes (Lieberman et al., 2010). The gait of these runners at self-selected speeds over 20-25 meters on a track were assessed using video and a three-dimensional infrared kinematic system. The researchers found that the shod runners tended to rear-foot strike and as a result put greater impact forces into the lower limbs, and they suggested that this finding supports the recent trend toward barefoot running as a means of reducing running injury. The findings must be interpreted with caution, as the study design entailed only a very short distance run, where fatigue is not a factor, as well as the use of a smooth track surface which is not

necessarily equivalent to the conditions in which most people run. The claim that barefoot running makes you move more efficiently is not supported by this study, as RE was not assessed. In fact, greater leg stiffness and increased ground reaction forces may be associated with improved RE (Anderson, 1996).

A study comparing a stiffer versus a control midsole found that the stiffer midsole resulted in a 1% reduction of the energy cost of running (Roy & Stefanyshyn, 2006). The researchers theorize that this improvement in RE could be attributed to a reduced dissipation of energy at the metatarsophalangeal (MTP) joint. The results support the idea that increased midsole stiffness improved RE, but did not find any changes in the energy absorption at the MTP joint, so the mechanism remains unknown.

The pursuit of scientific evidence regarding the best choice of footwear has largely been thwarted by the high degree of individual variation. A study comparing a firmer, more elastic shoe with a softer shoe found that individual responses varied, with some runners being more economical in the softer and others in the firmer shoe (Nigg, Stefanyshyn, Cole, Stergiou, & Miller, 2003). At this point, one can only rely on individual experimentation in order to determine the shoe (or lack thereof) that will maximize RE.

The existing body of research does confirm the importance of shoe choice for an individual, such that shoe choice should be consistent between testing sessions for each individual in order to eliminate variability due to shoe characteristics. Likewise, environmental conditions and clothing should be standardized in order to eliminate the introduction of variability from those factors.

Training to Improve Running Economy

A multitude of studies show better RE in well-trained versus novice athletes (Saunders et al., 2004b). This is likely due to a combination of neuromuscular, biomechanical, and physiological adaptations that result from habitual training. It is in line with basic concepts of exercise physiology that the body adapts to stresses and stimuli, so that practicing running will make an individual into a more economical runner. However, there appear to be limits to the adaptations made through habitual low to moderate intensity training, and evidence of improvements in RE are difficult to find in runners who are already highly-trained (Saunders et al., 2004b).

In trained populations, interval training has been shown to improve RE (Denadai, Ortiz, Greco, & de Mello, 2006). In this study, well-trained runners performed two sessions of interval training per week, with one group working at 95% of velocity at VO_{2MAX} and the other group working at 100% of velocity at VO_{2MAX} . Both groups improved in some measures, such as velocity at onset of blood lactate, but only the higher intensity group improved time trial performance and RE. A summary of the findings of a range of studies on anaerobic interval training concluded that high intensity interval training, including sprint intervals (intervals performed at much faster than the velocity at VO_{2MAX}) are important in improving distance running performance, and that part of the improvement is due to improved RE (Billat, 2001). In summary, the research suggests that running more and doing faster-paced workouts can both improve

economy, with well-trained runners achieving improvements only through higher intensity training.

Supramaximal high intensity interval training (HIT) has been shown to be an effective means of improving velocity at VO_{2MAX} , the time for which velocity at VO_{2MAX} can be sustained, and 3000 m time trial performance (Esfarjani & Laursen, 2007). In this study, the HIT group performed up to 12 x 30 seconds of running at 130% of their velocity at VO_{2MAX} with a 4:30 recovery period, while another group performed up to 8 x 60% of their maximal time at velocity at VO_{2MAX} . While the HIT group had small non-statistically significant improvement in velocity at lactate threshold and VO_{2MAX} , they improved in velocity at VO_{2MAX} , and the time for which that velocity can be sustained. As a percentage, their gains were greater than the lower intensity interval group. Both groups made statistically significant gains compared to controls in these measures, but the groups were not significantly different from each other. In the 3000-m time trial, both groups showed statistically significant improvements over controls. While the two groups were not significantly different from each other, the lower intensity interval group improved by a larger percentage. Despite the lack of statistical significance ($p = 0.27$) and the greater improvements in the HIT group in velocity at VO_{2MAX} and maximal time at velocity at VO_{2MAX} , the researchers recommend utilizing lower intensity intervals. The study did not assess RE, but the researchers acknowledge that improvement in RE is a possible explanation for the findings related to the HIT training group.

The relationship between interval training and RE was explored in study of 36 recreational male runners (Franch, Madsen, Djurhuus, & Pedersen, 1998). Three groups were assessed: continuous distance training (at higher than usual intensity), long interval training (4 minute repetitions with a 2 minute recovery), and short interval training (15 seconds on with 15 seconds of recovery). The distance training group ran greater volume at a lower average intensity, while the short interval group ran at the highest intensity but had the lowest volume of training. The long interval group was between the other two groups in average intensity and volume. All groups improved in VO_{2MAX} and the distance training and long interval training groups improved in RE, but the short interval group did not. Running economy was assessed at approximately 85% of VO_{2MAX} for each individual, a notable departure from typical protocols for assessing RE. The rationale for utilizing such a high intensity for assessing RE was that it would approximate the runners' 5-km or 10-km race pace. However, it is important to note that high capacity to deliver oxygen is critical to performance at those types of races, (Midgley, McNaughton, & Jones, 2007). Low oxygen utilization at faster paces may not be beneficial to performance, which calls into question the results of this trial. However, the smaller gains in multiple outcomes in the short interval group compared to the other groups does suggest that the 15 second on with 15 second recovery protocol is not the most effective protocol for eliciting physiological changes associated with improved distance running performance.

Another possible training tool for improving RE that has been suggested is the use of altitude training (Noakes, 2003). There have been mixed results on this topic, perhaps due to individual differences in the response to altitude, and/or the numerous confounding factors that could be introduced with relocation to altitude or the introduction of a hypoxic chamber. The most comprehensive examination of the topic, which included an analysis of the results of four different groups of researchers, concluded that exercise economy was not improved after acclimatization to altitude, including the live high/train low approach (Lundby et al., 2007).

Aside from running volume and manipulating the intensity of training, muscular strengthening interventions, including strength training and plyometrics, may improve RE. Strength training improves VO_{2MAX} and LT in previously untrained or recreational athletes, but not in well-trained athletes (Marcinik et al., 1991; McCarthy, Agre, Graf, Pozniak, & Vailas, 1995; Stone, Wilson, Blessing, & Rozenek, 1983). However, some studies have elicited improvements in either performance or RE through strength or plyometric training, likely due to improved RE (Hickson, Dvorak, Gorostiaga, Kurowski, & Foster, 1988; Johnson, Quinn, Kertzer, & Vroman, 1997; Paavolainen et al., 1999).

A 1988 study suggested that heavy resistance training could have benefits for endurance athletes (Hickson et al., 1988). In this study, subjects performed 10 weeks of high intensity lower body strength training (parallel squats, knee extensions, knee flexions, and toe raises). This study found no change in VO_{2MAX} or LT, but did find increased leg strength and significantly improved performance in a time-to-exhaustion

test. The study did not find a statistically significant change in 10-km time trial performance, but there was a trend towards improved performance and the cyclists in the study did improve in a time-to-exhaustion test. This suggests at the very least that heavy resistance training can be added to endurance training without producing negative adaptations, and that performance may be improved by such training in events where improved leg strength is beneficial.

In a study of 12 trained female distance runners who followed a 10 week strength training program of upper- and lower-body weight exercises, researchers found a correlation between increased strength and improved RE (Johnson et al., 1997). The subjects in this study did two to three sets of a number of exercises typically utilized in traditional strength training. The load varied from six-repetition maximum to twenty-repetition maximum. Subjects did not have any changes in VO_{2MAX} , LT, or body composition. They did, however, improve in RE by 4%. No time trial was done to confirm that the improvement in RE translated to improved running performance.

Paavolainen et al. utilized a training program comprised of sprints of 100 meters and less, jumping exercises, leg-press, and knee extensor-flexor exercises to elicit improvements in RE and time trial performance (1999). This study of well-trained male distance runners examined the effects of a nine-week program of explosive-strength training. The researchers suggest that the fast, low resistance strength-training utilized in the study would minimize muscle hypertrophy, but lead to beneficial neural adaptations. This program was effective in improving distance running performance.

The fact that improvement in 5-km time trial could not be attributed to VO_{2MAX} (which did not change after training) supports Noakes' idea that for many athletes, factors other than VO_{2MAX} , such as muscle power and RE, are the limiting factor on performance (Noakes, 1988). The idea that improvements in performance can be elicited through improved RE is supported by the strong correlation between the time trial improvement and the improvements in RE and on the maximal anaerobic test (Paavolainen et al., 1999).

The results of the previous study are somewhat difficult to interpret from a practical perspective due to the fact that the strength program involved a variety of exercises including plyometrics, low-load weight exercises and sprints. Another study that was more limited to plyometric exercises found improvements in both 3km time trial and RE after six weeks of plyometric training (Spurrs et al., 2003).

Another study used an isometric strengthening program with highly trained distance runners over an 8-week training program (Fletcher et al., 2010). The strengthening program was extremely limited and specific, with subjects performing just one exercise, isometric plantar-flexions, three times per week. Given the limited scope of the strengthening program, it is not surprising that no statistically significant change in RE was found. At the same time, the fact that tendon stiffness changes did correlate with change in RE provides evidence of a tendon stiffness component to RE. Given the limitations of this study, it is difficult to generalize, but it seems that further research on the link between tendon stiffness and RE is warranted.

Core stability training, defined as strengthening exercises targeting the lumbo-pelvic region, has been recommended for enhancing both performance and resistance to injury in healthy, athletic populations (Williardson, 2007). Core stability training is commonly practiced by athletes in a wide range of sports, and it has been suggested that it may provide some benefit for distance runners (Barnes, 2002). A six-week randomized trial of a Swiss ball core stability training program found an improvement in the Swiss ball group versus the control group in core stability, assessed via the Sahrman test of core stability (Stanton, Reaburn, & Humphries, 2004). However, no change was found in RE at any speed, VO_{2MAX} , or any other performance measure. There was also no correlation between core stability and any measure of performance.

The mechanisms by which various training interventions improve RE remain unclear. Many theories have been proposed in addition to previously discussed concept of musculo-tendinous stiffness. For example, some suggest that increased strength equates to lower force contribution of each fiber (Tanaka & Swensen, 1998). Others cite neural and muscular adaptations, including increased anaerobic enzymes, increased force production, improved motor unit recruitment and synchronization, greater rate of force development, improvements in the stretch-shortening cycle, and improved reflex activity resulting in shorter ground contact time (Jung, 2003; Kraemer, Deschenes, & Fleck, 1988). Some of these adaptations involve intrinsic properties of the muscle, some involve tendon and connective tissue, while others involve neuromuscular factors. Given

the manner in which all of these things can be interlinked and dependent in the body, it may be difficult to isolate the factors.

Summary

An understanding of the different contributors to RE can help shape training and other interventions designed to improve it. In novice runners, physiological adaptations to low-to-moderate intensity endurance training will likely elicit improvements in RE. Well-trained runners may require additional training interventions in order to continue to reduce their energy cost of running. High intensity interval training, both at and above velocity of VO_{2MAX} , is effective eliciting further improvements in RE.

With regard to footwear, experimenting with lighter shoes can be done by runners in order to assess whether any improvement in RE results. On the other hand, the arguments for barefoot running seem less centered around economy, and more on injury prevention. Given the limitations of the studies conducted thus far, it seems premature to suggest that barefoot running will improve RE.

The results showing improved RE from strength training and PLYO training are fairly consistent, but are limited by the lack of a clear understanding of why those improvements occur. Comparative studies of a variety of strength and PLYO protocols need to be done in order to further our understanding of how to best go about improving RE and performance through this type of training, for different populations. Core stability training, while widely practiced, is not supported in the literature as a means of improving RE. The evaluation of individual strengths, weakness, and capacity

for adaptation to various training stimuli, as well as distance of goal event, are all factors that may determine what type of training may best aid an individual in improving RE.

Accumulating running volume, utilizing high intensity interval training, strength and PLYO training have all been shown to improve RE and running performance. The use of lightweight shoes and periodic training at altitude may also be advantageous. Much research remains to be done on the precise mechanisms by which RE changes, and the best manner in which to elicit positive adaptations.

Impediments to Marathon Training and Performance

Marathon training and racing can be compromised by a number of factors, and many negative health consequences have been identified related to participation in marathon training and racing (Fredericson & Misra, 2007; Hanssen et al., 2011; Kyrolainen et al., 2000; Maughan & Miller, 1983; Neilan et al., 2006; Nieman et al., 2002; Rae et al., 2010; Satterthwaite et al., 1996; Siegel, Silverman, & Lopez, 1980; Van Middelkoop, Kolkman, Van Ochten, Bierma-Zeinstra, & Koes, 2008; Warhol, Siegel, Evans, & Silverman, 1985; Yared & Wood, 2009). Some, such as heat and hydration-related health problems, occur with highly variable frequency, depending on the environmental conditions and the hydration behaviors of the participants (Howe & Boden, 2007; Roberts, 2000; Robertson, 1988). Others, such as injury, muscle damage, and soreness, are more closely related to the training practices of the participants.

Injury

Research suggests that, despite the purported health benefits of marathon running, over 50% of marathon runners experience a running-related injury either in training or during and immediately after the event itself (Fredericson & Misra, 2007; Maughan & Miller, 1983; Van Middelkoop et al., 2008). In addition, over 90% of runners experience a “specific health problem” during the marathon or in the following week (Satterthwaite et al., 1999). Most of these complaints are not serious, and include such common ailments as blisters, stiffness and pain. Despite the inclusion of fairly trivial health problems, it is noteworthy that many of these ailments persist for a week or longer after the event. In addition, a small number of more serious complications were reported: 6% required immediate medical attention, and there was one hospitalization.

The research that has looked at injuries during training and the marathon itself is inconsistent in the definition of running injury, and in the methods of gathering data. Macera et al. characterized running injury as a “muscle, joint or bone problem/injury of the lower extremities (foot, ankle, Achilles tendon, calf, shin, knee, thigh, or hip) that the participant attributed to running” (1989). In this case, the injury had to be severe enough to cause the runner to alter training, use medication, or seek medical attention. This definition was also utilized in a retrospective/prospective design study of 725 male marathon participants (Van Middelkoop et al., 2008).

The prevalence of injury reported over the one-year period (including the 11 month retrospective survey and the prospective one month period) was 54.8%. This is similar to the 58% incidence rate found in a previous retrospective study on mostly male

marathoners (Maughan & Miller, 1983). A study of Danish marathon runners (again, mostly male, but including some women) reported only a 31% incidence of running injury in the previous year (Holmich, Christensen, Darre, Jahnsen, & Hartvig, 1989). Of the marathoners in this study, 65% had previously completed a marathon, indicating a more experienced population than the other studies.

In much of the literature, running injury is classified by site, rather than by medical diagnosis, with the knee, calf, and foot being the most common areas of injury (Maughan & Miller, 1983; Van Middelkoop et al., 2008). The vast majority of runners were able to recover either fully or partially from the injury (Maughan & Miller, 1983). Of 397 runners who reported an injury during the year, 30 did not start the marathon due to injury, and 18 of those who did start did not finish due to injury (Van Middelkoop et al., 2008). These data indicate that the vast majority of running injuries sustained during marathon training are relatively minor, and full recovery is typical.

Clinical data can give us more detailed insight into the nature and severity of running injuries. A report of over 2000 running injuries seen at a sports medicine clinic identified patella-femoral pain syndrome (PFPS) as the most common running injury, followed by iliotibial band friction syndrome (ITBS), plantar fasciitis, meniscal injuries, tibial stress syndrome, patellar tendonitis and Achilles tendinitis (Taunton et al., 2002). The lower leg (from the knee down) appears to be the most frequently affected area of the body. Though biomechanical variables were assessed in this study, the researchers were

unable to draw any conclusions due to the lack of a control population and the high potential for examiner bias with respect to a given injury. With respect to specific injuries, PFPS occurred more frequently in both men and women less than 34 years old. Having less than 8.5 years of activity was a risk factor for tibial stress syndrome in both men and women. Men younger than 34 had increased incidence of ITBS, patellar tendinopathy, and tibial stress syndrome versus their older counterparts. Low BMI was a risk factor in women for tibial stress fractures and spine injuries.

A clinical review of the literature on running injuries was unable to identify specific mechanisms of injury, but suggested that evaluation of foot pronation mechanics and hip stabilization may be important areas of evaluation (Ferber, Hreljac, & Kendall, 2009). Foot pronation mechanics studies have yielded conflicting results. Ferber reports that weakness of the muscles of hip stabilization has been shown in some studies on knee injury (both PFPS and ITBS), but the actual mechanism of injury is poorly understood.

Other risk factors for injury in marathon runners have been identified. A prospective cohort study found that lack of previous marathon experience, participation in other sports, illness, use of medication, and alcohol consumption more than once per month were all associated with injuries and other health problems (Satterthwaite et al., 1999). In the same study, men experienced more problems with the hamstring and calf, while women were at increased risk of hip problems. Stiffness and pain, as well as blisters and illness, were included in the analysis, so it's difficult to interpret the results

specific to running injury. Lack of running experience was identified in another study as a risk factor for running injury (Marti, Vader, Minder, & Abelin, 1988). A U.S.-based study of participants in a marathon training program found a slower, less experienced population of marathon participants than previously reported in the literature (Chorley, Cianca, Divine, & Hew, 2002). The vast majority (87.5%) trained at a 9-minute mile or slower, over half had not previously trained for a marathon, over a third were obese or overweight, and some had been sedentary in the previous three months.

Fatigue

Performance in the marathon is limited primarily by factors, such as VO_{2MAX} , LT, and RE, discussed above as predictors of marathon performance. In addition, other physiological changes, such as muscle damage and fatigue, occur during the course of a marathon.

In a study on well-trained triathletes, heart rate, VO_2 and energy expenditure increased throughout a marathon, while RER decreased (Kyrolainen et al., 2000). Increased energy expenditure and oxygen cost of running indicate increased work, which the researchers attribute to thermoregulatory demands, muscle damage, and increased dependence on fat for fuel, which is evidenced by the decreased RER. The thermoregulatory demands of running are great due to metabolic heat production of the working muscles (Cheuvront & Haymes, 2001). This is particularly apparent in hot and humid climates, where the body's cooling mechanisms can prove inadequate, resulting in relatively slower times.

Glycogen depletion of the working muscle fibers during prolonged exercise has been well established and thoroughly characterized in the literature, and has long been considered an important cause of fatigue during endurance activity lasting longer than two hours (Bergstrom & Hultman, 1967; Hultman, Bergstrom, & Roch-Norlund, 1971). While muscle glycogen does fall dramatically, it does not reach zero; rather, rates of glycogen metabolism slow dramatically when muscle glycogen stores fall to around 1/3 of normal levels (Bosch, Dennis, & Noakes, 1993). Due to the limits of glycogen storage and utilization, fat metabolism becomes important in prolonged exercise, and endurance training has been shown to increase the capacity for fat utilization in working muscle (Hollooszy & Coyle, 1984). Carbohydrate intake during prolonged exercise has been shown to diminish the depletion of liver glycogen, which has important ramifications for the maintenance of blood glucose and avoiding hypoglycemia, and possibly for sparing muscle glycogen as well (Jeukendrup, 2004).

While the glycogen depletion model is important to understanding fatigue and energy balance during prolonged exercise, undoubtedly fatigue is a complex phenomenon that has many other contributing factors. As such it cannot be understood as a linear process related to glycogen depletion or the accumulation of a metabolite, but rather should be considered as a control process mediated by the brain, in which various signals are interpreted by the individual in the context of the environment as well as past experiences and expectations (Lambert, St Clair Gibson, & Noakes, 2005). This complex-systems model explains how athletes are able to sprint at the end of a

race, achieving their highest work rate at a time when they should be physiologically least able to work hard. The role of the brain in regulating exercise has been more broadly characterized as the “Central Governor Model” (Noakes, 2003). Applied specifically to the marathon, this model explains how the runner sets an initial pace, alters it according to physiological signals, and responds to external stimuli, such as the sight of the finish line (Noakes, 2007).

Muscle Damage

Muscle damage and a temporary impairment of muscular function are known consequences of marathon running (Hikida, Staron, Hagerman, Sherman, & Costill, 1983; Kim, Lee, & Kim, 2009; Kyrolainen et al., 2000; Petersen, Hansen, Aagaard, & Madsen, 2007). Damage to the muscle membrane leads to the release of enzymes, such as creatine kinase (CK), into the blood plasma (Jones, Newham, Round, & Tolfree, 1986). Other enzymes such as lactate dehydrogenase, aspartate aminotransferase, and alkaline phosphatase also typically enter the bloodstream as a result of muscle damage (Kim, Lee, & Kim, 2007; Noakes & Carter, 1982). Myoglobin, neutrophil activity, inflammatory cytokines such as IL-6 and TNF- α also have been shown to increase with exercise-induced muscle damage (Kim et al., 2007; Peake et al., 2005). Cell signaling mechanisms associated with muscle damage and the adaptive response to exercise have been identified, with the mitogen-activated protein kinase (MAPK) family of kinases and transcription factors being important in genetic signaling and response to marathon running (Yu, Blomstrand, Chibalin, Krook, & Zierath, 2001). While many biomarkers

change with muscle damage, CK level in the blood plasma has been identified as a reliable indicator of exercise-induced muscle damage, with baseline levels of around 100 U/L rising to as high as 40,000 U/L after eccentric exercise (Jones et al., 1986).

Eccentric muscle contractions produce greater degrees of muscle damage than concentric contractions (Clarkson & Hubal, 2002; McHugh, Connolly, Eston, & Gleim, 1999; Proske & Morgan, 2001; Schwane, Johnson, Vandenakker, & Armstrong, 1983). Eccentric contraction, as the term is used in the literature, indicates a contraction in which the force produced by the muscle is less than the opposing load, which causes the muscle to lengthen as it contracts (McHugh et al., 1999; Proske & Morgan, 2001; Raven, 1991). Running in general involves eccentric contraction in the lower limb, and downhill running requires a much greater eccentric contraction. The increased damage from downhill versus flat running has been suggested to be due to greater impact peak force and parallel braking force peaks during downhill running (Gottschall & Kram, 2005).

Structural and ultrastructural changes in the muscle fiber can be assessed through muscle biopsy, but the technique is invasive and relies upon generalization to the whole muscle from a small localized sample (Clarkson & Hubal, 2002). Sarcomere disruption and impairment of excitation-contraction coupling are two areas that have been proposed as the source of muscle dysfunction after exercise-induced muscle damage (Proske & Morgan, 2001). Sarcomere disruption, the most likely culprit, can be seen in the form of the Z-disc streaming or disruption that is typical in damaged myocytes, (Clarkson & Hubal, 2002). The role of the Z-disc is to delineate the boundaries

of the sarcomere, and to serve as an anchor for the thin filament (Luther, 2009). It is thus critical to both the structure and function of the myocyte. Cytoskeletal proteins such as desmin appear to be most susceptible to damage, which may occur as a result of the active myofibrils being stretched beyond their optimal length of contraction, ultimately yielding and causing the passive structural proteins to absorb the force (Clarkson & Hubal, 2002; Proske & Morgan, 2001). Loss of both myofibrils and sarcoplasmic reticulum, mitochondrial damage, and endothelial damage have been shown to occur acutely in response to marathon running (Warhol et al., 1985). Follow up 10-12 weeks later showed a complete recovery from the exercise bout.

Running distances near the standard 26.2 mile marathon has been shown to dramatically increase CK levels in recreational runners, from 160 U/L at baseline to 1500 U/L or higher 24-hours after the completion of the run (Riley, Pyke, Roberts, & England, 1975; Siegel et al., 1980). Among competitive runners (sub-3:30), higher levels of CK (nearly 4500 U/L) were found (Siegel et al., 1980). A group of experienced male marathon runners completing the run in about four hours had lesser, though still statistically significant, elevations in plasma CK after the completion of a marathon (Kim et al., 2009). The researchers do not state the best times of these runners, but from the description of the population it seems plausible that they ran the marathon at a sub-maximal effort, which may account for the relatively smaller increases in CK (approximately 400 U/L at the completion and 550 U/L 24 hours post-).

While exercise intensity appears to be an important factor in the degree of CK increase, beyond a certain timeframe, the magnitude of plasma CK increase appears to be related more to the distance run, rather than pace or intensity (Berg & Haralambie, 1978; Kim et al., 2009). In one study, in impact-type exercise, plasma CK levels increased in a linear manner up to about 5 hours, and then began an exponential increase beyond that time threshold (Berg & Haralambie, 1978). The researchers proposed that this may be due to both the energy status of the cells (i.e. glycogen depletion) and the mechanical factors associated with impact-type exercise like running. Comparing CK levels in runners completing a standard marathon versus a 200-km ultramarathon, researchers found that both groups increased CK levels significantly, but the ultramarathoners reached much higher levels than the marathoners, and that among the ultramarathoners, CK levels were not related to running pace (Kim et al., 2009).

In support of the theory that time of the effort is more closely linked than exercise intensity with the extent of the damage, the highest reported levels of CK in runners were measured after 246-km ultramarathon run over rugged terrain, where the average finishing time of the study participants was over 33 hours (Skenderi, Kavouras, Anastasiou, Yiannakouris, & Matalas, 2006). In this study the mean CK level exceeded 40,000 U/L. However, there may be a further time threshold beyond which the extent of muscle damage due to exercise diminishes. A recent study conducted on runners of the 330-km Tors de Geants, a mountain footrace in the Italian Alps that takes several days to complete, found much lower levels of CK (mean of under 4,000 U/L) and less muscle

dysfunction (Saugy et al., 2013). The researchers suggest that in such a long event, participants must regulate themselves to much lower intensities (with a large amount of time spent walking) in order to complete the event, thereby preserving muscle function.

Delayed onset muscle soreness (DOMS) frequently accompanies exercise-induced muscle damage, but assessment by a visual analog scale is only weakly associated with the extent of the muscle damage (Nosaka, Newton, & Sacco, 2002). In a 56-km ultramarathon (9 miles longer than a standard marathon), those who had never run even a standard marathon had much higher (280% greater) levels of CK than those who had previously completed a marathon or ultramarathon (Noakes & Carter, 1982). The researchers attribute this to the protective effect of training and previous experience, though it is also worth noting that the runners from the experienced group finished on average at slightly over 4 hours, while the mean finish time for the novices was just under 6 hours.

The protective effect of repeated bouts of strenuous exercise has been well-established in research, with much greater evidence of muscle damage occurring in response to the first bout of exercise at a given load (Clarkson & Hubal, 2002; McHugh et al., 1999; Nosaka & Clarkson, 1995). In three successive bouts of eccentric strengthening exercise at the same load separated by 3 days, the first bout produced the highest CK levels and soreness, while the successive exercise bouts did not appear to impair recovery, or increase soreness or CK levels (Nosaka & Clarkson, 1995). The exact mechanism for the protective effect is unknown, but theories focusing on neural

adaptation, connective tissue adaptation, and adaptation within the muscle cells themselves have been proposed (McHugh et al., 1999). Given the evidence available to support each of these theories, it seems likely that adaptations in all three areas after an exercise bout combine to improve resistance to muscle damage in subsequent exercise bouts.

The protective effect can last for a relatively long period of time, even up to six months after the initial exercise bout (Clarkson & Hubal, 2002). However, the effect appears to diminish, and may differ depending on the specific exercise protocol. For example, a study comparing groups who did their second bout of a downhill running protocol 3, 6, and 9 weeks after the first found a protective effect for the 3 and 6 week groups, but not for the 9 week group (Byrnes et al., 1985).

Given what is known about the repeated bout effect, it is not surprising that novice marathoners experience not only increased likelihood of injury, but also greater levels of muscle damage than experienced runners (Noakes & Carter, 1982; Satterthwaite et al., 1999). However, even the novice marathoner may be able to mitigate muscle damage through proper training, as the protective effect of repeated bouts can be seen from a less intense initial exercise bout followed by a much more strenuous session (Brown, Child, Day, & Donnelly, 1997). This notion translates to the training commonly done by those who are preparing for a marathon, where the longest run is often in the approximately 20 miles, in preparation for a 26.2 mile race.

While repeated bouts may provide protection against damage, there may be too much of a good thing. Chronic endurance training at heavy loads has been postulated to lead to chronic, irreversible muscle damage in some athletes (Derman et al., 1997; Grobler et al., 2004). Fiber size variation, internal nuclei, and z-disc streaming were more common a group of endurance athletes with symptoms of chronic fatigue than in their matched endurance trained counterparts (Grobler et al., 2004). A possible mechanism for the failure of the adaptive response is the shortening of the DNA telomeres due to the repeated demands on the satellite cells in response to muscle damage (Collins et al., 2003). In one study, abnormally short DNA telomeres were seen in athletes with chronic fatigue (Collins et al., 2003). Experienced, asymptomatic, very seasoned endurance runners (averaging nearly 50,000-km of training) were not significantly different in TRF length (a measure of DNA telomere length) than sedentary individuals, but within the endurance group, there was a relationship between years and hours spent running and telomere length (Rae et al., 2010). This suggests that while normal endurance training does not necessarily result in chronic muscle pathology, it is a risk factor.

Summary

Injury during marathon training and racing are quite common. While most injury can be characterized as minor and temporary, some injury does preclude the possibility of participants to either start or finish the marathon. Steps should be taken to ensure that training loads are increased gradually, and that thorough screening is done to

identify potential problems. Any training (either type or volume) beyond the baseline required to successfully complete the event should be evaluated to ensure that the benefits of the added training do not come at a cost of an increased rate of injury.

Glycogen depletion, excessive heat production, and a variety of homeostatic disturbances play a role in fatigue. An important limiting factor on performance in the marathon, fatigue is best understood as a complex phenomenon of signals interpreted and integrated by the brain within the context of experiences and expectations of the runner.

Muscle damage is a known consequence of marathon running and long distance running training. The effects appear to be most profound on novices and those who are undertaking much greater training loads than that which they are accustomed. Very experienced runners are at risk for chronic muscle damage, where the adaptive response begins to falter. While many methods of assessment of muscle damage exist, the use of blood markers is most common. Plasma CK levels remain the most widely used marker, as this is a validated and reliable method of assessing muscle damage.

Plyometric and Explosive Speed Training

General Practices and Adaptations

Plyometric training (PLYO) consists of high velocity movements performed in rapid succession, with a lengthening (or eccentric) muscle contraction followed quickly

by a shortening (concentric) contraction (de Villarreal, Requena, & Cronin, 2012).

Plyometric training emphasizes the stretch-shortening cycle, which consists of a stretch (or lengthening) of the muscle imposed by an external force (gravity or an additional load) followed immediately by a concentric (or shortening) muscle contraction (Komi, 2000). The stretch imposed on the muscle-tendon complex engages the stretch reflex, thereby enhancing the concentric action as compared to an isolated concentric action.

The most common application of PLYO is in “jump training”, which consists primarily of jumps, skips, bounding and hops (de Villarreal et al., 2012). This type of training is commonly utilized by athletes in sports where jumping and explosive lower body movements are important, such as basketball, volleyball and the jumping events in track and field. The benefits of PLYO for improved vertical jumping ability have been well demonstrated in the literature and are widely utilized by athletes and coaches.

Sprint speed is more complex and multi-faceted than vertical jumping ability. Sprinting requires lower limb strength, power and acceleration, as well as precise neuromuscular control. Plyometric training appears to improve at least some of these aspects of sprint performance, according to a 2012 meta-analysis (de Villarreal et al., 2012). While the most obvious application of PLYO is for enhancement of jumping abilities, the benefits do seem to transfer to sprint speed.

Long term exposure to PLYO has been shown to increase bone mass, particularly in children and pre-menopausal women (Markovic & Mikulic, 2010). This benefit has implications for health and well-being, and is worth considering for a general fitness

population, regardless of whether it has any bearing on athletic performance. Low bone density has been identified as a risk factor for stress fractures in athletes (Bennell, Matheson, Meeuwisse, & Brukner, 1999; Myburgh, Hutchins, Fataar, Hough, & Noakes, 1990).

Short-term studies on PLYO have found numerous positive outcomes related to improved muscle and neuromuscular function: lower limb strength, power and speed (Markovic & Mikulic, 2010). These adaptations may be driven by any of a wide range of adaptations: improved neural drive, improved neuromuscular coordination, mechanical changes in the muscle-tendon complex, changes in muscle size and/or structure, and mechanical changes within the muscle fibers.

Conflicting results have been found with regard to mechanical changes in the muscle-tendon complex, as measured by musculo-tendinous stiffness: while some articles found that increased stiffness improves power and speed, others found a correlation between greater compliance and improved speed and power (Markovic & Mikulic, 2010). These inconsistencies may be due to the measurements being done on different units (Achilles vs. plantar flexors, e.g.). Similarly conflicting results were found with regard to changes in muscle size and structure and changes within the muscle fibers.

Positive neural adaptations have been more consistently shown to occur in response to PLYO (Markovic & Mikulic, 2010). Electromyography has been used to demonstrate neural changes in response to PLYO, specifically increased activity during

maximal voluntary contraction (MVC). While some equipoise remains, the trends across studies shows increased pre-activation, MVC, and activation during eccentric contraction.

While the literature on PLYO is dominated by studies on males, there is evidence that women can expect similar neuromuscular adaptations. Beneficial neuromuscular adaptations were seen in female athletes, specifically increased activation of the muscles of the hip (adductor, adductor-to-abductor coactivation, and a trend toward increased quadriceps-to-hamstring coactivation) (Chimera, Swanik, Swanik, & Straub, 2004). The experimental group in this study increased vertical jump height, but the change was not statistically significant.

Peak power and jump performance improved in women following unilateral or bilateral PLYO protocols (Makaruk, Winchester, Sadowski, Czaplicki, & Sacewicz, 2011). Likewise, a 6-week PLYO program improved countermovement jump height by 25% and peak power by over 11% in college women (Ebben, Feldmann, VanderZanden, Fauth, & Petushek, 2010). Other performance improvements from PLYO may also follow the same pattern in women and men, though more research on women needs to be done in order to confirm this.

Improvement in countermovement jump and peak power from PLYO training in women did not attenuate after 10 days (Ebben et al., 2010). This may have important implications for timing of training sessions and peaking, suggesting that training less frequently may still be effective in eliciting or at least maintaining favorable adaptations.

Plyometric training can lead to muscle damage in both endurance and power athletes (Kyrolainen, Takala, & Komi, 1998). A test protocol totaling 200 drop jumps and 200 weighted sledge drops induced increased serum protein markers, including CK, myoglobin, and carbonic anhydrase III (which occurs mostly in Type I muscle fibers) in both groups immediately after exercise, and continued to climb 2 hours after exercise in the endurance group only. While there is no clear explanation for this difference, it does suggest that endurance athletes are prone to greater muscle damage due to PLYO, and may take longer to recover between workouts than power athletes.

The time course of muscle damage and recovery has been characterized as similar to other forms of overload exercise, with an acute inflammatory response followed by as much as 3 days of decrement in performance following a PLYO session (Chatzinikolaou et al., 2010). In this study, a total of 50 jumps (multiple sets of hurdle hops and drop jumps) were performed by an athletic population not currently doing any PLYO training. While the researchers found no loss of strength after the session, jumping ability was diminished for 3 days. Elevations in blood markers followed a predictable pattern, with acute elevations in inflammatory markers (IL-6, IL-1b, CRP and cortisol) immediately after exercise and at 24 hours, while markers of muscle damage (CK and LDH) and DOMS peaked at 24-48 hours after exercise. The researchers recommend a 72-hour recovery period after a PLYO session that induces moderate amounts of muscle damage such as this one. By 4-5 days post-exercise, nearly all measures had returned to baseline.

Adaptation from PLYO appears to begin after just a single session, as evidenced by reductions in exercise induced muscle damage from a second session (Jamurtas et al., 2000; Marginson, Rowlands, Gleeson, & Eston, 2005). A study comparing eccentric, concentric, and PLYO training performed at 70% of maximal intensity found that delayed onset muscle soreness (DOMS) was higher in the eccentric and PLYO groups, but that there was no difference in CK levels (Jamurtas et al., 2000). After the second session, which was 6 weeks after the first, DOMS and CK were significantly lower in all groups.

Boys (ages 9-10) experienced less severe symptoms of exercise-induced muscle damage than men (20-29 years old) after a PLYO session intended to produce muscle damage (Marginson et al., 2005). The session consisted of 8 sets of 10 maximal intensity jumps done in rapid succession with a knee bend of 90-degrees on each jump, and one minute of recovery between sets. Both groups repeated the protocol two weeks later, and both experienced less severe symptoms of muscle soreness and less decrement in jump performance than after the first session. This suggests that repeated bouts of PLYO is protective against the more severe symptoms of muscle soreness. The repeated bout effect was stronger in men than boys, which suggests that the older group's higher degree of symptoms of muscle damage after the initial bout was due to less exposure to similar movements. The researchers note that children, as part of their daily life, are more likely than adults to participate in activities that include leaping and hopping movements. Creatine kinase or other markers of muscle damage were not assessed.

Explosive training, which could include PLYO, strength training performed at high velocities, and other types of training, has been defined as training that elicits maximal rate of force development, muscle activation, and synchronization (Stone, 1993). Michael Yessis, who has written several books for the general population on explosive training, uses the term to encompass both PLYO and other exercises that combine speed and strength (Yessis, 2000). The term explosive strength training has been used by researchers to characterize protocols that include PLYO, speed, and strength exercises performed at high velocities (Paavolainen et al., 1999). For the purposes of this review, explosive speed training will be defined as sprint training in which maximal or near maximal efforts are produced for very brief periods, in order to elicit maximal rates of force development and neural activation and synchronization in the movement pattern specific to running.

The adaptations to non-plyometric explosive speed training may vary according to the exercise. Exercises combining speed and strength are likely to produce neural adaptations specific to the movement performed (Behm, 1995; Paavolainen et al., 1999). Sprint training is defined as maximal, un-paced running efforts of 15 seconds or less with full recovery between repetitions (Ross et al., 2001). Given the specificity of neuro-muscular adaptations, this type of explosive exercise can be seen as having great potential for enhancing the training of athletes training to run longer distances.

Maximal intensity sprint training appears to improve muscle conduction velocity, an indicator of neuromuscular function linked closely with sprint speed (Ross & Leveritt,

2001). Improvement in sprinting as a result of training has been shown to occur over a long period of time, and cannot be explained by changes in muscle cross-sectional area or enzyme activity alone (Ross et al., 2001). Given the complexity of movements required by the running motion, neural and neuromuscular adaptations may continue to occur for longer periods of time than those seen in relatively simple movements such as isolated joint strength training. The specific adaptations that may result from sprint training include nerve conduction velocity, maximal EMG, motor unit recruitment and activation, and motor-neuron excitability.

Adding resistance to sprint training through either external loads (such as harness and band resistance) or through running uphill is another form of explosive speed training that has been shown specifically to enhance acceleration and decrease start time (Myer, Ford, Brent, Divine, & Hewett, 2007). Uphill sprinting results in a shorter stride, with more time spent in the propulsive phase, which may result in positive adaptations by overloading the muscles of propulsion, due to the greater force requirement (Paradisis & Cooke, 2001). This may explain the improvement seen in start time, and clearly has more to do with the concentric than the eccentric phase of muscle contraction.

Training Effects Related to Distance Running Performance

The question of whether the adaptations and outcomes that can be expected from PLYO and explosive speed training will transfer to beneficial adaptations for distance runners has been explored only to a limited degree. The practice of PLYO

training by distance runners is far from common, with even elite runners being characterized as unfamiliar with it (Saunders et al., 2006). Despite the novelty of this type of training for this population, there is evidence to suggest that some of the adaptations may transfer to distance running performance.

There have been some promising findings in the research on PLYO for runners competing at distances as long as 5-km (Paavolainen et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003). A study of trained male distance runners examined the effects of a 9-week program of explosive-strength training, and found improvements in RE and 5-km time trial performance (Paavolainen et al., 1999). This program consisted of sprints of 100 meters and less, jumping exercises, as well as lower leg strength training exercises done with low loads and high velocity of movement. In this study, the explosive-strength group showed significant improvement in the 5-km time trial, RE, 20 meter sprint, five jump test, and a maximal anaerobic test. The control group improved in $VO_{2\text{ MAX}}$, while the explosive-strength group remained the same. The fact that this change was not reflected in the 5-km time trial supports the idea that for many athletes, factors other than $VO_{2\text{ MAX}}$ (such as muscle power and RE) are the limiting factor on performance (Noakes, 1988). In fact, the researchers did find a significant relationship between the time trial improvement and the improvements in RE and the maximal anaerobic test (Paavolainen et al., 1999).

Another study on trained male distance runners examined the effects of PLYO on distance running performance, jump performance, musculo-tendinous stiffness, and

force measurements specific to the legs (Spurrs et al., 2003). In this study, a six-week PLYO program led to no changes in $VO_{2\text{ MAX}}$ or LT, but improvements in jump-specific measures such as the 5-bound test and counter movement jump height, and also in RE and the 3-km time trial. This study found increased lower leg musculo-tendinous stiffness in the PLYO group, and found a significant correlation between the increase in that measure and the improvements in RE. However, the change in time trial performance was not significantly correlated with changes in any of the other measures, though the researchers speculate that the 2.7% improvement in 3-km time trial was a result of improved RE.

In a randomized study of highly trained male distance runners, researchers reported an improvement in RE in the plyometric group at the fastest of three speeds tested (18 km/hr) and a trend toward improvement at the slower speeds (Saunders et al., 2006). There were no differences between the PLYO and control group in any cardiorespiratory or physiological measures, such as $VO_{2\text{ MAX}}$, LT, heart rate, and RER. Force plates were used to assess power and strength. While there were no significant differences between the two groups, the PLYO group improved by 14% in 5 jump plyometric test and in time to reach maximal development of force. Across all of the force plate measures, effect sizes were small, but the PLYO group consistently outperformed the control group. While the differences were not significant, and thus it would be premature to draw any conclusions from this specific to lower limb power and strength, the consistent trend suggests that this area may merit additional exploration

on a larger sample size with power to detect relatively small differences. Likewise, the improvement in RE at 18 km/hr is promising, but since no time trial or race was conducted in this study, we can only speculate on the effect of this PLYO program on running performance.

Turner et al. conducted a randomized trial of recreational male and female runners and found a statistically significant improvement in RE among the group that performed 6 weeks of PLYO training as compared to controls, who did no training in addition to their usual distance running (2003). The researchers acknowledge the limitation that the control group did no additional training, but do not believe that the effect could simply be due to additional training time. Interestingly, the improvements in RE came despite a lack of improvement in performance on any of the jump tests, which may in part be explained by the low intensity, intermittent (and thus not engaging the stretch-shortening cycle) nature of most of the exercises performed.

A 6-week study on adolescent cross country runners that was also relatively low in intensity and volume found no difference in any of the biomechanical, physiological or performance outcomes, including RE (Lathrop, Womack, & Paton, 2001). This study was conducted in conjunction with the summer training of a group of young cross country runners preparing for their fall season. Both the PLYO group and normal run training group improved RE and 3200-m time, but there was no difference between the training groups. The improvement to both RE and 3200-m performance in both groups

suggests that for this young, inexperienced population improves at a rapid rate, but that replacing running with PLYO training provided no additional benefit.

Though not specifically a performance outcome, the potential for the prevention of injury can, over time, allow the runner to train more consistently and theoretically to attain a higher competitive level. A study on the effect of PLYO training on female athletes (collegiate soccer and field hockey players) found improved hip activation, which may have important ramifications for injury prevention (Chimera et al., 2004). The importance of strength and resistance to fatigue of the hip musculature in prevention of running injury was discussed above (Ferber et al., 2009). Likewise, an 18-week PLYO training protocol reduced lower body movements during landing in the hip, knee, and ankle (Myer, Ford, McLean, & Hewett, 2006). Greater movements in the coronal plane on landing have been associated with ACL injury, so training to reduce those movements has been proposed as an effective means of injury prevention in athletes at risk of ACL injury. However, this study is limited by the fact there was no control group, but rather a dynamic stabilization/balance group that also improved; in addition, all the study participants did strength training and were active members of a volleyball team. Nonetheless, the potential for PLYO training to reduce incidence of lower limb injury is an interesting area for further research.

Specific Training Protocols

A wide range of PLYO and explosive speed training protocols have been studied by researchers and utilized by practitioners in the field. Some of the important variables

to consider are length of program, number of exercises, specific exercises, the relative difficulty and stress of those exercises, and volume of training (number of repetitions per set, sets per session, and sessions per week). Optimal levels of all of these variables could vary greatly depending on the target population and the other types of training and competition that the population will be engaging in simultaneously.

The explosive-strength training protocol that improved 5-km performance in trained male distance runners consisted of sprints of 100 meters and less, jumping exercises, leg-press, and knee extensor-flexor exercises (Paavolainen et al., 1999). The exercises were done with low loads (0-40% of one-repetition maximum), at high speeds, for a total of 30-200 repetitions per exercise. The researchers suggest that the fast, low resistance strength-training in combination with other high velocity PLYO and speed training activities will minimize muscle hypertrophy, but will lead to beneficial neural adaptations.

While the previous study is complicated by the fact that it included multiple types of training (high velocity strength training, PLYO, and explosive speed), another study looked exclusively at the effects of PLYO on distance running performance (Spurrs et al., 2003). In this study, 17 trained male distance runners followed a 6-week program of PLYO exercises. Subjects performed three to four jumping, bounding, or hopping exercises per session. Sessions were done two to three times per week, with a progressive increase in the total volume over the course of the 6-week study.

Saunders et al. utilized a 9-week program consisting of 3 sessions per week in a study of highly-trained distance runners (Saunders et al., 2006). Like the Paavolainen study previously cited, the protocol included both jumping and strength training performed at a high velocity of movement with a relatively low load. The researchers tested subjects after both 5 and 9 weeks of training, and found no statistically significant change in RE at 5 weeks, but an improvement in economy in the PLYO group at 18 km/hr (the highest of 3 speeds tested) at 9 weeks. In weeks 6-9, the athletes performed many of the same exercises, adding only two new ones: continuous hurdle jumps and scissor jumps for height. The two possible conclusions are either that more than 5 weeks are needed to illicit a statistically significant improvement in such a small group, or that the two added exercises may have been somewhat more demanding and/or effective in improving RE.

Turner et al. employed a more basic and low volume PLYO protocol, which they deemed appropriate to the more recreational population in their study (2003). Subjects performed 5-6 exercises per session, with the same exercises being repeated every session. The exercises were warm-up jumps (performed at 50% of max. effort), double-leg jumps (done intermittently, not continuously), single-leg jumps (done intermittently), single-leg springing jumps (done continuously but sub-maximally), split squat jumps (maximal and continuous), and double leg springing jumps uphill (continuous, but sub-maximal). The researchers reported that each session took only 10-15 minutes, and training sessions were not observed by the researchers. There were

no differences in pre- and post- jump tests in either the experimental or control group, which suggests that the training was not challenging enough to elicit the adaptations necessary to improve jumping ability.

The 6-week study on adolescent cross country runners progressed from a focus on low intensity (weeks 1-2) to moderate (weeks 3-4) to moderate and high (weeks 5-6) intensity exercises (Lathrop et al., 2001). The sessions were done 2-3 days per week and consisted of 4-6 exercises, with 2-4 sets of each exercise and 4-10 repetitions per set. Each session included exercises from three categories: jumps, bounds and skips, and hops. The exact exercises performed in each session are not published, and the researchers relied on the participants' coaches to conduct the majority of the sessions. Examples of the exercises utilized are given, and included standard PLYO exercises such as squat jumps, alternate-leg bounding, and hurdle hops. The researchers cite a textbook on PLYO as the source of their exercises (Radcliffe & Farentinos, 1999).

This approach of adapting an exercise protocol from a textbook has been used by other researchers as well (Chimera et al., 2004). In this study, 2 sessions per week were done for 6 weeks, which is similar to the above study. However, the volume was markedly higher, with a typical set consisting of 30 or more (up to 70) jumps. The population in this study was collegiate female athletes, a more experienced, athletic population, which is likely the reason why researchers provided them with a protocol of much greater volume. At the same time, fewer exercises were included: wall touches, split squat jumps, lateral cone jumps, cone hops with 180-degree turn, and drop jumps

were the only exercises, versus the over 25 exercises listed in the previously discussed study on cross country runners (Chimera et al., 2004; Lathrop et al., 2001). Given the learning component of any neuromuscular exercise, and the short duration of the study, the cross country study may have been hindered by the excessive number of exercises for a relatively novice population.

Summary

A strong body of literature exists on the general physiological adaptations and outcomes related to PLYO training. The potential for PLYO to improve performance in explosive activities that rely on the lower body, such as jumping and sprinting, has been characterized fairly thoroughly in the literature as well. In contrast, the research on PLYO and distance runners has mostly been done in the last 15 years, often in relatively small studies of trained male distance runners. Training protocols have varied, sometimes relying exclusively on jumping exercises, and sometimes including strength training and sprints.

Plyometric training does not have an effect on $VO_{2\text{ MAX}}$ or LT, but does appear to have the potential to improve RE. While only two of the studies discussed actually looked at performance outcomes (3-km and 5-km time), enhanced RE has been shown to be an important factor in running performance. The research presented above, while far from unequivocal, does support the use of PLYO for distance runners.

While PLYO does seem to have the potential to improve RE, the lack of a clear understanding of why those improvements occur represents a serious limitation to the

literature. Hypotheses regarding the mechanisms by which PLYO may improve athletic performance include changes in a number of anaerobic and neuromuscular characteristics: improved neural drive, improved neuromuscular coordination, mechanical changes in the muscle-tendon complex, changes in muscle size and/or structure, and mechanical changes within the muscle fibers (Markovic & Mikulic, 2010). Which of these are most important for influencing distance running performance remains to be determined, though the factors related to neural activation appear to more consistently be affected by PLYO.

There is a dearth of literature comparing multiple PLYO protocols, or comparing the effect of a PLYO program on different populations (such as middle-distance runners vs. marathon runners). Randomized studies of multiple training protocols and multiple populations could further our understanding of the volume, intensity and length of training programs necessary to maximize improvements in RE and performance through PLYO. This type of research could also give us insight into the applications for different demographics, including women, novice athletes, and other populations outside of trained male distance runners.

Injury and injury prevention is another area in which the literature is lacking. Some studies have supported the use of PLYO in the prevention of lower limb (particularly ACL) injuries. However, others have clearly demonstrated the potential for muscle damage and possible injury due to excessive use of PLYO. Few studies on the effect of PLYO training reported adverse events in any detail, with the occasional

exception of stating the number of subjects who did not complete the study due to injury or illness (Paavolainen et al., 1999). Injury rates and other negative outcomes, such as training sessions missed due to soreness, between groups has not been reported, likely due to the small sample size of these studies.

The evidence on PLYO training suggests that distance runners may benefit from it. However, many questions remain, including frequency of training session, specific type and number of exercises, duration of program, number of sets and reps, and the best phase or phases of training in which to include PLYO in a periodized scheme. Many areas merit further study in order to give direction to athletes and coaches. In light of these findings, implementation of a PLYO program may be of benefit to distance runners, but given the lack of data on injury and the potential for muscle damage, it is advisable for coaches and athletes to proceed with caution. A PLYO program should evolve along with the athlete's capabilities, beginning with a modest volume and progressively increasing in a manner that will maximize positive adaptations while minimizing injury risk.

Conclusions

Plyometric and explosive speed training has been shown to improve RE and, in some cases distance running performance, without impacting VO_{2MAX} or LT. For athletes training for distance running, PLYO may provide a beneficial neuromuscular stimulus. Much research remains to be done on the precise mechanisms by which performance

and RE improve, and the best manner in which to elicit positive adaptations for distance running performance. Likewise, long distance running such as half-marathon and marathon performance has not been examined in relation to PLYO and explosive speed training, yet the improvements in RE suggest a possible benefit for those events.

Running economy can be affected by a wide range of physiological, anthropometric, and biomechanical factors. Plyometric training is one of a number of interventions that may have some efficacy in improving RE. Few studies have examined RE at a range of paces in order to ascertain the intensity and methodological approach that is most useful in predicting running performance at different distances. Most research has only reported RE in relatively simple terms of oxygen utilization, whereas some of the scientific literature suggests that there may be more meaningful ways of characterizing it. These alternatives include oxygen utilization calculated per km (or other unit of distance run), RER at a given pace, energy cost (taking into account both oxygen utilization and RER), allometrically-scaled oxygen utilization (as $\text{ml}/\text{Kg}^{0.75}/\text{min}$), and RER VAR.

Marathon performance is a multi-faceted and complex topic, and one that cannot be reduced to a single or even a few factors. The traditional model of performance, focused on $\text{VO}_{2\text{MAX}}$ and LT, are valuable and remain important in modeling running performance. However, the growing population of runners engaged in longer events such as half marathons and marathons demands a more nuanced view of the important factors in marathon performance. Today's marathon runners are on average

slower than the average runner of 30 years ago, but they are not uninterested in achieving certain levels of performance. At the same time, health and wellness are increasingly important motivations for those engaged in long distance running, so injury rates, soreness, and muscle damage are important aspects that should be reported with respect to specific training practices.

CHAPTER 3: Effects of Plyometric and Explosive Speed Training on Speed, Jumping Ability, and Distance Running Performance in Recreational Marathoners

Abstract

Plyometric and explosive speed training (PLYO) improve jumping ability and sprint speed, respectively, in interventions focused on improving those variables. In competitive distance runners, this type of training may also improve running economy (RE) and performance at distances up to 5k. **Purpose:** This study examined whether a PLYO intervention would be effective at improving sprint speed and jumping ability in recreational marathoners, and whether the effects would transfer to variables related to distance running performance. **Methods:** Twenty-two subjects, ages 18-23, (20.3 ± 1.3 [mean \pm S.D.] years) from a university marathon training course were randomized to either a PLYO or core strength (CORE) training group. Both groups performed one 15-20 minute training session per week for 12 weeks in addition to their running training in preparation for a 26.2 mile road marathon. Sprint and jump dependent variables measured before and after training were flying 30-m run (30FLY), 60-m run (60M), 200-m run (200M), standing long jump (SLJ), 10-bound test (10BD), and vertical jump (VJ). Running performance variables assessed were RE and respiratory exchange ratio (RER) during a sub-maximal 30-minute run, VO_{2MAX} , body mass (BM), 2-mile time trial (2MI), and 26.2 mile marathon (MARA). With the exception of MARA, all variables were assessed pre- and post-training. **Results:** In the sprint tests, the PLYO group improved in

both the 200M ($p \leq 0.001$) and 60M ($p = 0.004$), and showed a strong trend toward improvement in the 30MFLY ($p = 0.051$). The difference from the CORE group was statistically significant only in the 200M ($p = 0.002$). The CORE group did not change from baseline in any of the sprint or jump variables, but had a trend toward a decrement in performance in the SLJ ($p = 0.067$). While the PLYO group did not significantly change from baseline in any of the jump variables, they were significantly different from the CORE group in SLJ ($p = 0.024$). In the distance running performance variables, there were no differences between the groups. Both groups improved in 2MI ($p \leq 0.001$), VO_{2MAX} ($p = 0.026$ for CORE vs. $p = 0.002$ for PLYO), and RE ($p = 0.01$ for both groups). Both groups were also significantly slower ($p \leq 0.001$ for CORE vs. $p = 0.004$ for PLYO) than predicted in the marathon, based on their 2MI results. There were no changes or differences in RER or BM in either group. **Conclusion:** Low-volume PLYO training is effective in improving sprint speed and maintaining jumping ability in recreational marathoners, but the effects do not transfer to distance running performance in this population.

Introduction

Plyometric training consists of high velocity movements performed in rapid succession, with a lengthening (or eccentric) muscle contraction followed quickly by a shortening (concentric) contraction (de Villarreal et al., 2012). Short-term studies on PLYO training have found numerous positive outcomes related to improved muscle and neuromuscular function: lower limb strength, power and speed (Markovic & Mikulic, 2010). These adaptations may be driven by a wide range of underlying mechanisms: improved neural drive, improved neuromuscular coordination, mechanical changes in the muscle-tendon complex, changes in muscle size and/or structure, and mechanical changes within the muscle fibers. Plyometric training is commonly utilized by athletes in sports where jumping and explosive lower body movements are important. The most common application of PLYO is in “jump training”, which consists primarily of jumps, skips, bounding and hops done specifically to enhance jumping ability (de Villarreal et al., 2012).

Sprint training (or explosive speed training) is defined as maximal, un-paced running efforts of 15 seconds or less with full recovery between repetitions (Ross et al., 2001). Improvement in sprinting as a result of training has been shown to occur over a long period of time, and cannot be explained by changes in muscle cross-sectional area or enzyme activity alone (Ross et al., 2001). The specific adaptations that may result from sprint training include increased nerve conduction velocity, maximal EMG, motor unit recruitment and activation, and motor-neuron excitability.

Either of these forms of training, or a combination, may have benefits for distance runners. Plyometric training has been shown to improve RE and/or performance in shorter (up to 5k) races, as well as performance on a number of lower limb power tests in competitive runners (Paavolainen et al., 1999; Ramirez-Campillo et al., 2014; Saunders et al., 2006; Spurrs et al., 2003). Recreational runners may improve RE with a relatively low intensity and volume PLYO program, with no changes in VO_{2MAX} or jump height and efficiency (Turner et al., 2003). Maximal intensity sprint training appears to improve muscle conduction velocity, an indicator of neuromuscular function linked closely with sprint speed (Ross & Leveritt, 2001). While the importance of sprint speed to top caliber distance runners is readily apparent due to the importance of the finishing sprint, the value to recreational runners is less clear. However, it is plausible that the improvements in power and efficiency in the running stride could potentially benefit recreational runners as well.

Long term exposure to PLYO has been shown to increase bone mass, particularly in children and pre-menopausal women (Markovic & Mikulic, 2010). This benefit has implications for health and well-being, and is worth considering for a general fitness population, regardless of whether it has any bearing on athletic performance. Likewise, higher intensity forms of training are effective in maintaining muscle mass, an important indicator of health in aging populations (Koopman et al., 2009).

The effect of PLYO training on recreational runners training for a marathon has not been studied, and this population is likely to be unique, given the demanding

aerobic training required. Some studies on untrained subjects have found increases in VO_{2MAX} in response to certain forms of strength training (McCarthy et al., 1995; Stone et al., 1983). Short, high-intensity interval training has been shown to elicit favorable metabolic adaptations similar to those achieved through endurance training, but with substantially less exercise time (Burgomaster et al., 2008; Gibala, 2006). However, in subjects already engaged in endurance training, this type of very short, high intensity exercise has not been shown to improve VO_{2MAX} (Jung, 2003; Paavolainen et al., 1999).

While many studies on distance runners have utilized 2-3 sessions per week (Paavolainen et al., 1999; Ramirez-Campillo et al., 2014; Spurrs et al., 2003; Turner et al., 2003), relatively infrequent training sessions appear to be effective for women (Ebben et al., 2010). More than 10 weeks and 20 sessions of plyometric training sessions enhances vertical jump performance more than shorter programs, and men have a greater response than women with respect to improved vertical jump height (Saéz-saez de Villarreal, Kellis, Kraemer, & Izquierdo, 2009). Finding the correct balance between adequate training stimulus and recovery within the context of an endurance athlete's training schedule is a challenge.

Core training, which is widely practiced by runners and other athletes, has not been shown to improve running performance or RE (Stanton et al., 2004). It is often utilized for purported injury prevention benefits by athletes, and while the evidence for this is minimal, a core training group provides a useful, ecologically valid control group. The use of a CORE group as a control allowed for matching of training time, with both

groups doing muscular strengthening exercise, but only the PLYO group utilizing high velocity and eccentric-overload exercises.

There is evidence for a detrimental effect of marathon training and racing on muscle function, strength, and power (Luden et al., 2012). However, with effective training and a proper taper, muscle strength and power can be maintained or even improved (Trappe et al., 2006). Maintaining or improving muscle function over the long term has implications related not only to performance, but also to health (Koopman et al., 2009). Chronic endurance training at heavy loads has been postulated to lead to chronic, irreversible muscle damage in some athletes (Derman et al., 1997; Grobler et al., 2004), so forms of training that maintain or improve muscle function could have both a health and performance benefit.

Finishing times for recreational marathon runners vary widely and models of performance are limited by the unpredictability of the event, differences in motivation, pacing strategies, and the varied psychological and physiological responses to the experience of participating in an event of this nature. A wide range of physiological, anthropomorphic, and training factors have been identified as related to marathon finish time (Arrese et al., 2005; McKelvie et al., 1985). While a recreational population is less concerned with performance measures than competitive runners, the effect of higher intensity forms of training on this population is germane given the recent trend toward higher intensity forms of training such as CrossFit, boot camps, and other strength and power-oriented programs. Whether PLYO training has an effect on sprint

and jump performance in this population, and whether there is any transfer of effects to factors related to distance running performance are important questions that should be studied in order to make evidence-based recommendations to the growing population of recreational long-distance runners. Thus, the purpose of this study was to determine if PLYO training would be effective in improving speed and jumping ability in recreational runners engaged in a marathon training program, and whether any improvements would transfer to distance running performance for this population.

Methods

Experimental Design.

The study was a 12-week exercise intervention utilizing a randomized-controlled parallel group design. The two groups were PLYO and CORE, and the outcomes assessed fall into two categories: 1) sprint and jump performance, and 2) distance running performance. All dependent variables except marathon finish time were assessed pre- and post- to evaluate the effects of the training intervention.

The objective of the study was to determine the effect of a 12-week PLYO program on sprint and jump performance, and distance running performance variables in college-aged recreational runners enrolled in a marathon training class. Training sessions were supplemental to a marathon training program followed by enrolled students through a university course. The additional training sessions consisted of one 15-20 minute workout per week. The training protocol was low to moderate in volume,

and was consistent with what has been previously utilized for recreational athletes in prior studies (Lathrop et al., 2001; Turner et al., 2003). The CORE workouts matched for time and approximate number of repetitions, but movements were performed at slow-to-moderate velocity, and were focused on abdominal, back, and hip strength. For both groups, the additional training was progressive in nature, beginning with a lower number of repetitions and sets in the early sessions, and increasing gradually over the course of the training program. The outcomes assessed were the following:

1. Sprint and jump performance: vertical jump (VJ), 60-m run (60M), 200-m run (200M), flying 30-m run (30FLY), 10-bound test (10BD), and standing long jump (SLJ).
2. Distance running performance: 2-mile time trial (2MI), 26.2 mile marathon (MARA), VO_{2MAX} , and running economy (RE) and respiratory exchange ratio (RER) during a sub-maximal 30-minute run.

Testing was done in the week prior to the commencement of the 12-week training intervention and within a week of the final training session, with the exception of the VO_{2MAX} test, which was done prior to the initiation of the run-in period (6-8 weeks prior to the commencement of the training intervention), and during week 11 of the training intervention. All students in the class do a VO_{2MAX} test prior to the beginning the running training, and near the end of the course. These values were used rather than requiring an additional lab visit and VO_{2MAX} test.

Participants.

Healthy young adults enrolled in a marathon training course were recruited to participate in a 12-week exercise intervention to be done concurrently with a marathon training program. A study coordinator emailed all students and then conducted information sessions for interested students. Inclusion criteria were:

1. Enrollment in the University of Minnesota PE 1262 Marathon Training course, which requires a physical and physician's approval for participation.
2. Willingness to commit to an extra 15-20 minute training session once per week.
3. Willingness to be randomized into one of two exercise groups.

Exclusion criteria were any pre-existing conditions, such as a muscle or tendon injury, history of injury, or any other health condition that would indicate against the completion of either the PLYO or CORE protocol. Information sessions were conducted prior to enrollment, in order to explain the nature of the study and attendant risks, and to answer any questions from potential subjects. Consent was obtained prior to any testing or training sessions. All procedures and protocols were approved by the Institutional Review Board at the University of Minnesota.

A total of 26 subjects were enrolled and randomized, with randomization carried out separately for males and females in order to achieve balance between the groups by sex. Block randomization, with blocks of four, was used to minimize the possibility of unbalanced allocation. Two subjects, one from each group, dropped the course early in the semester and were excluded from the study. One of these subjects did experience quadriceps pain during the sprint and jump pre-testing. The subject returned another

day and successfully complete testing, and was randomized to PLYO. His reason for dropping the course is unknown. The other subject struggled with injury and other health issues, apparently unrelated to the CORE training, and dropped the course.

A quasi-intention-to-treat analysis was done, with two subjects (one from each group) being excluded from the analysis due to missing over half of the sessions for reasons unrelated to training or health (personal issues and class absences). One other subject in the PLYO group missed over half of the sessions, but cited knee pain as her reason for not wanting to complete the rest of the training sessions. In the spirit of the intention-to-treat analysis, she was included, as the pain could possibly have been related to completion of the training; she did report being sore for several days after the PLYO sessions.

The subjects ranged from 18 to 23 years of age. The two groups were very similar in age (CORE: 19.8 ± 1.3 years; PLYO: 20.8 ± 1.3 years) and sessions completed (CORE: 10.8 ± 1.5 sessions; PLYO: 10.6 ± 2.0 sessions). Analysis of training logs after the completion of the study confirmed that the groups ran similar total mileage for the marathon training period (CORE: 474 ± 115 miles; PLYO: 500 ± 98 miles). Descriptive data are shown in Table 1.

	PLYO	CORE
N	11	11
Sex	7F, 4M	5F, 6M
Age (years)	20.8 ± 1.3	19.8 ± 1.3
Running mileage	500 ± 98	474 ± 115
Training sessions	10.6 ± 2.0	10.8 ± 1.5

Table 1. Descriptive data of subjects by group. Age, mileage, and training session are reported as means ± S.D.

Subjects were encouraged to complete all training sessions and exercises if possible, but were advised that they could stop participation in one or all parts of the study at any point and for any reason. If a training exercise caused sharp pain, injury or discomfort beyond what the subject was accustomed to, they were instructed to cease the exercise and inform research staff. Subjects who missed part or all of a training session were asked to report their reason for the missed session.

Training.

Training sessions were conducted once per week, after a Wednesday class session that included a run of approximately 40 minutes, with a variety of workouts commonly done by distance runners including tempo runs, hill repeats, and fartlek runs. Upon returning from the run, subjects had 10-15 minutes to recover, drink and/or eat a small snack. All sessions were supervised, except for week 7, which fell during the student's spring break. Research staff provided instructions and assistance with proper form and safe execution of exercises. For the one unsupervised session, subjects were

sent a reminder email to complete their prescribed training and at their next training session, they were asked to report whether or not they completed the training.

The training intervention consisted of a PLYO group that performed a series of 6 jumping and sprinting exercises per session, with 1-3 sets of 8-20 reps per exercise in the case of the jumping exercises, and 2-4 reps of the sprinting exercises. Exercises alternated every other week. Odd week exercises were 50-m build-up, 30-m fly, standing long jump, alternate leg bound, single leg forward hop, and squat jumps. Even week exercises were 60-m sprint, in-and-out sprint with two 10-m fly zones, lateral cone jumps, forward-and-backward cone jumps, lunge jumps, and either depth jumps or box jumps. Specifics of the PLYO protocol are shown in Table 2.

CAT		SPR	SPR	SPR	SPR	HOR	HOR	HOR	HOR	HOR	VERT	VERT	VERT	VERT
Sess. #	Date	50-m Build	30-m Fly	60-m spr.	In-n-Out	Frog Hops	Alt. Leg Bound	S.Leg Fwd Hop	Lat. Cone Jumps	F/B Cone Jumps	Squat Jump	Split Scissor Jump	Depth Jump	Box Jump
1	5-Feb	2	2			1x10	2x10	1x8			1x10			
2	12-Feb			2	2				1x10	1x10		1x10	1x8	
3	19-Feb	3	3			2x8	2x15	1x12			2x8			
4	26-Feb			3	3				1x15	1x15		2x8	1x12	
5	5-Mar	3	3			2x10	2x20	2x10			2x10			
6	12-Mar			3	3				2x10	2x10		2x10	1x15	
7	19-Mar	4	4			2x15	3x15	2x12			2x15			
8	26-Mar			4	4				2x15	2x15		2x15		1x10
9	2-Apr	4	4			2x15	3x20	2x15			2x15			
10	9-Apr			4	4				2x20	2x20		2x15		1x15
11	16-Apr	3	3			1x20	2x20	1x20			1x20			
12	23-Apr			2	2				1x20	1x20		1x20		1x10

Table 2. Week-by-week breakdown of the specific number of sets and repetitions for the PLYO training protocol. SPR = sprint exercise. HOR = horizontal jump exercise. VERT = vertical jump exercise.

The CORE group also did six exercises per week with exercises alternating on a weekly basis. Exercises focused on the abdominal, back, hip, and gluteal muscles. The routine consisted of 1-3 sets of 10-30 reps per exercise or 30-60 seconds for the isometric exercises (planks and side planks). Odd week exercises were crunches, sit-ups, supermans, planks, fire hydrants, and bridges. Even week exercises were side crunches, v-sits, back-ups, side planks, Swiss Ball adductors, and bird dogs. The CORE protocol is shown in Table 3.

CAT		ABS	ABS	ABS	ABS	BACK	BACK	BACK	BACK	HIP/GL	HIP/GL	HIP/GL	HIP/GL
Sess. #	Date	Crunch	Side crunch	Sit-ups	V-Sits	Super-man	Back-Ups	Plank	Side Plank	Fire Hydrant	Sw. Ball Adductors	Bridging	Bird Dog
1	5-Feb	1x20		1x20		1x20		30s		1x20		1x20	
2	12-Feb		1x20		1x20		1x10		30s		1x20		1x20
3	19-Feb	1x30		1x30		1x30		45s		1x30		1x30	
4	26-Feb		1x30		1x30		1x15		45s		1x30		1x30
5	5-Mar	2x20		2x20		2x20		60s		2x20		2x20	
6	12-Mar		2x20		2x20		2x10		60s		2x20		2x20
7	19-Mar	2x30		2x30		2x30		2x45s		2x30		2x30	
8	26-Mar		2x30		2x30		2x15		2x45s		2x30		2x30
9	2-Apr	3x30		3x30		3x30		2x60s		3x30		3x30	
10	9-Apr		3x30		3x30		3x15		2x60s		3x30		3x30
11	16-Apr	2x30		2x30		2x30		60s		2x30		2x30	
12	23-Apr		2x30		2x30		2x15		60s		2x30		2x30

Table 3. Week-by-week breakdown of the specific number of sets and repetitions for the CORE training protocol. ABS = abdominal exercise. BACK = back exercise. HIP/GL = hip or gluteal exercise.

For both groups, all exercises were performed with body weight only, with no external resistance or assistance. Approximately one minute of recovery was given between all sets and exercises, with more recovery time allowed.

The marathon training program performed by both groups as part of the university course consisted of a 5 month progressive build-up of mileage, with no

difference in the total volume between the groups. Students ran 4-5 days per week, with an average weekly mileage of 20-25 miles and a peak of 35-40 miles. Long runs were done weekly, and built up to 20 miles by the peak training period. Included in the 5 month build-up, subjects underwent 6 weeks of training that served as a run-in period and allowed standardization of training status prior to the beginning of the study. Week 1 training consisted of 90 minutes of running, building to 160 minutes by Week 6.

Data Collection Procedures.

Anthropometric characteristics

Height and weight were measured pre- and post-, prior to the treadmill RE test. Subjects removed footwear, and height was measured to the nearest $\frac{1}{4}$ inch using an Accustat Genentech Stadiometer (San Francisco, CA). Weight was measured in pounds to the nearest tenth using a ProDoc Detecto (PD300) scale (Webb City, MO). During weighing, subjects wore light, minimal clothing, such as running shorts or half-tights and a jog-bra for women.

Sub-maximal 30-minute running test and VO_{2MAX} test

For the submaximal running test, subjects ran on a motorized Woodway Pro XL 27 treadmill (Waukesha, WI) for a total of 33 continuous minutes, including a 3-minute warm-up and 6 stages of 5-minutes each. They were advised to follow a dietary regiment similar to that which they typically use prior to a race or challenging workout. Stages were calculated off recent 2-mile time trial finish time. The warm-up was done at 63% of 2-mile velocity, and the 6 stages of 5 minutes each were at 68%, 73%, 78%, 83%,

88%, and 93% of 2-mile velocity. The final stage velocity is equivalent to a predicted 10k velocity, based on commonly utilized race pace conversion charts (Daniels, 2013).

Though this was not meant to be a maximal effort, the duration and intensity were moderately challenging. Research staff emphasized that if at any point the subject wished to stop the test, he or she was free to do so, by stepping on the rails of the treadmill or by hitting the stop button. A face mask and pneumatech were worn for gas analysis via Ultima CPX metabolic cart (MCG Diagnostics, St. Paul, MN). Standard calibration procedures were used prior to each testing session. In order to assess metabolic response to exercise of moderate duration over a range of sub-maximal paces, RER and RE in ml/kg/km were calculated by taking average values over the 30 minutes. Stage-by-stage analysis was considered, but shed no additional light on the variables of interest.

For the sub-maximal running test, there were 3 subjects who stopped during the final 5 minute stage (2 from the CORE group and 1 from the PLYO group) and one subject (PLYO group) whose test was stopped when the metabolic cart lost power partway through the final stage of the test. For those subjects, the values obtained during the completed portion of the final stage were averaged and extended to the full 5 minutes to avoid any skewing of the data due to failure to run the full final stage.

The VO_{2MAX} test was performed with the same treadmill and metabolic cart during a separate visit, and the same procedures were used for height and weight. After an initial 6-minute warm-up at 65% of the subjects initial 2-mile test velocity, a

graduated protocol was utilized, with velocity increasing up to 2-mile velocity at 1.0% incline, and then increasing in incline by 1.5% each minute until volitional exhaustion was reached.

Running performance assessment

The 2-mile time trials (2MI) were conducted as part of the PE 1262 Marathon Training course curriculum, as was the 26.2 mile marathon run (MARA). The 2MI runs were held on a 200-m indoor track. Each subject ran 16 laps plus the additional 18 meters to make the run 2 miles. Each runner had an assigned lap counter who tracked laps and marked the completion of each lap, as well as recording 1-mile split time and 2-mile finish time. Finish times were collected immediately and entered into a data tracking sheet. The pre-test 2MI was completed at the start of the marathon training class, after the run-in period, but prior to the initiation of the training intervention. The post-test was completed near the conclusion of the training intervention, 10 days prior to the MARA. The MARA was run on a certified course as part of an event open to the general public. Chip times were gathered from online race results, and training logs were used to confirm the accuracy of the times. Research staff were also on hand to confirm finish times in order to minimize the possibility of timing errors. Predicted marathon time was calculated from the post-test 2MI, using the RunSmart online calculator, which is based on previously published race time predictor charts (Daniels & Gilbert, 1979). Difference between actual and predicted MARA time is reported as a percentage.

Sprint and jump testing

Sprint and jump tests consisted of the following, performed in this order: flying 30-m run with a 20-m acceleration zone (30FLY), standing long jump (SLJ), 60-m run (60M), the 10-bound test (10BD)—a series of 10 alternate leg strides with the goal of covering as much distance as possible) and 200-m run (200M). A standard warm-up, including a 5 minute jog, and 10 minutes of dynamic warm-up drills and accelerations, was performed prior to the commencement of testing.

The sprint tests were timed electronically using Brower Timing Systems TC-Timing wireless timing gates (Draper, UT). The 30FLY was timed using two sets of timing gates. The 60M and 200M were timed using the touchpad starter, set to start on release, and one set of timing gates. The 60M was run on the straightaway, and the 200M was run in the outside lane (Lane 6) of the indoor track to reduce the severity of the curve. The 10BD was performed on an indoor track surface on the long jump runway, and the SLJ was done into a standard sand landing pit at the indoor track facility. Jump measurements were taken using a fiberglass measuring tape (Empire, Mukwonago, WI) with two researchers spotting and measuring. Distances of all trials were recorded immediately by research staff. Distance was measured from the scratch line to furthest back point of contact upon landing (in most cases, the heel). Distance was measured to the nearest half inch for the SLJ, and to the nearest inch for the 10BD. An additional research staff member was on hand in addition to the pair that did the measuring, in order to double-check any markings.

Subjects were given 3 attempts to produce maximal efforts in the jumps, with at least 1 minute of rest between attempts, and at least 3 minutes between tests. They were given a single attempt in each of the sprints, to minimize the effect of fatigue. The 200M was done last as it was likely produce greater fatigue than the other tests. In case of a problem with the timing equipment in any of the sprint tests, the subject was recalled, given adequate rest, and allowed another attempt. All timing and measurement procedures were performed consistently and were the same for pre- and post-testing.

On a separate visit, prior to the submaximal 30-minute running test, vertical jump (VJ) was assessed using the Vertec Jump and Reach system (Huntington Beach, CA). Subjects performed a self-paced 5 minute warm-up jog and were given the opportunity to perform practice jumps. Three minutes of rest was taken between the warm-up and the VJ.

Calibration of the Vertec was done for each subject. Subjects performed 3-6 maximal effort countermovement jumps with stationary feet, with at least 30 seconds of rest in between attempts. Jump height to the nearest $\frac{1}{2}$ inch was recorded for all jumps. Subjects were asked to perform at least three attempts, and to continue until they failed to improve on two consecutive attempts, with a maximum of 6 jumps allowed.

Statistical Analysis.

Statistical analysis was done using SPSS, Version 21. Means and standard deviations were calculated for each measure using standard methods. The two groups of related dependent variables, sprint/jump performance and distance running performance, were assessed separately using MANOVA. Baseline measures were analyzed using independent samples t-tests to detect differences between the groups before the intervention. Paired samples t-tests were used to assess changes from baseline by group.

Data were tested for normality and homoscedasticity using the Shapiro-Wilk and Levene tests. Pre-test 30FLY violated normality according to the Shapiro-Wilk test ($p=0.033$), as did post-test RE ($p=0.005$) and post-test RER ($p=0.037$). Post-test RER also violated the assumption of homoscedasticity, according to the Levene test ($p=0.019$), while all other variables showed a normal distribution and homogeneity of variance. Non-normal variables were not transformed prior to MANOVA, as all other sprint, jump, distance running and anthropomorphic variables were normal, and MANOVA is considered robust against small violations of normality. For the baseline measures, paired samples t-tests were compared with Wilcoxon Signed Rank tests for 30FLY, RER, and RE, and as the non-parametric test yielded very similar results, t-test p-values were used for all variables for the sake of consistency.

Between groups analysis on the dependent variables was calculated based on percent change from baseline. Percent change was used rather than the raw data in order to capture changes accurately for this heterogeneous group. The percent change

values were also tested for normality and homoscedasticity. When examined on percent change, 10BD ($p=0.031$), VJ ($p=0.027$), and RE ($p\leq 0.001$) were non-normally distributed. Follow-up analysis of normally distributed variables was done using independent samples t-tests, while non-normally distributed variables were tested using the Mann-Whitney U Test.

An exploratory MANOVA was run to assess differences in the effect of training by sex and performance level. Performance level was determined based on pre-test 2 mile time, with the top 6 males and females being assigned to the FAST group, and the remainder (7 females and 5 males) being assigned to the SLOW group. The cut-points were 12.5 minutes for men and 15.5 minutes for women. Univariate ANOVA was also used in select variables for post-hoc analysis to explore for interactions by performance level and sex.

Results

Baseline analysis revealed no differences between groups, though there was a trend toward lower BM in the PLYO group ($p=0.063$). Results are presented in Tables 4 (sprint and jump variables) and 5 (distance running performance variables), along with post-test values and percent change, for the whole group, as well as for men and women separately.

Variable		CORE (n=11, 5 women)			PLYO (n=11, 7 women)			p-value
		Pre-	Post-	% change	Pre-	Post-	% change	
200M (sec.)	All	34.28 ± 5.39	33.78 ± 4.89	-1.3 ± 3.0	36.52 ± 6.24	34.64 ± 6.46†	-5.8 ± 3.7‡	0.006
	Men	29.94 ± 1.27	29.88 ± 1.71	-0.3 ± 3.5	31.64 ± 4.52	29.20 ± 4.81	-8.6 ± 2.5	
	Women	39.49 ± 2.92	38.47 ± 2.41	-2.6 ± 1.9	39.31 ± 5.45	37.75 ± 5.19	-4.1 ± 3.3	
60M (sec.)	All	9.83 ± 1.40	9.67 ± 1.19	-1.8 ± 7.2	10.45 ± 1.37	9.88 ± 1.51†	-6.2 ± 6.9	0.154
	Men	8.74 ± 0.55	8.82 ± 0.89	0.4 ± 9.0	9.54 ± 1.08	8.59 ± 0.79	-11.1 ± 8.6	
	Women	11.15 ± 0.74	10.69 ± 0.44	-4.3 ± 3.9	10.97 ± 1.29	10.62 ± 1.33	-3.4 ± 4.2	
30FLY (sec.)	All	4.23 ± 0.77	4.20 ± 0.56	-0.3 ± 6.1	4.44 ± 0.72	4.31 ± 0.67	-3.0 ± 2.9	0.191
	Men	3.66 ± 0.20	3.78 ± 0.30	3.0 ± 3.0	3.84 ± 0.38	3.72 ± 0.30	-3.3 ± 3.0	
	Women	4.91 ± 0.60	4.71 ± 0.30	-4.2 ± 7.0	4.78 ± 0.65	4.64 ± 0.57	-2.9 ± 3.4	
SLJ (in.)	All	87.3 ± 21.1	83.3 ± 17.8	-4.5 ± 7.6	78.1 ± 16.3	79.5 ± 15.1	1.9 ± 4.1‡	0.024
	Men	103.2 ± 14.1	96.6 ± 11.0	-6.9 ± 8.3	93.5 ± 15.6	94.6 ± 11.3	1.7 ± 5.5	
	Women	68.2 ± 5.3	67.4 ± 7.7	-1.6 ± 6.3	69.4 ± 8.6	70.8 ± 8.6	2.0 ± 3.6	
10BD (ft.)	All	70.4 ± 10.4	67.8 ± 10.9	-4.2 ± 7.6	65.0 ± 8.4	64.9 ± 9.0	-0.5 ± 6.9	p = 0.332
	Men	78.1 ± 6.5	74.7 ± 10.4	-5.4 ± 8.4	73.1 ± 5.9	74.4 ± 4.1	1.8 ± 5.6	
	Women	61.2 ± 5.0	59.5 ± 2.1	-2.8 ± 7.2	60.4 ± 5.7	59.4 ± 5.7	-1.9 ± 7.6	
VJ (in.)	All	22.7 ± 7.6	21.8 ± 5.6	-3.0 ± 8.2	20.2 ± 5.0	19.8 ± 4.5	-1.6 ± 6.1	p = 0.847
	Men	28.3 ± 5.8	26.1 ± 3.4	-8.0 ± 13.3	25.4 ± 3.0	24.3 ± 3.9	-5.6 ± 10.9	
	Women	16.1 ± 1.5	16.7 ± 2.3	3.0 ± 8.2	17.2 ± 2.9	17.3 ± 2.5	0.7 ± 4.6	

Table 4. Pre- and post-training sprint and jump performance variables. All results are ± S.D. P-values are two-tailed, based on t-tests of % change by group.

†Significantly different from baseline. ‡Significantly different from CORE group.

Variable		CORE (n=11, 5 women)			PLYO (n=11, 7 women)			Sig.
		Pre-	Post-	% change	Pre-	Post-	% change	
VO ₂ MAX (ml/kg/min)	All	53.6 ± 8.3	57.4 ± 7.5†	6.5 ± 7.9	50.5 ± 8.8	57.8 ± 8.3†	12.5 ± 9.7	p = 0.124
	Men	59.1 ± 6.4	62.2 ± 5.6	4.7 ± 10.6	55.2 ± 13.0	65.4 ± 4.7	16.2 ± 14.5	
	Women	47.1 ± 4.7	51.5 ± 4.9	8.7 ± 2.3	47.7 ± 4.3	53.5 ± 6.6	10.4 ± 5.4	
2 mile TT (min.)	All	14.0 ± 2.0	13.3 ± 1.7†	-5.1 ± 2.2	14.7 ± 2.4	14.0 ± 2.3†	-4.3 ± 3.1	p = 0.521
	Men	12.8 ± 0.9	12.1 ± 0.8	-5.0 ± 2.3	12.5 ± 2.2	12.2 ± 2.5	-2.6 ± 3.1	
	Women	15.5 ± 2.0	14.7 ± 1.5	-5.3 ± 2.3	16.0 ± 1.3	15.1 ± 1.4	-5.4 ± 2.8	
Marathon (min) (predicted vs. actual)	All	202.5 ± 25.0	237.1 ± 31.6†	14.5 ± 4.0	213.9 ± 33.5	255.5 ± 66.2†	14.0 ± 10.2	p = 0.891
	Men	185.7 ± 12.1	217.8 ± 14.2	14.7 ± 3.9	186.6 ± 36.8	218.7 ± 91.2	10.1 ± 14.8	
	Women	222.7 ± 21.3	260.4 ± 31.7	14.2 ± 4.5	229.5 ± 20.3	276.5 ± 41.5	16.2 ± 7.0	
Body Mass (Kg)	All	73.5 ± 9.6	72.9 ± 9.6	-0.9 ± 3.0	65.8 ± 8.5	65.8 ± 7.8	0.0 ± 3.5	p = 0.510
	Men	79.8 ± 8.0	79.9 ± 6.5	0.2 ± 3.2	71.8 ± 4.8	71.5 ± 1.8	-0.4 ± 4.4	
	Women	65.9 ± 4.4	64.5 ± 3.8	-2.2 ± 2.6	62.4 ± 8.5	62.5 ± 8.1	0.2 ± 1.9	
RE (ml/kg/km)	All	218.6 ± 19.4	192.9 ± 37.0†	-16.5 ± 20.5	216.3 ± 17.9	200.2 ± 29.5†	-9.6 ± 13.2	p = 0.519
	Men	219.9 ± 18.7	193.7 ± 36.0	-16.0 ± 16.6	211.9 ± 17.3	198.4 ± 24.7	-7.3 ± 6.5	
	Women	217.1 ± 22.3	192.0 ± 42.3	-17.2 ± 26.5	218.8 ± 19.0	201.2 ± 33.7	-10.9 ± 16.3	
RER	All	1.031 ± 0.048	1.049 ± 0.096	1.3 ± 6.3	1.028 ± 0.048	0.997 ± 0.045	-3.4 ± 6.7	p = 0.112
	Men	1.047 ± 0.054	1.105 ± 0.087	4.9 ± 6.1	1.023 ± 0.041	1.013 ± 0.038	-1.1 ± 4.0	
	Women	1.012 ± 0.035	0.982 ± 0.058	-3.1 ± 2.9	1.031 ± 0.054	0.988 ± 0.049	-4.7 ± 7.9	

Table 5. Pre- and post-training distance running performance variables. All results are ± S.D. P-values are two-tailed, based on t-tests of % change by group.

†Significantly different from baseline.

Assessment with MANOVA found that there was an effect of training group on the dependent variables related to sprint and jump performance (30FLY, SLJ, 60M, 10BD, 200M, VJ). Pillai's Trace Test Statistic showed a significant interaction effect between test, time and training group ($p=0.045$). Levene's Test of Equality of Error Variances was non-significant for all measures, indicating that homogeneity of variance was satisfied. Dependent variables associated with distance running performance (VO_{2MAX} , BM, RE, RER, 2-MILE, and MP) were also assessed with MANOVA, and Pillai's Trace Test Statistic found no significant interaction between test, time and training group for these measures ($p=0.691$). Though there was no group effect on distance running performance measures, the outcomes are reported and discussed below.

Paired sample t-tests found that the CORE group did not change from baseline in any of the sprint or jump variables, but had a trend toward a decrement in performance in the SLJ ($p = 0.067$). On the other hand, the PLYO group improved in both the 200M ($p \leq 0.001$) and 60M ($p = 0.004$), and showed a strong trend toward improvement in the 30MFLY ($p = 0.051$). In the distance running performance variables, both groups improved in 2MI ($p \leq 0.001$), VO_{2MAX} ($p = 0.026$ for CORE vs. $p = 0.002$ for PLYO), and RE ($p = 0.01$). Both groups were also significantly slower ($p \leq 0.001$ for CORE vs. $p = 0.004$ for PLYO) than predicted in the marathon, based on their 2MI results.

Univariate tests (independent t-tests for normally distributed variables and Mann-Whitney U Test for non-normally distributed variables) of percent change showed a significant difference between the PLYO and CORE groups in the 200M ($p = 0.006$) and

the SLJ ($p = 0.024$). The PLYO group improved 5.7% compared to 1.3% for the CORE group in the 200M. The PLYO group improved more than the CORE group in the other sprint variables, but the differences were not significant: a 6.2 vs. 1.8% improvement in the 60M ($p = 0.154$) and a 3.0 vs. 0.3% improvement in the 30MFLY ($p = 0.191$). Changes in sprint performance by group are shown below in Figure 1.

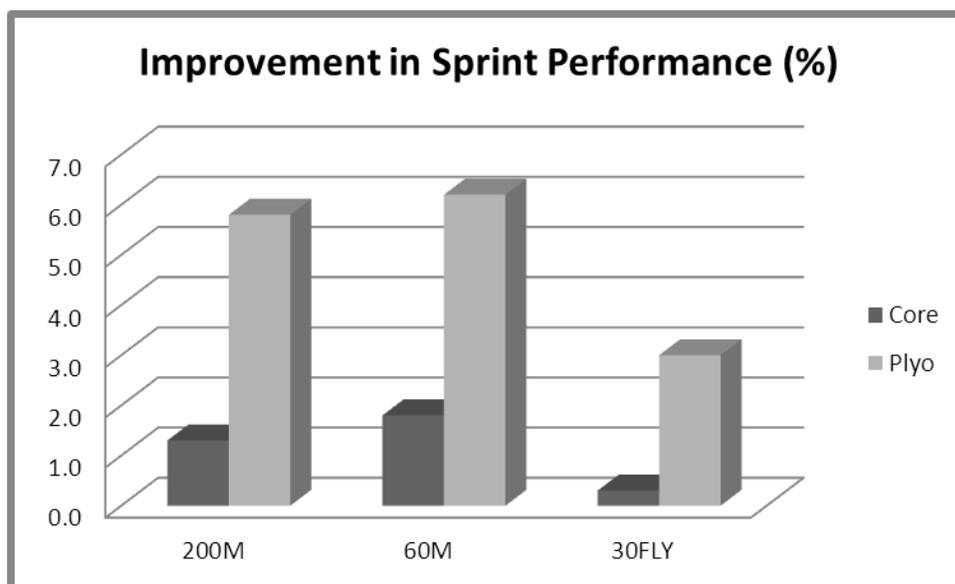


Figure 1. Percentage improvement in sprint performance by group for the 200M, 60M, and 30MFLY.

In all of the jump variables, the CORE group decreased in jump distance or height, whereas the PLYO group increased slightly or decreased less than the CORE group. In the SLJ, the PLYO group improved 1.9% vs. 4.5% decrease in the CORE group ($p = 0.024$). In the 10BD and VJ, both groups decreased, but the PLYO group decreased less than the core group. For the 10BD, the PLYO group decreased 0.5% vs. 4.2% decrease in

the CORE group ($p = 0.332$). In the VJ, the PLYO group decreased 1.6% vs. 3.0% decrease in the CORE group ($p = 0.847$).

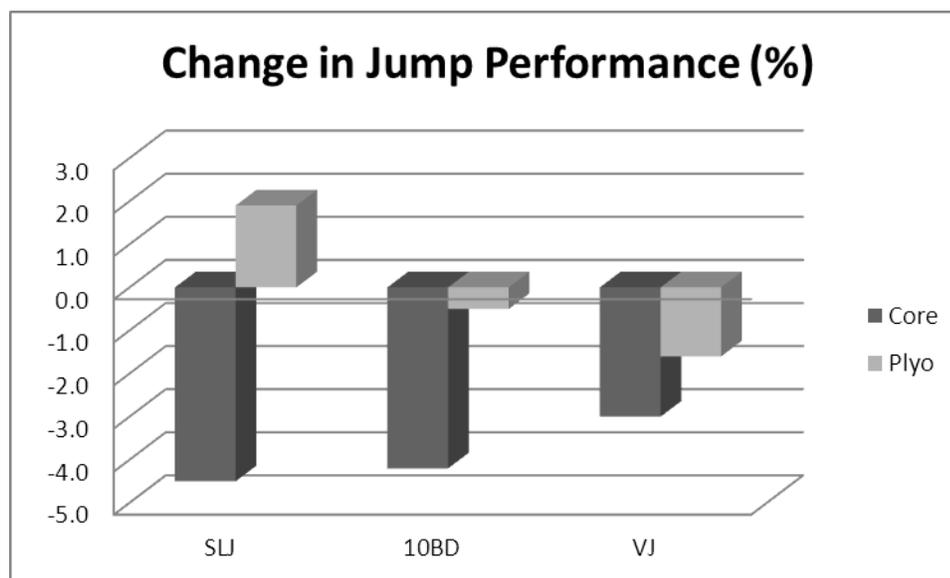


Figure 2. Percentage change in jump performance by group for the SLJ, 10BD, and VJ.

The univariate tests related to running performance, which would need to be interpreted with caution, given the failure to reject the null hypothesis of a difference between groups in MANOVA, did not find any significant differences between the groups. Nonetheless, some interesting trends were observed that may warrant further investigation. In the 2MI, improvements were very similar between the groups, with the CORE group improving by 5.1 vs. 4.3% in the PLYO group ($p = 0.521$). Marathon time as a function of predicted times were also very similar between the groups, with the PLYO group running 14.0% slower than predicted vs. the CORE group running 14.5% slower ($p = 0.891$). Body mass was also very similar between the groups, with the CORE group

losing 0.9% vs. 0.0% (no change) in the PLYO group ($p = 0.510$). There was no difference in the change in RE between the groups, with CORE improving by 16.5% and the PLYO group improving by 9.6% ($p = 0.519$).

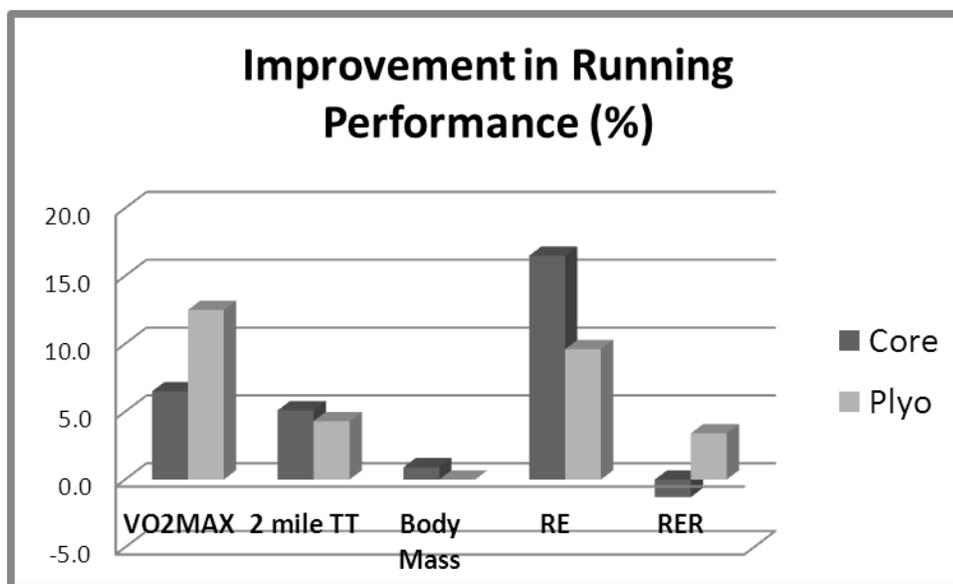


Figure 3. Percentage improvement by group in distance running performance variables: VO₂MAX, 2MI, BM, RE, and RER. Reductions in 2MI, BM, RE (per km), and RER are inverted here in a positive direction, so that all positive percentages indicate adaptations consistent with improvement in running performance.

Non-significant, but potentially positive adaptations from the PLYO training were observed in VO₂MAX and RER. In VO₂MAX, the PLYO group improved by 12.5% vs. 6.5% in the CORE group ($p = 0.124$). Average RER dropped by 3.4% vs. an increase of 1.3% in the CORE group ($p = 0.112$). While neither of these changes were statistically significant, they may warrant further research.

With respect to sex differences in response to the training intervention, no interaction of test, time, training group and sex was seen for either set of variables:

sprint and jump performance ($p=0.283$) or distance running performance ($p=0.619$). Results for all tests are reported by sex, but men and women were pooled for analysis. Similarly, stratification between FAST and SLOW groups revealed no interaction between test, time, training group and performance level for sprint and jump ($p=0.569$) or distance running performance ($p=0.551$). Researchers observed that the three fastest and two slowest finishers from the study in the marathon were from the PLYO group. As an exploratory exercise, a univariate ANOVA of percent difference from predicted marathon time was performed, by performance level and training group. This analysis showed a significant interaction between training group and performance level ($p = 0.047$).

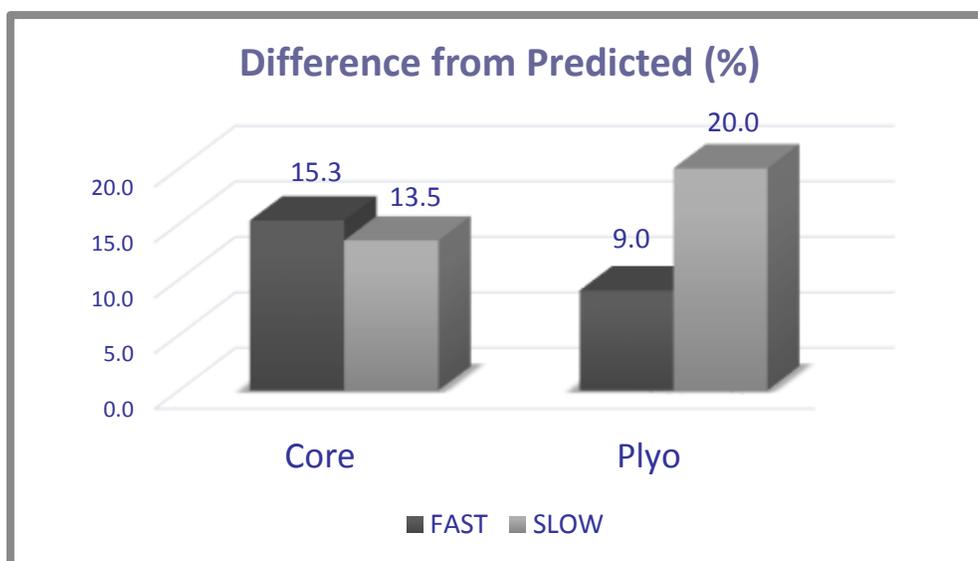


Figure 4. Percent slower than predicted in the marathon, based off 2MI performance, by group and performance level.

Discussion

This study examined the effects of a 12-week PLYO training program on sprint and jump performance, and distance running performance in a population of recreational marathon runners. This study was novel in examining this type of training for marathon runners. While marathon training and PLYO training have very different physiological aims, it appears that among this population, beneficial adaptations specific to both types of training can be made when training is done concurrently over a 12-week period.

Sprint performance improved and jump performance was maintained in the PLYO group, whereas the CORE group did not change in sprint performance, and decreased in measures of jump performance. The frequency and volume of PLYO training was relatively low in comparison with other studies (Paavolainen et al., 1999; Ramirez-Campillo et al., 2014; Spurrs et al., 2003; Turner et al., 2003). Other studies of PLYO for distance runners have all targeted a population training for shorter races (up to 5-km). The lower frequency and volume of training in this program was intentionally conservative, as the primary concern for this population was completion of the marathon, and not to maximize speed and/or power gains. However, it appears that this low volume was effective in improving speed and maintaining jumping performance. Greater improvements may be possible with a more aggressive training protocol in those who are able to tolerate such a program. Intermittent testing and monitoring throughout the training period could also be considered, with volume and frequency adjusted based on individual adaptation and tolerance for training.

Another possible factor to consider is the timing of the training sessions.

Plyometric training typically is considered highly stressful and is thus recommended to be performed by athletes who are in a well-rested state (Radcliffe & Farentinos, 1999; Yessis, 2000). Subjects in this study performed their training sessions shortly after a relatively short, but moderate-to-high intensity running workout. This was done to improve recruitment and compliance, as well as to maximize temporal distance from the weekly long run, but it is possible that the fatigue from running may have compromised the efficacy of the PLYO intervention, particularly with respect to power development and jump performance.

The failure of the PLYO training to produce an improvement in jump variables is somewhat surprising given the abundance of literature on PLYO training and improved jump performance (Saéz-saez de Villarreal et al., 2009). The two dropouts and two exclusions from analysis led to an imbalance between men and women in the groups, with only four men in the PLYO group and six in the CORE group. Given the evidence that women may not have the same magnitude of response to PLYO training, specifically in terms of jump performance (Saéz-saez de Villarreal et al., 2009), this could have reduced the power of the present study to find differences between the groups, though no interaction between sex and training group was detected. The lack of improvement in jump variables in the PLYO group could also suggest that a greater frequency or volume of jump training would be beneficial. On the other hand, the volume of sprint training appeared adequate to produce significant change. The fact that the CORE group

experienced a decrement in jump performance, while the PLYO group maintained jumping ability does suggest a positive effect of PLYO training on muscular function. The risks and benefits of increasing the volume or frequency of jump training are not clear, and should be implemented with caution in this population.

Among this population, adaptations made through PLYO training did not transfer to improved distance running performance. Unlike other studies that have shown improved time trial performance in 3k to 5k distances and/or improved RE (Paavolainen et al., 1999; Ramirez-Campillo et al., 2014; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003), this study found no difference in 2MI performance or RE between the groups. In fact, the CORE group improved more in RE, though the difference was not significant. The lack of an effect on distance running performance may be due to a number of factors. First, and perhaps most importantly, is the dramatic change in running performance experienced by the group as a whole due to the demanding nature of the marathon training program. The magnitude of changes seen in all participants in response to the running training performed as part of the marathon class may have obscured any impact on distance running performance from the PLYO or CORE training intervention. The lack of an effect of training group on distance running performance is not entirely surprising, as any adaptation to a 15-20 minute weekly session would be expected to be very small in contrast with the relatively high volume running training performed by both groups. Indeed the effect of time on the distance running performance variables was significant ($p \leq 0.001$) for the whole population. None of the

other studies cited above implemented increases in running training volume. While the 6-week run-in period in this study represented an attempt to reduce the magnitude of changes due to the running training, the marathon training program required long runs of up to 20 miles, whereas the run-in period had no runs longer than 8 miles. Another study that found no effect of PLYO on RE, 3200-m run or VO_{2MAX} involved high school cross country runners during their summer training (Lathrop et al., 2001). While miles per week at the initiation of the study were not reported, the average participant had run in less than five of the previous six weeks, and then averaged between 25-30 miles per week during the study. Both the experimental and control group improved RE and 3200-m performance, but there was no effect of training group. In the discussion, the researchers cite the low mileage and relative inexperience (average of less than 3 years of running experience) of their study population as possible reasons for not finding effects from the PLYO training. The use of a more highly trained at baseline, or more experienced population may facilitate a clearer picture of the effect of PLYO training on distance running performance variables in marathon runners.

The slower than predicted MARA performances across groups can likely be attributed to two factors: (1) the population of inexperienced marathoners, and (2) the challenges (hills, environmental conditions) of road running versus the indoor track, where the 2-mile used to calculate predicted marathon time was run.

The challenges and limitations of measuring performance in a recreational group of runners is another consideration and limitation of the present study. Though the

subjects were instructed to give their best effort in the 2MI, it seems plausible that recreational runners may not run as near their physiological capabilities as competitive runners. It is also possible that inadequate recovery from a very long training run, held 3 days prior to the 2MI, limited the subjects' ability to run as fast as they may have. However, there was a significant improvement from baseline across both groups. The timing of the 2MI, while not ideal, was necessary given the need to schedule three other testing visits, all of which were somewhat demanding, while allowing subjects adequate time to rest and taper for the marathon. Ideal assessment on any of these outcomes would have involved a full taper prior to testing, but that was not feasible in this case.

The phenomenon of the three subjects failing to complete the sub-maximal test may also indicate some degree of lingering fatigue, either physical or psychological. The early termination of this test may have some relevance relative to distance running performance, but clearly it did not occur with enough frequency to make any statements about differences between groups or factors that may contribute to an inability to complete this particular test.

The trend toward lower RER and higher VO_{2MAX} in the PLYO group warrants further investigation. While VO_{2MAX} has not been shown to improve from PLYO training in runners (Lathrop et al., 2001; Paavolainen et al., 1999; Saunders et al., 2006; Spurrs et al., 2003; Turner et al., 2003), it may be possible, particularly in this more recreational population that is unaccustomed to higher intensity training. While one of the above studies did use average runners (Turner et al., 2003), many of the exercises included in

the program were either intermittent or sub-maximal (thus arguably outside of the standard definition of plyometric), and no explosive speed training was included. Studies on untrained athletes have shown increases in VO_{2MAX} with high intensity muscular strength exercise (McCarthy et al., 1995; Stone et al., 1983). Short, high intensity interval training has been shown to elicit favorable metabolic adaptations such as increased fat utilization (Burgomaster et al., 2008; Gibala, 2006). The trend toward lower RER (and increased fat metabolism) may be reflective of similar adaptations. Larger studies, or studies in more homogeneous groups designed to specifically address these questions may shed more light on these observed trends.

The post-hoc analysis showing a significant interaction between marathon finish time, training group, and performance level clearly should be interpreted with caution. However, it does suggest that a more pointed study of the effects of PLYO training on competitive marathoners is warranted. It is possible that a baseline level of distance running ability is an important prerequisite to being able to transfer the benefits of PLYO training to marathon performance, and that less trained individuals may benefit more from a basic strengthening routine such as the CORE program that served as the control group in this study. Separating the explosive speed and plyometric components of training may also elucidate the effects of these types of training on different sub-groups of marathon runners. In addition, an examination of the biomechanical and cellular mechanisms associated with changes in performance parameters in marathon runners

could shed light on the best practices of implementing and monitoring high intensity forms of training in marathon runners.

Conclusion

The results of this study suggest that PLYO training can effectively be implemented to improve speed and maintain jumping ability in a population of recreational runners concurrently engaged in marathon training. Increased frequency or volume of jump training may be necessary to induce improvements in jumping ability, but that may not be feasible or productive in this population. Unlike some other studies of PLYO training and distance runners, no improvement in distance running performance was observed. This may be due to the magnitude of physiological stress and changes from marathon training alone. The trends toward improved VO_{2MAX} and lower RER in the PLYO group suggest potential performance benefits from PLYO training for marathon runners. The interaction between performance level and training group suggest that PLYO training may have a positive effect on marathon performance in the faster runners, but a negative effect on slower runners. It is possible that a more individualized PLYO program, with a lesser load on some subjects and a more demanding load on others, could produce more stronger effects, but any increased load must be balanced with the potential negative effects of additional physiological stress.

CHAPTER 4: Plyometric Training for Recreational Marathon Runners: Effects on Training Variables, Injury, and Muscle Damage

Abstract:

Core training (CORE) and plyometric and explosive speed training (PLYO) have been proposed as means of reducing injury and enhancing muscle function in various populations. The effects on recreational marathoners, already engaged in demanding training, are unknown. **Purpose:** This study examined the effects on injury, muscle damage, and training variables of an additional weekly session of PLYO or CORE training, compared to no additional training (CON). Subjects from the three groups, doing the same marathon training, were compared for the following during 8-week run-in (RI) and 13-week marathon training (MT) periods: Missed days of training (MISSED DAYS), days missed due to injury (INJ DAYS), rate of perceived exertion (RPE), soreness, and readiness to run. Muscle damage, measured with creatine kinase (CK) levels, were compared between CORE and PLYO groups pre- and post-marathon. **Methods:** Thirty four subjects, ages 18-23 (20.7 ± 1.3 [mean \pm S.D.] years) enrolled in a university marathon training course concurrently performed either a weekly PLYO, CORE, or no additional training (CON). All subjects kept a training log for the duration of their training. The PLYO and CORE training sessions were performed once per week for 12 weeks, during the MT period. The training log variables were assessed during RI and MT periods. In addition, blood samples were taken from 16 participants (8 CORE and 8

PLYO) pre- and post-marathon for assessment of CK. **Results:** During RI, there were no differences between the groups for the training log variables. During MT, there were no differences between the groups, though the PLYO group had fewer MISSED DAYS than CORE or CON (PLYO: 1.7 ± 2.9 , CORE: 4.2 ± 5.1 , CON: 4.5 ± 4.8) and fewer INJ DAYS (PLYO: 1.2 ± 2.6 , CORE: 2.7 ± 5.1 , CON: 4.1 ± 4.9). Within groups analysis comparing the RI and MT periods showed that during MT, there was an increase in days missed due to injury for the CORE group ($p=0.003$), increased RPE for CORE ($p=0.028$) and CON ($p=0.010$), and an increase in soreness for the CON group ($p=0.010$). The PLYO group did not approach significant change in any of the variables between the RI and MT periods. The PLYO group had lower pre-marathon CK levels than the CORE group (81 ± 36 vs. 136 ± 59 U/L; $p=0.042$) and a trend toward lower post-marathon CK levels (486 ± 186 vs. 578 ± 71 ; $p=0.133$). **Conclusion:** The results suggest that a brief weekly PLYO training session concurrent with marathon training may be not only equal, but is superior to CORE or CON in improving training variables of recreational marathoners.

Introduction

Despite the purported health benefits of marathon running, over 50% of marathon runners experience a running-related injury either in training or during and immediately after the event itself (Fredericson & Misra, 2007; Maughan & Miller, 1983; Van Middelkoop et al., 2008). Over 90% of runners experience a “specific health problem” during the marathon or in the following week (Satterthwaite et al., 1999). Adding any additional physical stress to the training practices of this population should be done with caution. Compared with more experience runners, novice marathoners experience not only increased likelihood of injury, but also greater levels of muscle damage (Noakes & Carter, 1982; Satterthwaite et al., 1999).

Core training is widely recommended to runners as a means of decreasing susceptibility to injury (Williardson, 2007), but there is little evidence for its efficacy for injury prevention. On the other hand, some studies suggest that plyometric training (PLYO) may provide a protective effect against injury, and a repeated bout effect may protect against muscle damage in those engaged in a consistent and moderate training program (Chimera et al., 2004; Venckunas et al., 2012). However, PLYO can lead to temporary muscle damage in both endurance and power athletes (Kyrolainen et al., 1998), which is a serious concern for a population already exposed to substantial physiological stress.

Rate of perceived exertion (RPE) has been validated to provide a reproducible scale of intensity of exercise (Aliverti et al., 2011; Grant et al., 1999). Similarly, numeric

scales have been used to assess degree of muscle soreness (Andersen et al., 2013).

Researchers have recently attempted to capture recovery from previous exercise bouts using a similar approach of self-evaluation using a subjective scale of perceived recovery status (Laurent et al., 2011). The present study adopted the terminology “Readiness to Run”, rather than perceived recovery status in order to simplify the language, which was an important consideration given the number of variables being collected in the training log.

Muscle damage and a temporary impairment of muscular function is a known consequence of marathon running (Hikida et al., 1983; Kim et al., 2009; Kyrolainen et al., 2000; Petersen et al., 2007). Damage to the muscle membrane leads to the release of enzymes, such as creatine kinase (CK), into the blood plasma (Jones et al., 1986). Other enzymes such as lactate dehydrogenase, aspartate aminotransferase, alkaline phosphatase also typically enter the bloodstream as a result of muscle damage (Kim et al., 2007; Noakes & Carter, 1982). Myoglobin, neutrophil activity, inflammatory cytokines such as IL-6 and TNF- α also have been shown to increase with exercise-induced muscle damage (Kim et al., 2007; Peake et al., 2005). Cell signaling mechanisms associated with muscle damage and the adaptive response to exercise have been identified, with the mitogen-activated protein kinase (MAPK) family of kinases and transcription factors being important in genetic signaling and response to marathon running (Yu et al., 2001). While many biomarkers change with muscle damage, CK level in the blood plasma has been identified as a reliable indicator of exercise-induced

muscle damage, with baseline levels of around 100 U/L rising to as high as 40,000 U/L after eccentric exercise (Jones et al., 1986).

Eccentric muscle contractions produce greater degrees of muscle damage than concentric contractions (Clarkson & Hubal, 2002; McHugh et al., 1999; Proske & Morgan, 2001; Schwane et al., 1983). Eccentric contraction indicates a contraction in which the force produced by the muscle is less than the opposing load, which causes the muscle to lengthen as it contracts (McHugh et al., 1999; Proske & Morgan, 2001; Raven, 1991). While running in general does involve eccentric contraction in the lower limb, downhill running requires a much greater eccentric contraction. The increased damage from downhill versus flat running has been suggested to be due to greater impact peak force and parallel braking force peaks during downhill running (Gottschall & Kram, 2005).

Running distances near the standard 26.2 mile marathon has been shown to dramatically increase CK levels in recreational runners, from 160 U/L at baseline to 1500 U/L 24-hours after the completion of the run (Riley et al., 1975; Siegel et al., 1980). Among competitive runners (sub-3:30), higher levels of CK (nearly 4500 U/L) were found (Siegel et al., 1980). A group of experienced recreational male marathon runners completing the marathon in about four hours had lesser, though still statistically significant ($p \leq 0.01$), elevations in plasma CK (approximately 400 U/L at the completion and 550 U/L 24 hours post-marathon) (Kim et al., 2009).

The protective effect of repeated bouts of strenuous exercise has been well-established, with much greater evidence of muscle damage occurring in response to the first bout of exercise at a given load than to subsequent bouts (Clarkson & Hubal, 2002; McHugh et al., 1999; Nosaka & Clarkson, 1995). The exact mechanism for the protective effect of repeated bouts is unknown, but theories focusing on neural adaptation, connective tissue adaptation, and adaptation within the muscle cells themselves have been proposed (McHugh et al., 1999). Whether the benefits of eccentric strengthening exercises transfer to a protective effect during long distance running, such as marathon running, is not known.

Research on injuries during training and the marathon itself is inconsistent in the definition of running injury, and in the methods of gathering data on injury. Macera et al. characterized running injury as a “muscle, joint or bone problem/injury of the lower extremities (foot, ankle, Achilles tendon, calf, shin, knee, thigh, or hip) that the participant attributed to running” (1989). In this case, the injury had to be severe enough to cause the runner to alter training, use medication, or seek medical attention. This definition was also utilized in a retrospective/prospective design study of 725 male marathon participants (Van Middelkoop et al., 2008). The prevalence of injury reported over the one-year period (including the 11 month retrospective survey and the prospective one month period) was 54.8%. This is similar to the 58% incidence rate found in a previous retrospective study on mostly male marathoners (Maughan & Miller, 1983). A study of Danish marathon runners (again, mostly male, but including

some women) reported only a 31% incidence of running injury in the previous year (Holmich et al., 1989). Of the marathoners in this study, 65% had previously completed a marathon, indicating a more experienced population than the other studies.

In much of the research, running injury is classified by site, rather than by medical diagnosis, with the knee, calf, and foot being the most common areas of injury (Maughan & Miller, 1983; Van Middelkoop et al., 2008). The vast majority of runners were able to recover either fully or partially from the injury (Maughan & Miller, 1983). Of 397 runners who reported an injury during the year, 30 did not start the marathon due to injury, and 18 of those who started did not finish due to injury (Van Middelkoop et al., 2008). These data indicate that the vast majority of running injuries sustained during marathon training are relatively minor, and full recovery is typical.

Clinical data can give us more detailed insight into the nature and severity of running injuries. A report of over 2000 running injuries seen at a sports medicine clinic identified patella-femoral pain syndrome (PFPS) as the most common running injury, followed by iliotibial band friction syndrome (ITBS), plantar fasciitis, meniscal injuries, tibial stress syndrome, patellar tendonitis and Achilles tendinitis (Taunton et al., 2002). The lower leg (from the knee down) appears to be the most frequently affected area of the body.

Risk factors for injury in marathon runners have been identified, including less running experience, demographics, medical problems, previous injury, and training practices (Chorley et al., 2002), running and sports history and habits, smoking and

alcohol use, prescription medication use, demographic and anthropometric factors (Satterthwaite et al., 1999). Lack of running experience has been identified previously as a risk factor for running injury (Marti et al., 1988). A study of participants in a marathon training program in the U.S. reported a slower, less experienced population of marathon participants than previously reported in the literature (Chorley et al., 2002). The vast majority (87.5%) trained at a 9-minute mile or slower, over half had not previously trained for a marathon, over a third were obese or overweight, and some had been sedentary in the previous three months.

Characterizing the severity of sports injury has been approached historically in a number of ways (van Mechelen, 1997). Days of training or sport participation missed due to injury has commonly been used, though categories and definitions have varied. The NAIRS (US National Athletic Injury/Illness Reporting System), for example, utilized the following definition: 1-7 days = minor, 8-21 days = moderately severe, and >21 days = serious (van Mechelen, 1997). For a recreational runner, participating in running activities 4-5 days per week, 7 days missed due to injury equals nearly a week and a half, so this categorization was eschewed in favor of the categories suggested by a consensus group for use with soccer players: 1-3 days = minimal, 4-7 = mild, 8-28 = moderate, and >28 = severe (Fuller et al., 2006).

Thus, the purpose of this study was to compare plyometric and explosive speed (PLYO) with core stability training (CORE) as methods of improving training variables, reducing injury incidence and reducing muscle damage and soreness in a population of

recreational marathon runners. Differences in the self-assessed training variables were analyzed between three groups: a group performing a weekly PLYO training session, a group performing a weekly CORE session, and a control group (CON) that performed no additional prescribed training sessions.

Methods

Experimental Design.

The study was a 12-week exercise intervention utilizing a randomized-controlled parallel group design, with a PLYO and CORE group, as well as a control group (CON) selected at random from the class members who were not in the intervention, but who had consented to having their training log data assessed for research purposes. This study was designed to assess the training variables of the two groups, to determine if there were differences in level of soreness (SORE), readiness to run (READY), RPE during running, training days missed (MISSED DAYS), and days missed due to injury (INJ DAYS). In addition, specific to the marathon, muscle damage (CK) and/or SORE following the marathon run were assessed in the PLYO and CORE groups only.

An 8-week run-in (RI) period of 4-5 days per week of running was completed by all subjects prior to the commencement of the intervention. The longest run during that time was 8 miles, and no high intensity training was prescribed in the training program. Subjects kept a training log during that period as well, so this period could be used to establish baseline levels for all of the variables during normal running training, as

opposed to those seen during marathon training (MT). This allowed researchers to compare training variables during normal running training vs. MT. For the variables RPE, SORE, and READY, a value was entered by participants for each training day, and averages of those values was taken for each individual during both RI and MT.

In addition, CK levels were taken for the PLYO and CORE groups before and after the marathon to determine whether there was a difference between groups.

Participants in the CORE and PLYO groups were also asked to report their level of soreness at the following time-points after the completion of the marathon: in the first hour, the night of the marathon, and 1, 2, and 3 days after the completion of the run.

Participants.

The study population consisted of healthy young adults training for a marathon through a university marathon training class. Running training consisted of 16.5 ± 5.9 miles per week during RI and 27.1 ± 5.0 during MT. The PLYO and CORE groups were recruited from the class to participate in a 12-week exercise intervention. Inclusion and exclusion criteria, and the enrollment and randomization process for those two groups are described in the previous chapter. The CON group was randomly selected from students from the same class. Inclusion criteria were:

- 1) Had signed consent form indicating willingness to have training log data used for research purposes.
- 2) Filled out training log completely for the entirety of the study period.

Students whose logs were missing data were not entered into the pool of

potential control subjects, and subjects in either the PLYO or CORE groups who did not fill out a log consistently were excluded.

For the CON group, an assigned research ID number of all eligible students (n = 68) was entered into SPSS and the random sample function was used to select 11 subjects, with 6 females and 5 males being selected in order to maintain a balance.

Training log variables.

Readiness to run (READY) and soreness (SORE) were characterized on a 1-10 scale. For READY, 1 was equal to “not ready to run at all” and 10 was equal to “as ready to run as possible”. For SORE, 1 was equal to “no soreness” and 10 was equal to “the most soreness possible”. Data for days missed was gathered from a yes or no column in the training log, described as “Missed/Altered Training due to Injury, Pain, Illness”. A comments column was provided and logs were assessed to interpret how many of the reported missed days were due to injury. Illness, life stress, being too busy, and no reported reason for missing a day were counted towards total days missed (MISSED DAYS), but not counted toward days missed due to injury (INJ DAYS). Additional injury status of subjects by group was done by classifying subjects according to the following categories: 0-3 days = minor or no injury (NO INJ), and 4+ days as injury (INJ). This classification is based on the categories established in previous research (Fuller et al., 2006), but combines mild, moderate and severe injury categories into a single category. This was deemed expedient in light of the small sample size and relatively low numbers of injured participants.

Muscle damage.

Blood samples were taken pre- and post- marathon to assess CK levels, which are a reliable marker of muscle damage. Samples of 3 ml were collected from the antecubital vein of subjects on 2 occasions, 2 days prior to the marathon and one day after the marathon. Samples were collected in lithium heparin 3 ml vacutainer tubes (Beckton Dickinson, Franklin Lakes, NJ), stored on ice, and centrifuged @ 2600 rpm for 15 minutes (Eppendorf, Hamburg, Germany). The plasma was micro-pipetted into a 2.0 ml micro-centrifuge tube (Fisher Scientific, Waltham, MA) and stored at -80° C. All the pre-test samples were collected during the morning (7:45 to 11:30 a.m.) 2 days prior to the marathon, and all of the post-test samples, except one, were collected during the same time frame the day after the marathon. The one post-test not taken during that time was attempted, but no sample was drawn despite repeated attempts, likely due to dehydration. The subject was instructed to consume adequate water and return the next day, and a sample was successfully drawn the following morning.

Creatine kinase levels were determined using a colorimetric CK assay kit (BioAssay Systems, Fremont, CA) according to kit specifications. The assay relies on an enzyme-catalyzed reaction with readings of optical density at 340 nm. Samples were thawed on ice, and 10 µl samples, in triplicate, were transferred to a Corning Costar 96-well plate (Sigma-Aldrich, St. Louis, MO) and combined with the reconstituted reagent using a multi-channel pipette prior to the assay. Readings were done on a Synergy H1 96-well plate reader (Biotek Instruments, Winooski, VT). The pre-test values were

calculated using the standard formula (using readings at 20 and 40 min.), as none of the values exceeded 300 U/L, the upper limit of the range for that formula. As at least some of the post-test values were expected to exceed that range, the formula using readings at 20 and 25 min (range: 30 to 1800 U/L) was used for the post-marathon samples.

Averages of the 3 samples are reported.

Statistical analysis.

Statistical analysis was done using SPSS, Version 21. Means and standard deviations were calculated for each measure using standard methods. Data were tested for normality and homoscedasticity using the Shapiro-Wilk and Levene tests. Average running mileage per week was compared between groups and between RI and MT periods using ANOVA. For the other training log factors, independent samples Kruskal-Wallis ANOVA tests were used to detect differences between groups. Differences between the RI and MT were assessed using the Wilcoxon Signed-Rank test. These non-parametric tests were chosen due to the non-normal distributions of most of the training log data. Though the data appeared normally-distributed for RPE and READY, non-parametric tests were used due to the ordinal nature of the variables (Hildebrand, 1977). The variables MISSED DAYS and INJ DAYS were reported in this fashion, but were transformed to a per week number prior to comparing RI and MT periods to account for the difference in length of those periods. In addition, INJ DAYS was transformed into a categorical variable, with the categories defined as no injury/minimal injury = 0-3 days of missed training, substantial injury = greater than 3 days of missed training. Due to the

small sample size, Fisher's Exact Test was used rather than a Chi-square test to assess this variable. For CK, the pre-test data was normally distributed and was not altered. The post-test CK data was not normal according to the Shapiro-Wilk test ($p = 0.009$). It was log-transformed prior to assessment with a standard independent samples t-test, but the difference in p-values was so minimal that the original data and statistics were reported.

Results

Baseline data for the three groups, including demographic variables, body mass, percent body fat, and VO_{2MAX} are found in Table 6. This data is gathered as a standard practice for the class.

Group	N	Sex	Age (years)	% Body fat	BM (kg)	VO_{2MAX}
CORE	12	f = 6	20.2 ± 1.4	19.2 ± 8.3	72.6 ± 9.5	52.8 ± 8.5
PLYO	11	f = 7	21.0 ± 1.0	19.2 ± 7.7	65.0 ± 8.0	50.5 ± 8.8
CON	11	f = 6	21.0 ± 1.1	19.3 ± 5.6	70.3 ± 8.3	46.2 ± 14.5

Table 6. Demographic/baseline data for CORE, PLYO and CON groups. ANOVA detected no differences between the groups at $p \leq 0.05$.

In the RI period (prior to the PLYO or CORE intervention), there were no differences between the groups in any of the training log variables. The Kruskal-Wallis ANOVA for MISSED DAYS ($p = 0.645$), INJ DAYS ($p = 0.133$), RPE ($p = 0.216$), READY ($p =$

0.446), and SORE ($p = 0.421$) found no difference between the 3 groups in the RI period.

During the MT period, there were no differences between groups in RPE ($p = 0.379$),

SORE ($p = 0.985$), READY ($p = 0.527$), MISSED DAYS ($p = 0.099$), or INJ DAYS ($p = 0.103$).

The PLYO group had fewer MISSED DAYS during MT (1.7 ± 2.6) than either than CORE

(4.2 ± 5.1) or CON (4.1 ± 4.9) groups, and also fewer INJ DAYS (PLYO: 1.2 ± 2.6 , CORE: 2.7

± 5.1 , CON: 4.1 ± 4.9) but the differences were not statistically significant. Means,

standard deviations and medians by group for both the run-in and marathon training

periods are reported in Table 7.

Variable	Run-in period				Marathon training period				P-value (by time)
	Group	Mean \pm SD	Median	P-value (by group)	Group	Mean \pm SD	Median	P-value (by group)	
MISSED DAYS	ALL	2.3 \pm 3.8	1	0.645	ALL	3.5 \pm 4.4	2	0.099	0.638
	CORE	1.4 \pm 2.4	0.5		CORE	4.2 \pm 5.1	2		0.182
	PLYO	2.2 \pm 2.6	1		PLYO	1.7 \pm 2.9	1		0.284
	CONT	3.4 \pm 5.8	0		CONT	4.5 \pm 4.8	3		0.678
INJ DAYS	ALL	1.1 \pm 3.4	0	0.133	ALL	2.6 \pm 4.4	1	0.103	0.130
	CORE	0.1 \pm 0.3	0		CORE	2.7 \pm 5.1 [†]	1		0.003
	PLYO	1.1 \pm 1.8	0		PLYO	1.2 \pm 2.6	0		0.953
	CONT	2.3 \pm 5.7	0		CONT	4.1 \pm 4.9	3		0.314
RPE	ALL	11.7 \pm 2.2	11.4	0.216	ALL	12.3 \pm 2.0 [†]	12.1	0.379	0.003
	CORE	11.2 \pm 2.0	11.3		CORE	12.2 \pm 2.4 [†]	12.2		0.028
	PLYO	12.9 \pm 2.6	12.9		PLYO	12.8 \pm 2.3	12.2		0.790
	CONT	11.1 \pm 1.6	11		CONT	11.8 \pm 1.3 [†]	11.2		0.010
READY	ALL	6.5 \pm 1.6	6.7	0.446	ALL	6.8 \pm 1.6	6.9	0.527	0.203
	CORE	6.2 \pm 1.7	6.4		CORE	6.4 \pm 1.8	6.2		0.388
	PLYO	6.4 \pm 1.6	6.7		PLYO	6.7 \pm 1.5	7.0		0.534
	CONT	7.0 \pm 1.6	7.3		CONT	7.1 \pm 1.6	7.3		0.534
SORE	ALL	3.1 \pm 1.1	3.0	0.421	ALL	3.4 \pm 1.4	3.2	0.985	0.078
	CORE	3.2 \pm 1.0	3.3		CORE	3.4 \pm 1.4	3.2		0.583
	PLYO	3.2 \pm 1.1	3.0		PLYO	3.3 \pm 1.2	3.6		0.697
	CONT	2.7 \pm 1.3	2.5		CONT	3.3 \pm 1.7 [†]	2.9		0.010

Table 7. Mean, S.D., and median for training log variables by group for RI and MT periods. P-value by group indicates difference between groups within the time period. P-value by time indicates change between RI and MT period within group. [†]Significantly different from RI @ $p \leq .05$.

Differences between the RI period and the MT period were assessed within groups by time (Wilcoxon Signed Rank test) to assess change from baseline. There were no differences in MISSED DAYS between the RI and MT periods for any of the groups. For INJ DAYS, the CORE group missed significantly more training days during the MT period ($p = 0.003$), whereas the CON group missed more but not significantly ($p = 0.314$) and the PLYO group did not change between the two time periods ($p = 0.953$). The population as a whole increased in average RPE between the RI and MT periods ($p = 0.003$). The PLYO group did not change ($p = 0.790$) whereas the other two groups did: CORE ($p = 0.028$) and CON ($p = 0.010$). There were no changes in READY for any of the groups. There was a trend toward an increase in SORE across the whole population ($p = 0.078$). The CON group increased significantly ($p = 0.010$), whereas the CORE ($p = 0.583$) and PLYO ($p = 0.697$) groups did not change. Training mileage did not differ between groups for either RI or MT, but was significantly higher for all groups during MT, as shown in Table 8.

	RI	MT	P-value (time)
CORE	15.8 ± 6.2	26.2 ± 5.0 [†]	≤ 0.001
PLYO	17.3 ± 5.3	28.2 ± 5.0 [†]	≤ 0.001
CON	16.4 ± 6.6	27.2 ± 5.3 [†]	≤ 0.001
p-value (group)	0.827	0.648	

Table 8. Running mileage in RI and MT by group. P-value by in bottom row indicates difference between groups within the time period. P-value in right column indicates change between RI and MT period within group. [†]Significantly different from RI @ $p \leq .05$.

The SORE ratings taken after the marathon compared only the CORE and PLYO groups. There were no differences in the Kruskal-Wallis ANOVA tests for SORE at 1 hour after the marathon ($p = 0.640$), the evening of marathon day ($p = 0.450$), or 1 day ($p = 0.857$), 2 days ($p = 0.496$), and 3 days ($p = 0.362$) after the marathon. Results are shown in Table 9.

Time after marathon	Group	Mean \pm SD	Median	P-value
1 hour	ALL	7.5 \pm 2.7	8	0.640
	CORE	7.2 \pm 3.0	8	
	PLYO	7.8 \pm 2.4	8	
12 hours	ALL	7.5 \pm 2.3	8	0.450
	CORE	6.9 \pm 2.8	8	
	PLYO	8.1 \pm 1.7	8	
24 hours	ALL	7.7 \pm 1.6	8	0.857
	CORE	7.6 \pm 1.6	8	
	PLYO	7.7 \pm 1.7	8	
48 hours	ALL	5.5 \pm 1.6	5	0.496
	CORE	5.8 \pm 1.5	6	
	PLYO	5.4 \pm 1.8	5	
72 hours	ALL	3.1 \pm 1.1	3	0.362
	CORE	2.9 \pm 1.1	2.5	
	PLYO	3.3 \pm 1.2	3	

Table 9. Ratings (1-10) of SORE at different time points post-marathon, reported by group.

Those missing more than 3 days due to injury were categorized as having substantial injury (SI), whereas those missing 3 days or less were considered minimally or not impacted by injury (NI). The number of subjects with SI during the marathon training period were as follows: CORE, 2 of 12; PLYO, 1 of 11; CON, 3 of 11. Fisher's Exact

tests showed no difference between the groups, with the lowest p-value (PLYO vs. CON group) not approaching significance ($p = 0.586$).

Pre-marathon CK levels were significantly lower for the PLYO (81 ± 36) than the CORE (136 ± 59) group ($p = 0.042$). Post-marathon CK was again lower for PLYO (486 ± 186) than CORE (578 ± 71), but the difference was not significant ($p = 0.133$). The post-test data were not normally distributed, according to the Shapiro-Wilk test ($p = 0.009$), but transformation of the data to a normal distribution resulted in a nearly identical p-value ($p = 0.120$), so the data are reported in their original (non-transformed) units. Post-marathon CK was significantly higher than pre- for both groups and for the whole population ($p \leq 0.001$). Data for CK are reported in Table 10.

	PRE	P-value (group)	POST	P-value (group)	P-value (time)
ALL	108 ± 55		$532 \pm 121^{\dagger\dagger}$		≤ 0.001
CORE	136 ± 59		$578 \pm 71^{\dagger\dagger}$		≤ 0.001
PLYO	$81 \pm 36^{\dagger}$	0.042	$486 \pm 186^{\dagger\dagger}$	0.133	≤ 0.001

Table 10. Pre- and post-marathon CK levels by group. All results are \pm S.D. † Significantly different from CORE @ $p \leq 0.05$. †† Significantly different from baseline @ $p \leq 0.05$.

Discussion

This study of recreational marathon runners compared a once per week exposure to low-volume PLYO training to CORE and CON groups, assessing injury, soreness, readiness to run, and RPE during training, as well as soreness and muscle

damage after the marathon. Marathon training is a challenging undertaking, and the impact of any auxiliary exercises done in addition to running must be carefully considered. Injury prevalence is high in marathon training (Macera et al., 1989; Maughan & Miller, 1983; Van Middelkoop et al., 2008), and additional training such as CORE has been proposed as a means of preventing injury (Williardson, 2007). On the other hand, PLYO training can lead to muscle soreness and damage, though the effect is diminished with repeated exposure (Jamurtas et al., 2000). Long distance running can also lead to muscle soreness and damage (Jones et al., 1986; Kim et al., 2009), and the researchers hypothesized that a proper volume of PLYO training could provide a protective effect against soreness and muscle damage from running.

The results of this study suggest that PLYO training for recreational runners at relatively low frequencies and volumes can be considered safe, and may provide some benefits. While there were no differences between the groups during the marathon training period in MISSED DAYS, INJ DAYS, READY, SORE, or RPE, the changes within groups between the RI and the MT period, and the lower pre-marathon CK levels suggest some benefit to the PLYO training. The PLYO group reported a slightly higher (non-statistically significant) RPE than the other groups during the RI, and did not increase in RPE during MT. The CORE and CON group, on the other hand, reported a statistically significant increase in RPE from RI to the MT. The PLYO group reported the fewest INJ DAYS, but the difference was not statistically significant. The CORE group increased significantly in INJ DAYS from RI to MT, whereas the CON group had higher,

but not significantly more INJ DAYS during MT, and the PLYO group remained almost exactly the same despite the much higher training load. The CON group increased significantly in SORE, whereas the PLYO and CORE groups did not change. Changes between RI and MT are depicted in Figure 5.

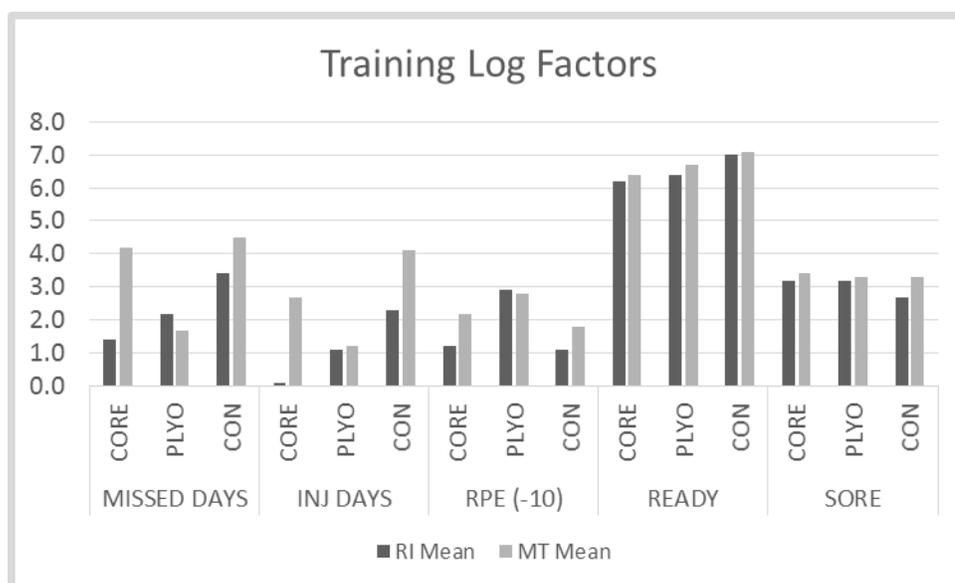


Figure 5. Training log factors by groups and between RI and MT periods.

The SORE ratings after the marathon showed no differences between the CORE and PLYO groups, and the CK values were likewise not significantly different. However, the baseline values were lower for the PLYO group, and there was a trend toward lower CK values post-marathon as well. The physiological challenge of running a marathon may be so great that it blunted any differences between the groups, or it may be that the heterogeneous nature of the population precluded prescription of a proper training load. While some may have struggled to adapt to the PLYO training, others may have benefited more from additional time and/or sessions. The previous chapter cites a post-

hoc analysis that suggests the faster runners benefited more in terms of distance running performance from PLYO training, whereas the slower runners may actually have been better served avoiding the additional stress.

Clearly, more research needs to be done with respect to proper training load for various levels of marathon runners, but this study establishes a level of PLYO training that appears safe and potentially beneficial for this population. Tools for monitoring adaptation to training load, such as intermittent testing, could assist in adjusting training volumes and frequencies to maximize individual response.

Conclusion

When compared to CORE and CON, a relatively low-volume weekly PLYO session appears to have no negative impact on recreational marathon runners, and may provide some benefits specific to injury prevention, protection from muscle damage in training and maintaining rather than increasing RPE. Implementation of a proper training volume, frequency, and intensity presents a challenge to the practitioner, and caution should be taken in exposing to additional stress during a MT period. Those with higher beginning levels of fitness and competitive aspirations may be an easier population to study in terms of avoiding excessive physiological stress. However, with proper caution, PLYO training can be not only safe, but beneficial to a heterogeneous population of recreational marathon runners.

CHAPTER 5: Modeling Marathon Performance Using Running Economy and Metabolic Factors During Sub-Maximal Running: Boston Qualifiers vs. Recreational Runners

Abstract:

Running economy (RE), or the oxygen cost of running at submaximal paces, has been identified as an important factor in distance running performance. Previous studies have produced inconsistent results on the importance of RE in performance due to different methods of calculating RE, lack of examination of RE at a range of velocities, and a lack of consideration of related metabolic factors such as respiratory exchange ratio (RER). **Purpose:** This study examined RE, RER, and RER variability (RER VAR) during submaximal running as predictors of marathon performance (MP) in competitive (COMP) and recreational (REC) runners. Running economy was reported at 6 velocities for all runners, with stages established from 75 to 100% of 10-km velocity, based on recent race or time trial performances. The research hypothesis was that COMP runners would be more economical per km than REC runners, and that within groups the use of allometric scaling of RE at submaximal paces near marathon pace would be the strongest predictor of MP. Lower RER and higher RER VAR were also hypothesized as potential correlates of better MP. **Methods:** Twenty-nine runners (ages 18-47, 14 female) were classified as competitive (COMP: n = 12, 3f, age 30 ± 8 years) or recreational (REC: n = 17, 11f, 20 ± 1 years), with a predicted Boston Marathon qualifying time (3:05 for men and 3:35 for women) set as the cut-off. A 6-stage, incremental, sub-

maximal 30-minute treadmill run, beginning at 75% of 10k race velocity and finishing at 100% of 10k velocity was run by subjects in the 2 weeks prior to running a 26.2 mile road marathon. The dependent variable, MP, was calculated as percent difference from predicted marathon finish time, based on races of 2 miles up to 10-km. The independent variables RE, RER, and RER VAR, were calculated at each of the 6 stages. Running economy was calculated in four ways: Oxygen use in ml/kg/min (O_2); allometrically-scaled oxygen use, in ml/kg^{0.75}/min (ALLO O_2); oxygen use corrected for velocity, in ml/kg/km (O_2 PER KM); and allometrically-scaled oxygen use corrected for velocity, in ml/kg^{0.75}/km (ALLO O_2 PER KM). **Results:** The COMP runners were significantly higher than REC runners in O_2 ($p \leq 0.001$) and ALLO O_2 ($p \leq 0.001$), and lower in O_2 PER KM ($p = 0.005$) and ALLO O_2 PER KM ($p = 0.015$). No differences between groups in RER and RER VAR were found except RER VAR at 10k pace, where the COMP runners were significantly lower than the REC group ($p = 0.039$). For all runners (ALL), O_2 PER KM and ALLO O_2 PER KM at all stages were significantly correlated with MP. Within groups, MP was not significantly correlated with O_2 PER KM at any stage. However, MP was correlated with ALLO O_2 PER KM within groups in some cases: COMP runners at 75% ($p=0.044$), 80% ($p=0.040$), and REC runners at 85% ($p=0.038$). Stepwise linear regression models included the following variables: ALL runners, O_2 PER KM at 85% of 10k velocity and RER at 80% of 10k velocity (R-square = 0.530); COMP runners, ALLO O_2 PER KM at 80% of 10k velocity (R-square = 0.400); REC runners, ALLO O_2 PER KM at 85% of 10k velocity (R-square = 0.256). **Conclusion:** Competitive runners are more economical per

km than REC runners, but RER and RER VAR are not different between groups. The use of allometric scaling in calculating RE, while not necessary for a widely varied population, becomes important in finding differences when studying more homogenous groups. In this study, ALLO O₂ PER KM at 80-85% of 10k velocity was the best predictor of MP within groups.

Introduction

Running economy (RE) is quantified as the energy required by an individual to run at a submaximal pace (Saunders et al., 2004b). It is typically assessed using treadmill testing and a metabolic cart to measure oxygen utilization. Running economy is typically expressed as VO_2 (in mL/kg/min) at a specified sub-maximal pace or paces. Some studies report RE in meters covered per ml/kg (Turner et al., 2003) or in ml/kg/km in order to allow for comparison of economy at different velocities (Foster & Lucia, 2007). While reporting per kg of body mass is common, research indicates that the relationship between body mass and oxygen cost do not increase proportionately, and thus body mass should be scaled allometrically, raising body mass to a power of between 0.66 and 0.75 (Berg, 2003; Bergh et al., 1991; Helgerud, 1994; Saunders et al., 2004a; Storen et al., 2011).

Running economy studies have high test-retest reliability (1.5-5.0%) among a range of populations (Armstrong & Costill, 1985; Pereira & Freedson, 1997; Saunders et al., 2004a). Typical error can be reduced by ensuring that proper controls are taken to standardize time of testing, testing equipment, nutritional status, recent training, environmental conditions, footwear, and other potential confounding variables (Pereira & Freedson, 1997; Saunders et al., 2004a).

Respiratory exchange ratio (RER) during submaximal exercise indicates the ratio of fat to carbohydrate that is being utilized for energy by the exercising athlete (Coyle,

1995; Hawley & Spargo, 2007; Jeukendrup & Wallis, 2005). While it falls outside the scope of the traditional definition of RE, RER at a submaximal pace reflects metabolic economy, as glycogen is spared by those who burn fat at a higher proportion. Elite male and female distance runners have been shown to be more able to utilize fat during exercise, which allows them to spare glycogen and thereby increase endurance capacity (Hawley & Spargo, 2007). This may be a particularly important factor in events like the marathon, where glycogen depletion can be a limiting factor to performance (Saunders et al., 2004b). Increased fat metabolism likely occurs due to adaptations at the cellular level within the working muscle, such as increased mitochondrial density, and increased levels of mitochondrial oxidative enzymes such as succinate dehydrogenase (SDH) and citrate synthase (CS). Muscle triglyceride content and utilization has been shown to increase with training, which may allow the endurance-trained athlete to rely more heavily upon lipid metabolism than their untrained counterparts (Goodpaster et al., 2001; Hurley et al., 1986).

Breathe-by-breathe RER variability (RER VAR) has recently been explored as a possible means of assessing aerobic fitness, and possibly metabolic flexibility. While this remains a relatively new area of research, there is evidence that training increases RER VAR in both adolescent female soccer players and novice college-aged marathoners (Biltz et al., 2011; Brown, 2013). No assessment of RER VAR at a range of paces has been published, nor has RER VAR been examined as a possible predictor of running performance.

While there is debate on the best way of quantifying it, RE is an important aspect of distance running performance, as a more economical runner can do the same amount of work with less energy utilization (Saunders et al., 2004b). This likely allows the runner to cover a greater distance without experiencing as much fatigue when compared to a less economical runner (Joyner & Coyle, 2008). The aim of this study was to examine RE and related factors in marathon runners, reporting data at a range of sub-maximal paces (from 75 to 100% of 10k race pace), and looking both at differences between COMP and REC runners and factors within groups. Factors related to RE were used to create models of MP as a difference from predicted finish time factors for the whole population and by group. The research hypothesis was that RE, calculated per km and utilizing allometric scaling, would be the strongest predictor of marathon performance (MP), with more economical runners attaining times closer to their predicted marathon finish times, while less economical runners would be slower than their predicted finish times.

Methods

Experimental Design.

This study utilized a cross-sectional design, with the dependent variable of interest being marathon performance (MP) calculated as percent difference from predicted marathon finish time based on races of 2 miles up to 10-km. The independent variables explored were RE and related metabolic factors gathered during a six-stage,

incremental, sub-maximal 30-minute treadmill run, beginning at 75% of 10k race velocity and finishing at 100% of 10k velocity. Running economy was calculated in four ways to provide a comparison between the methods of reporting. The four methods were:

- 1) Oxygen use in ml/kg/min (O_2)
- 2) Allometrically-scaled oxygen use, in ml/kg^{0.75}/min (ALLO O_2)
- 3) Oxygen use corrected for velocity, in ml/kg/km (O_2 PER KM)
- 4) Allometrically-scaled oxygen use corrected for velocity, in ml/kg^{0.75}/km (ALLO O_2 PER KM)

Subjects were stratified by group as competitive (COMP) or recreational (REC) runners with a predicted Boston Qualifying (3:05 for men and 3:35 for women) time being the cut-off, in order to assess whether there are differences between those two groups in factors related to RE and RER at a range of submaximal intensities, as well as to assess whether the two populations would yield different linear regression models of predicting MP.

Participants.

Enrollment in the study required completion of a time trial or road race of 2 miles to 10-km in the two months prior to running a road marathon, as well as a lab visit to complete the 30-min submaximal treadmill run. Exclusion criteria included any health condition that would contra-indicate a 30-min run of moderately challenging nature on the treadmill, or the inability to complete the 30-min run.

Two pools of subjects were recruited for this study. Students enrolled in the University of Minnesota PE 1262 Marathon Training course made up the majority of the study population. They completed the 30-minute submaximal running test as part of another study. In order to get an adequate sample size of competitive runners, emails to local running clubs and running distribution lists were sent. Prior to enrollment, a consent form was provided for review, and researchers explained the nature of the study and attendant risks via phone or email, and answered any questions from potential subjects. Consent was obtained in person prior to any testing. All procedures and protocols were approved by the Institutional Review Board at the University of Minnesota.

Four participants were unable to complete the 30-minute sub-maximal run, and all but one was excluded from analysis. In all excluded cases, average O_2 use during the final stage attempted was lower than the previous stage (indicated that VO_{2PEAK} had been reached) and RER values were well above 1.0 even during the penultimate stage. This physiological data, in combination with the subjects' inability or unwillingness to continue led us to the interpretation that a maximal effort was given, significant anaerobic metabolism was occurring, and that assessment of aerobic factors was confounded by the maximal nature of the test for these participants. One other subject's data was excluded from analysis for similar reasons. Though this subject completed the test, physiological data and subjective reporting indicated maximal effort, and statistical analysis identified this subject's data as an outlier across RE

variables. One of the excluded subjects cited illness, and the others fatigue related to training as possible explanations for being unable to continue.

The subject who did not complete the final stage, but was included in the analysis cited discomfort running with the gas analysis mask as the reason for cessation of the test. An RER of less than 1.0 was observed, indicating a submaximal effort. During one test, loss of power to the metabolic cart occurred during the final stage. For these two subjects who are included though their final stage did not last 5 minutes, the data collected during the final stage was considered sufficient for inclusion in the analysis.

Subject characteristics are shown below in Table 11. In summary, the COMP group was older, ran faster in the marathon, and closer to their predicted marathon time.

Group	Age (years)		Marathon Time (min.)		MP (% diff)	
ALL	24 ± 7		225.1 ± 51.2		9.9 ± 8.6	
COMP	30 ± 8 [†]	p =	178.1 ± 12.5 [†]	p ≤	1.7 ± 3.2 [†]	p ≤
REC	20 ± 1	0.002	258.2 ± 40.7	0.001	15.7 ± 5.8	0.001

Table 11. Marathon time and MP, as percent difference from predicted finish time for COMP and REC runners. All results are ± S.D. P-values are two-tailed. [†]Significantly different from REC group.

Data Collection Procedures.

Anthropometric characteristics

Height and weight were measured prior to the treadmill test. Subjects removed footwear, and height was measured to the nearest ¼ inch using an Accustat Genentech Stadiometer (San Francisco, CA). Weight was measured in pounds to the nearest tenth

using a ProDoc Detecto (PD300) scale (Webb City, MO). During weighing, subjects wore light, minimal clothing, such as running shorts or half-tights and a jog-bra (women).

Sub-maximal 30-minute running test

Subjects ran on a motorized Woodway Pro XL 27 treadmill (Waukesha, WI) for a total of 33 minutes, including a 3-minute warm-up and 6 stages of 5-minutes each. They were advised to refrain from strenuous activity for 48 hours prior to testing, and to follow a dietary regiment similar to that which they typically use prior to a race or challenging workout. Stages were calculated off a recent race performance, ranging in distance from 2-mile up to 10k. Recent race times were converted to a 10-km race equivalent using commonly utilized race pace conversion charts (Daniels, 2013). The warm-up was done at 70% of 10-km velocity, and the 6 stages of 5 minutes each were at 75%, 80%, 85%, 90%, 95%, and 100% of 10-km velocity. Though this was not meant to be a maximal effort, the duration and intensity were moderately challenging. Research staff emphasized that if at any point the subject wished to stop the test, he or she was free to do so, simply by stepping on the rails of the treadmill or by hitting the stop button. A face mask and pneumatech were worn for gas analysis via metabolic cart (Medgraphics, St. Paul, MN, USA). Standard calibration procedures of the metabolic cart were used prior to each testing session.

In order to assess metabolic response to exercise of moderate duration over a range of sub-maximal paces, a number of factors were assessed at each of the 6 stages,

and as averages over the entirety of the 30-minute test. Running economy was assessed and reported in four ways: O_2 , ALLO O_2 , O_2 PER KM, and ALLO O_2 PER KM.

Respiratory exchange ratio was assessed and reported as both an average (again, for each of the 6 stages and as an average across the 30 minutes). In addition, RER VAR analysis was done by stage and across the 30 minutes to calculate Sample Entropy (SampEn) scores. Kubios Heart Rate Variability Software, Version 2, (University of Kupio, Kupio, Finland) was used to assess breathe-by-breathe RER VAR. Default values of $m = 2$ and $r = 0.2 * SD$ were used in the calculation of the SampEn scores.

Marathon Performance

Predicted marathon finish time was calculated from the shorter race or time trial using commonly utilized race pace conversion charts (Daniels, 2013). Chip times were used for marathon finish times, and times were confirmed with subject via phone or email. Percent difference from expected finish time was then calculated and reported as the marathon performance (MP) variable. A positive percent indicated a slower than predicted marathon finish time, while a negative percent indicated a faster than predicted marathon time.

Statistical Analysis.

Statistical analysis was done using SPSS, Version 21. Means and standard deviations for all subjects and the two groups are reported. Descriptive data are compared using independent samples t-tests. Data were tested for normality and homoscedasticity using the Shapiro-Wilk and Levene tests. Comparisons between the

groups were done to assess whether factors related to RE are different between COMP and REC runners. Average values across the 6 stages were entered into a MANOVA: O₂, ALLO O₂, O₂ PER KM, and ALLO O₂ PER KM, RER, and RER VAR. Follow-up analysis was done for both the 30-min averages and for each of the 6 stages, using independent samples t-tests, or with non-parametric tests in a few cases where the assumption of normality was not met. Significance for all tests set at $p \leq 0.05$.

Factors related to RE and RER were assessed for correlations with percent difference from predicted marathon finish time, and multiple linear regression modeling was done for ALL, COMP and REC runners. The variables O₂ PER KM and ALLO O₂ PER KM, RER, and RER VAR, at each of the six stages, as well as the average of all six stages, were entered into the multiple linear regression. The variables O₂ and ALLO O₂ were not included as they were not meaningful in relation to performance due to lack of correction for different velocities between subjects. Stepwise regression was done with $p \leq 0.05$ set as the threshold. Regressions were done for ALL, COMP, and REC runners to assess whether different factors are more important in predicting MP in these two populations.

Results

Analysis of averages across the six stages for O₂, ALLO O₂, O₂ PER KM, and ALLO O₂ PER KM, RER, and RER VAR indicated a significant difference between COMP and REC

runners ($p \leq 0.001$). Box's Test of Equality of Covariance Matrices indicated equality of covariance between the groups ($p = 0.376$). The assumption of normality was met with the exception of AVE RER ($p = 0.021$). Levene's Test of Equality of Error Variances indicated homoscedasticity for all variables except O_2 ($p = 0.027$) and ALLO O_2 ($p = 0.035$). Given the very small p-value of the MANOVA and the test's robustness to minor violations of the assumptions of normality and homoscedasticity, the likelihood of a difference between the groups can be stated with confidence.

For the stage-by-stage analysis, the data for met the assumption of normality, with the following exceptions: RER 95 ($p = 0.014$), RER 100 ($p = 0.001$), AVE RER ($p = 0.021$), and RER VAR 95 ($p = 0.038$). Non-parametric tests were used to compare groups for these variables.

The COMP runners were significantly higher than REC runners in O_2 ($p \leq 0.001$) and ALLO O_2 ($p \leq 0.001$), and lower in O_2 PER KM ($p = 0.005$) and ALLO O_2 PER KM ($p = 0.018$). Average velocity during the 30-min sub-maximal treadmill run was significantly faster for COMP (8.6 mph) than REC (6.9 mph) runners ($p \leq 0.001$).

		% of 10k race velocity						
		75%	80%	85%	90%	95%	100%	AVE
Velocity (mph)	ALL	6.5 ± 1.0	6.9 ± 1.0	7.4 ± 1.1	7.8 ± 1.1	8.3 ± 1.2	8.8 ± 1.3	7.6 ± 1.1
	COMP	7.4 ± 0.4†	7.9 ± 0.5†	8.4 ± 0.5†	8.9 ± 0.5†	9.4 ± 0.6†	9.9 ± 0.6†	8.6 ± 0.5†
	REC	5.8 ± 0.7	6.3 ± 0.8	6.7 ± 0.8	7.1 ± 0.8	7.6 ± 0.9	8.0 ± 1.0	6.9 ± 0.9
	P-value	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001
O ₂ (ml/kg/min)	ALL	35.0 ± 4.2	37.7 ± 4.5	40.4 ± 4.8	43.0 ± 5.1	45.4 ± 5.4	47.1 ± 5.7	41.4 ± 4.9
	COMP	38.1 ± 2.4†	40.8 ± 2.3†	43.6 ± 2.3†	46.6 ± 2.5†	49.2 ± 2.7†	51.1 ± 3.2†	44.9 ± 2.4†
	REC	32.8 ± 3.8	35.5 ± 4.5	38.1 ± 4.8	40.5 ± 4.9	42.6 ± 5.2	44.4 ± 5.4	39.0 ± 4.7
	P-value	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001
ALLO O ₂ (ml/kg ^{0.75} /min)	ALL	100.6 ± 13.4	108.4 ± 14.4	116.0 ± 15.1	123.6 ± 16.0	130.3 ± 16.7	135.4 ± 17.3	119.0 ± 15.2
	COMP	109.9 ± 7.9†	117.7 ± 7.9†	125.8 ± 7.5†	134.4 ± 8.0†	141.9 ± 8.1†	147.4 ± 8.8†	129.5 ± 7.7†
	REC	94.0 ± 12.6	101.8 ± 14.4	109.0 ± 15.4	115.9 ± 15.8	122.1 ± 16.5	127.0 ± 16.9	111.6 ± 15.0
	P-value	p ≤ 0.001	p = 0.002	p = 0.002	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001	p ≤ 0.001
O ₂ PER KM (ml/kg/km)	ALL	203.4 ± 18.2	204.7 ± 17.7	205.4 ± 17.0	205.9 ± 16.8	205.1 ± 16.1	202.0 ± 18.0	204.6 ± 16.7
	COMP	193.2 ± 11.3†	193.8 ± 11.3†	194.9 ± 9.0†	196.0 ± 9.6†	196.0 ± 9.8†	193.2 ± 10.2†	194.7 ± 9.8†
	REC	210.5 ± 18.2	212.4 ± 17.5	212.8 ± 17.5	211.5 ± 16.8	211.5 ± 16.8	208.2 ± 19.9	211.6 ± 17.3
	P-value	p = 0.009	p = 0.003	p = 0.003	p = 0.005	p = 0.008	p = 0.025	p = 0.005
ALLO O ₂ PER KM (ml/kg ^{0.75} /km)	ALL	584.0 ± 55.0	587.9 ± 52.7	589.6 ± 50.0	590.7 ± 49.3	588.8 ± 46.7	579.7 ± 50.6	586.8 ± 49.0
	COMP	558.1 ± 44.8†	560.1 ± 40.9†	562.7 ± 33.4†	566.0 ± 35.0†	566.0 ± 33.1†	557.8 ± 32.2†	561.8 ± 35.3†
	REC	602.3 ± 55.4	607.5 ± 52.2	608.6 ± 51.8	608.1 ± 51.3	604.9 ± 48.9	595.1 ± 56.2	604.4 ± 50.5
	P-value	p = 0.031	p = 0.014	p = 0.012	p = 0.020	p = 0.024	p = 0.048	p = 0.018
RER	ALL	0.94 ± 0.05	0.97 ± 0.06	0.98 ± 0.06	1.00 ± 0.06	1.02 ± 0.07	1.06 ± 0.09	0.99 ± 0.06
	COMP	0.93 ± 0.03	0.97 ± 0.04	0.98 ± 0.05	0.99 ± 0.05	1.01 ± 0.06	1.04 ± 0.06	0.98 ± 0.05
	REC	0.94 ± 0.07	0.97 ± 0.07	0.99 ± 0.07	1.00 ± 0.07	1.03 ± 0.08	1.08 ± 0.10	1.00 ± 0.07
	P-value	p = 0.613	p = 0.743	p = 0.759	p = 0.506	p = 0.440	p = 0.263	p = 0.496
RER VAR (SampEn)	ALL	1.14 ± 0.21	1.17 ± 0.23	1.15 ± 0.25	1.11 ± 0.25	1.05 ± 0.28	0.93 ± 0.25	1.13 ± 0.21
	COMP	1.08 ± 0.26	1.13 ± 0.29	1.12 ± 0.32	1.07 ± 0.23	0.94 ± 0.34	0.82 ± 0.23†	1.08 ± 0.25
	REC	1.19 ± 0.16	1.20 ± 0.17	1.16 ± 0.19	1.15 ± 0.27	1.12 ± 0.22	1.01 ± 0.24	1.16 ± 0.17
	P-value	p = 0.180	p = 0.391	p = 0.647	p = 0.431	p = 0.095	p = 0.039	p = 0.309

Table 12. RE factors by stage in COMP and REC runners. All results are ± S.D. P-values are two-tailed. †Significantly different from REC @ p ≤ .05.

Stage-by-stage statistics are reported in Table 12, and reflect the same patterns seen in the averages across the 30-min run. No differences were found between the groups with respect to RER and RER VAR, except RER VAR 100, where the COMP runners were significantly lower than REC.

Correlations with MP are reported for the 6 stages and 30-min average for all the RE and RER variables in Table 13. Correlations and p-values are reported for ALL, COMP,

and REC. For ALL, O₂ and ALLO O₂ were both significantly inversely related to MP for all of the stages and for the 30-min average. However, when subjects were divided by group, neither COMP nor REC runners showed any statistically significant relationships between O₂ or ALLO O₂ and MP.

		% of 10k race velocity												AVE	p-value
		75%	p-value	80%	p-value	85%	p-value	90%	p-value	95%	p-value	100%	p-value		
O ₂ Use (ml/kg/min)	ALL	-0.465†	.011	-0.423†	.022	-0.420†	.023	-0.447†	.015	-0.473†	.010	-0.471†	.010	-0.460†	.012
	COMP	0.392	.208	0.338	.283	0.201	.531	0.185	.565	0.045	.889	0.000	.999	0.189	.557
	REC	0.064	.807	0.064	.806	0.101	.699	0.083	.752	0.071	.787	0.043	.870	0.072	.783
ALLO O ₂ Use (ml/kg ^{0.75} /min)	ALL	-0.411†	.027	-0.379†	.043	-0.375†	.045	-0.403†	.030	-0.427†	.021	-0.436†	.018	-0.412†	.026
	COMP	0.553	.062	0.519	.084	0.434	.158	0.424	.169	0.313	.321	0.263	.408	0.435	.158
	REC	0.089	.734	0.091	.729	0.128	.624	0.108	.679	0.102	.696	0.081	.758	0.102	.697
O ₂ per KM (ml/kg/km)	ALL	0.606†	.000	0.646†	.000	0.652†	.000	0.615†	.000	0.584†	.001	0.497†	.006	0.619†	.000
	COMP	0.482	.113	0.504	.095	0.419	.175	0.415	.180	0.239	.455	0.164	.610	0.386	.215
	REC	0.420	.093	0.426	.088	0.453	.068	0.407	.105	0.406	.106	0.326	.201	0.419	.094
ALLO O ₂ per KM (ml/kg ^{0.75} /km)	ALL	0.580†	.001	0.623†	.000	0.640†	.000	0.599†	.001	0.586†	.001	0.514†	.004	0.611†	.000
	COMP	0.588†	.044	0.598†	.040	0.569	.054	0.564	.056	0.453	.140	0.408	.188	0.555	.061
	REC	0.454	.067	0.473	.055	0.506†	.038	0.460	.063	0.473	.055	0.396	.115	0.479	.052
RER	ALL	0.111	.587	0.078	.686	0.069	.722	0.108	.576	0.141	.464	0.190	.323	0.127	.512
	COMP	0.103	.751	0.117	.716	0.181	.574	0.282	.375	0.296	.350	0.358	.254	0.249	.436
	REC	0.043	.870	0.029	.911	-0.003	.991	-0.071	.787	-0.035	.895	-0.049	.851	-0.019	.942
RER Variability (SampEn)	ALL	0.085	.660	-0.002	.990	0.019	.992	0.114	.556	0.220	.251	0.380	.051	0.112	.563
	COMP	-0.240	.452	-0.254	.426	0.096	.766	-0.098	.761	0.020	.952	-0.130	.703	0.049	.881
	REC	-0.271	.292	-0.309	.227	-0.240	.354	0.006	.982	-0.143	.583	0.193	.473	-0.181	.487

Table 13. Correlations with MP (% difference from expected marathon time). All results are \pm S.D. P-values are two-tailed. †Significantly correlated @ $p \leq .05$

Running economy variables, when corrected for pace (O₂ PER KM and ALLO O₂ PER KM), were significantly related to MP for ALL at all stages and 30-min average. The correlation was in the positive direction, with higher O₂ PER KM equating to a higher MP (or a slower than expected time). For both groups, the trend for all of the stages and the

30-min average was in the same positive direction, and the REC runners showed a strong trend towards a relationship ($p = 0.068$ at 85% and $p = 0.094$ for the 30-min ave.). When scaling for BM was applied (ALLO O₂ PER KM), some statistically significant relationships were found within both the COMP and REC groups. While the 30-min ave. was not significantly related to MP, a strong trend was observed in both groups ($p=0.061$ for COMP and $p=0.052$ for REC). Some stages were significantly correlated to MP within groups (COMP runners: 75% ($p = 0.044$), 80% ($p = 0.040$), and REC runners: 85% ($p = 0.038$), while many others showed a trend of $p \leq 0.10$). The RER and RER VAR variables were not significantly related to MP for any of the stages or on average. On the whole, these variables were very weakly correlated with MP and showed no consistency in direction of relationship. However, RER VAR 100 approached significance ($p = 0.051$) with lower variability correlated with better MP.

The multiple linear regression model for ALL runners included O₂ PER KM at 85% of 10k velocity (R-square = 0.401) and RER at 80% of 10k velocity, which raised the R-square to 0.530. The regression equation produced by this model is $y = -126.49 + 0.382(\text{O}_2 \text{ PER KM @ 85\%}) + 59.41(\text{RER @ 80\%})$. For COMP runners the linear regression model included only ALLO O₂ PER KM at 80% of 10k velocity, which yielded an R-square of 0.400. The regression equation for COMP runners is $y = -27.11 + 0.051(\text{ALLO O}_2 \text{ PER KM @ 80\%})$. For REC runners the linear regression model included only ALLO O₂ PER KM at 85% of 10k velocity, which yielded an R-square of 0.256. The regression equation for REC runners is $y = -19.01 + 0.057(\text{ALLO O}_2 \text{ per KM @ 85\%})$.

Discussion

The findings of this study are that of the variables assessed, ALLO O₂ PER KM produces the most sensitive model of RE as a predictor of MP among COMP and REC runners, and that RER and RER VAR are neither different between groups, nor important predictors of MP. Without correcting for velocity, O₂ (ml/kg/min) utilized in the submaximal run is inversely related to MP and is higher in COMP than REC runners, as shown in Figure 6.

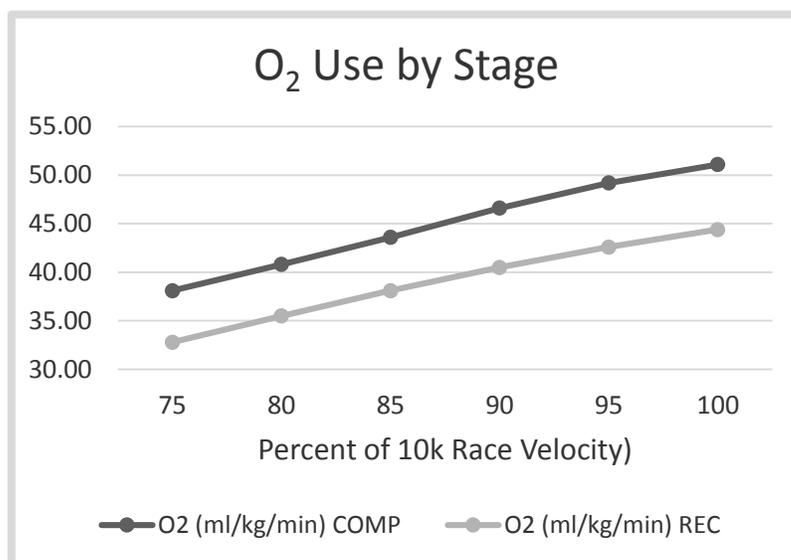


Figure 6. COMP and REC groups O₂ by stage.

This reflects not a true difference in RE, but rather the higher O₂ demand of running faster velocities. Allometric scaling does not substantially change this result. The fact that higher O₂ utilization is correlated with better MP suggests, at first glance, that less economical runners (those with higher O₂ use) are more successful in achieving

their potential at the marathon distance. However, the analysis by group reveals that this statistic is misleading and is simply a reflection of the faster pace and thus higher O₂ utilization sustained by the COMP runners. Elite runners have been reported to have much higher VO_{2MAX} values than average (Joyner & Coyle, 2008; Saltin & Astrand, 1967), so the fraction of maximal O₂ consumption is likely similar or even lower in the COMP group.

When corrected for pace (ml/kg/km), a direct rather than inverse relationship was observed between RE and MP. Differences between COMP and REC runners were seen at all stages and for the 30-min ave. in both O₂ PER KM and ALLO O₂ PER KM, as shown in Figure 7.

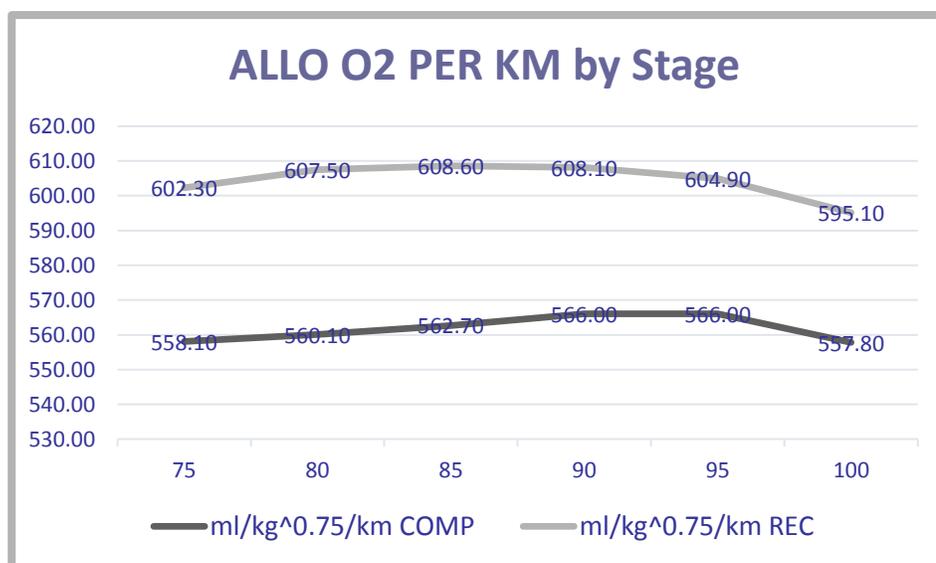


Figure 7. ALLO O₂ PER KM by stage for COMP and REC runners.

The O₂ PER KM measure of RE significantly correlated with MP for ALL runners, but not for REC or COMP groups. This not entirely surprising in light of the literature on

allometric scaling suggesting that reporting O_2 utilization per kg is flawed due to the non-linear relationship between the cost of running and body weight. Heavier runners have been reported to be more economical as a result of this likely flawed manner of reporting RE, whereas lower BM has been identified as an important attribute in distance running performance (Bale et al., 1986; Mello et al., 1988; Sinnett et al., 2001).

Allometric scaling, in combination with reporting RE as a per km value, appears to be more successful in modeling marathon performance for more homogenous groups. In the variable that used correction for velocity and allometric scaling, ALLO O_2 PER KM, some stages were significantly related to MP in COMP (75 and 80% of 10-km velocity) and REC runners (85% of 10-km velocity), with other stages and averages across the 30-min approaching significance. Used in combination with races or time trials of shorter distance, ALLO O_2 PER KM appears to be an important predictor of MP.

The multiple linear regression models for COMP, REC, and ALL participants differed slightly. The selection of ALLO variables for both the COMP and REC runners may reflect the importance of utilizing allometric scaling for more homogenous populations. On the other hand, in ALL runners (a heterogenous population), it appears that scaling may be less important, and that RER may be an important secondary factor in predicting marathon performance. The r-square values indicate that while RE factors can be important in predicting marathon performance, there are clearly other factors to consider in order to produce a stronger predictive model.

Conclusion

Runners classified as COMP used more O₂ than those classified as REC during their sub-maximal RE test, but ran faster and therefore used significantly less O₂ per km. The use of allometric-scaling did not shed any additional light on the analysis for ALL runners, but improved RE as a predictor of MP within both COMP and REC groups. There were no differences between the groups in RER or RER VAR, and those variables were not significantly related to MP. However, RER was included as a variable in the multiple linear regression model for ALL, so it may have a small but important impact on MP particularly in heterogeneous groups.

CHAPTER 6: Conclusion

Competitive runners training for distances up to 5-km have previously shown improved performance and RE in response to PLYO training. Recreational marathon runners appear to differ in their response to this type of training. While this population did benefit from PLYO training in improving sprint performance, maintaining jump performance, and gaining protection against some of the negative changes associated with marathon training, REC runners did not improve distance running performance with PLYO training. The findings of this study suggest the possibility that more competitive marathon runners may experience a performance benefit in addition to the other benefits seen in the REC population. Running economy, characterized as oxygen utilization per km, appears to be an important factor in marathon performance, but the PLYO training protocol utilized in this study did not have an effect on RE. In addition, the results suggest that allometric scaling is important in utilizing RE in modeling marathon performance, particularly in more homogenous groups.

Chapter 7: References

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CHAPTER 8: Appendices**8.1 IRB approval letters****UNIVERSITY OF MINNESOTA***Twin Cities Campus**Human Research Protection Program
Office of the Vice President for Research**D528 Mayo Memorial Building
420 Delaware Street S.E.
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January 16, 2014

Christopher J Lundstrom
Kinesiology
Room 100 CookeH
2061A
1900 University Ave SE
Minneapolis, MN 55455

RE: "Effect of Plyometric vs. Core Training on Marathon Training, Running Economy, and Performance"
IRB Code Number: **1312M46121**

Dear Dr. Lundstrom,

The Institutional Review Board (IRB) received your response to its stipulations. Since this information satisfies the federal criteria for approval at 45CFR46.111 and the requirements set by the IRB, final approval for the project is noted in our files. Upon receipt of this letter, you may begin your research.

IRB approval of this study includes the consent form dated January 9, 2014.

The IRB would like to stress that subjects who go through the consent process are considered enrolled participants and are counted toward the total number of subjects,

even if they have no further participation in the study. Please keep this in mind when calculating the number of subjects you request. This study is currently approved for 80 subjects. If you desire an increase in the number of approved subjects, you will need to make a formal request to the IRB.

For your records and for grant certification purposes, the approval date for the referenced project is December 10, 2013 and the Assurance of Compliance number is FWA00000312 (Fairview Health Systems Research FWA00000325, Gillette Children's Specialty Healthcare FWA00004003). Research projects are subject to continuing review and renewal; approval will expire one year from that date. You will receive a report form two months before the expiration date. If you would like us to send certification of approval to a funding agency, please tell us the name and address of your contact person at the agency.

As Principal Investigator of this project, you are required by federal regulations to inform the IRB of any proposed changes in your research that will affect human subjects. Changes should not be initiated until written IRB approval is received. Unanticipated problems or serious unexpected adverse events should be reported to the IRB as they occur.

The IRB wishes you success with this research. If you have questions, please call the IRB office at 612626-5654.

Sincerely,



Christina Dobrovolny, CIP
Research Compliance Supervisor
CD/ac

CC: Morgan Betker, Alena Brooks, Matthew Fautsch, Stacy Ingraham, Jason Kask, Greg Rhodes, Hayley Russell, Jarred Sampson

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09/05/2013

Christopher J Lundstrom
Kinesiology
Room 100 CookeH
1900 University Ave SE
Minneapolis, MN 55455

RE: "Relationship Between Running Economy and Marathon Finish Time in Competitive Runners"
IRB Code Number: **1308M40941**

Dear Dr. Lundstrom:

The Institutional Review Board (IRB) received your response to its stipulations. Since this information satisfies the federal criteria for approval at 45CFR46.111 and the requirements set by the IRB, final approval for the project is noted in our files. Upon receipt of this letter, you may begin your research.

IRB approval of this study includes the consent form received September 4, 2013 and the recruitment e-mail received August 13, 2013.

The IRB would like to stress that subjects who go through the consent process are considered enrolled participants and are counted toward the total number of subjects, even if they have no further participation in the study. Please keep this in mind when calculating the number of subjects you request. This study is currently approved for 80 subjects. If you desire an increase in the number of approved subjects, you will need to make a formal request to the IRB.

For your records and for grant certification purposes, the approval date for the referenced project is September 3, 2013 and the Assurance of Compliance number is FWA00000312 (Fairview Health Systems Research FWA00000325, Gillette Children's Specialty Healthcare FWA00004003). Research projects are subject to continuing review and renewal; approval will expire one year from that date. You will receive a report form two months before the expiration date. If you would like us to send certification of approval to a funding agency, please tell us the name and address of your contact person at the agency.

As Principal Investigator of this project, you are required by federal regulations to inform the IRB of any proposed changes in your research that will affect human subjects. Changes should not be initiated until written IRB approval is received. Unanticipated problems or serious unexpected adverse events should be reported to the IRB as they occur.

The IRB wishes you success with this research. If you have questions, please call the IRB office at 612-626-5654.

Sincerely,



Christina Dobrovolny, CIP
Research Compliance Supervisor
CD/ks

CC: Stacy Ingraham

8.2 Consent forms

CONSENT FORM

Effect of Plyometric vs. Core Training on Marathon Training, Running Economy, and Performance

You are invited to participate in a research study of the effect of plyometric versus core training on marathon training, running economy, and performance. You were selected as a possible participant because you are enrolled in the University of Minnesota course, PE 1262: Marathon Training. We ask that you read this form and ask any questions you may have before agreeing to be in the study.

This student research study is being conducted by Chris Lundstrom, Ph.D. student, along with Morgan Betker, M.S. student, and Dr. Stacy Ingraham, all from the University of Minnesota-Twin Cities School of Kinesiology. It is funded by TC Running Company, which will provide gift certificates of \$100 or less that will be distributed by random drawing at the conclusion of the study. The study is completely optional, and has no bearing on grading or participation in PE 1262.

Study Purpose

The purpose of the study is to determine the effect of two different 12-week training programs (plyometric versus core training) on recreational runners training for a marathon. Differences between the two groups will be looked at for all of the following: Sprinting and jumping ability, running economy, two-mile and marathon finish time, muscle damage, and self-reported injury and soreness.

Study Procedures

Participants will be placed in either a core or plyometric training group by chance. The core program will consist of abdominal, back and hip exercises, such as crunches and planks. The plyometric program will consist of sprinting and jumping exercises such as hops and 50 meter sprints. The training involves one session of 15-20 minutes per week, for 12 weeks. The training for both groups will begin with basic exercises and become more challenging over the 12 weeks. The exercises are short in duration. The exercise intensity is moderate to high.

Before and after the 12 weeks of training, a number of tests will be done:

- Anaerobic field tests:

- One maximal effort sprint for each of the following: 60-m run, 200-m run, and flying 30-m run (a 30-m sprint with 20-m to build up speed). Sprints will be done on the indoor track and timed by researchers.
- Three maximal effort jumps of each of the following: standing long jump and 10-bound test (alternate leg jumps for maximal distance). The 10-bound test will be done on the indoor track, and the standing long jump will be done into a sand landing pit at the indoor track.
- Rest between tests will be at least one minute between attempts, and at least 3 minutes between tests.
- Anaerobic lab tests:
 - Three maximal vertical jumps, starting from both a squatting position and from a standing position. This involves standing on a force plate and jumping and reaching as high as possible for each jump.
 - A Wingate cycle test on a stationary bike. This involves a short warm-up, followed by a maximal 30 second effort.
- Running economy: A 33-minute run on a treadmill. The pace will begin at a low intensity level and get faster over six stages, finishing at a moderately hard pace (approximately 10-km race pace). This involves wearing a facemask in order to measure oxygen use.
- Blood sample: Less than a teaspoon of blood will be taken two times during the study. The blood will be drawn by putting a needle into a vein in the arm. The blood sample will be tested for creatine kinase, which is a marker of muscle damage. A sample will be taken 1-2 days before and 1-2 days after the marathon run (done as part of PE 1262).
- Training log data: Training logs used for PE 1262 will be examined after the study to assess training days missed due to injury (or other reasons), comments on pain/injury, soreness, preparedness to run, and rate of perceived exertion during select runs.
- Running performance: The 2-mile time-trials and the marathon will be done as part of PE 1262. Records of those performances will be used for data analysis.

Study timeline:

Event	Estimated Time Commitment	Start Date	End Date
Enrollment	30 min.	22-Jan	3-Feb
Field pre-testing	45 min.	27-Jan	1-Feb
Lab pre-testing	75 min	29-Jan	4-Feb

Training intervention	15-20 min./week	5-Feb	23-Apr
Field post-testing	45 min.	23-Apr	28-Apr
Lab post-testing	60 min	26-Apr	30-Apr
Pre-marathon blood draw	15 min.	2-May	3-May
Post-marathon blood draw	15 min.	5-May	6-May

Risks of Study Participation

Certain changes can occur during the testing or training. Muscular soreness and stiffness are common effects of muscular strengthening exercises such as core and plyometric training. Other, less common symptoms that may occur during training or testing include abnormal blood pressure, fainting, irregular, fast or slow heart rhythm, and in rare instances, heart attack, stroke, or death. Every effort will be made to minimize these risks by evaluation of preliminary information relating to your health and fitness (gathered as part of PE 1262 requirements) and by careful observation during exercise and testing. Emergency equipment and trained personnel are available to deal with unusual situations that may arise.

As part of enrollment in PE 1262, you are expected to report certain information about your health. Health-related information will be reviewed by Dr. Stacy Ingraham, and will not be shared with research staff. If Dr. Ingraham is informed of a health issue that makes your participation in part or all of this study inadvisable, she will provide that information to you and note your health condition in a secure file. She will share your condition with the PI only by participant number. You will be advised to stop participating in any activity that may be detrimental to your health, given the reported condition. The Study Coordinator will be informed of the parts of the study that you are advised to not participate in, but the details of your condition will not be shared.

You may choose not to participate in any part of the training or testing due to pain, discomfort, or any other reason, without being removed from the study. You may choose to stop participation in the study at any time, and for any reason.

To protect against the risk that participation in this study will have any influence on grading for PE 1262, the instructor responsible for grading, Chris Lundstrom, will not have access to a list of participants until after final grades have been submitted. Scheduling for testing and training sessions will be done by Morgan Betker. You may request that Chris Lundstrom not be present at either the testing or training sessions, to ensure that no evaluation is being done that could influence grading. All data including missed sessions of training or testing and reported health information will be recorded by a participant ID number in order to protect the confidentiality of participants.

Benefits of Study Participation

There is no direct benefit to subjects who participate in this research. This training intervention and testing may provide insight into your response to muscular strengthening exercises and to running at a range of sub-maximal intensities. This may allow you to tailor your training and racing according to your own physiological responses.

Study Costs/Compensation

There are no costs associated with participating in this study. There is no payment for participation. Participants will be eligible for a random drawing for gift certificates of no more than \$100 provided by the study sponsor, TC Running Company.

Research Related Injury

In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment and follow-up care as needed. Care for such injuries will be billed in the ordinary manner to you or your insurance company. If you think that you have suffered a research related injury, let the researchers know right away.

Confidentiality

The records of this study will be kept private. In any publications or presentations, we will not include any information that will make it possible to identify you as a subject. Your record for the study may, however, be reviewed by departments at the University with appropriate regulatory oversight. Study data will be stored and communicated between researchers only by participant number, and will not reveal your identity. To these extents, confidentiality is not absolute. Study data will be encrypted according to current University policy for protection of confidentiality.

Voluntary Nature of the Study

Participation in this study is voluntary. Your decision whether or not to participate in this study will not affect your current or future relations with the University. If you decide to participate, you are free to withdraw at any time without affecting those relationships.

Contacts and Questions

The researchers conducting this study are Chris Lundstrom, Morgan Betker, and Stacy Ingraham. You may ask any questions you have now, or if you have questions later, **you are encouraged to** contact them:

Chris Lundstrom
Primary Investigator
lund0982@umn.edu
612-381-7970

Morgan Betker
Co-Investigator and Study Coordinator
betke015@umn.edu
563-210-2543

Dr. Stacy Ingraham
Co-Investigator and Advisor
ingra013@umn.edu
612-626-0067

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Fairview Research Helpline at telephone number 612-672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at *Fairview Research Administration, 2344 Energy Park Drive, St. Paul, MN 55108*.

You will be given a copy of this form to keep for your records.

Statement of Consent

I have read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature of Subject _____

Date _____

Signature of Person Obtaining
Consent _____

Date _____

UNIVERSITY OF MINNESOTA

Driven to DiscoverSM

Laboratory of Physiological Hygiene and Exercise Science
University of Minnesota – School of Kinesiology
27 University Recreation Center
1906 University Avenue S.E.
Minneapolis, Minnesota 55455
Phone: 612.625.5506

Informed Consent – Running Economy

Informed consent for an Exercise Test

1. Purpose and Explanation of the Test

You will perform an exercise test on a motor-driven treadmill. The exercise intensity will begin at a low level and will be advanced in stages depending on your fitness level. During the test you will be wearing a facemask or mouthpiece and breathing valve that allows for exhaled air to be analyzed. We may stop the test at any time because of signs of fatigue or changes in your heart rate, or symptoms you may experience. It is important for you to realize that you may stop when you wish because of feelings of fatigue or any other discomfort.

2. Attendant Risks and Discomforts

There exists the possibility of certain changes occurring during the test. These include abnormal blood pressure, fainting, irregular, fast or slow heart rhythm, and in rare instances, heart attack, stroke, or death. Every effort will be made to minimize these risks by evaluation of preliminary information relating to your health and fitness and by careful observations during testing. Emergency equipment and trained personnel are available to deal with unusual situations that may arise.

3. Responsibilities of the Participant

Information you possess about your health status or previous experiences of heart-related symptoms (e.g. shortness of breath with low-level activity, pain, pressure, tightness, heaviness in the chest, neck, jaw, back, and/or arms) with physical effort may affect the safety of your exercise test. Your prompt reporting of these and any other

unusual feelings with effort during the exercise test itself is very important. You are responsible for fully disclosing your medical history, as well as symptoms that may occur during the test. You are also expected to report all medications (including nonprescription) taken recently and, in particular, those taken today, to the testing staff.

4. Benefits to Be Expected

There is no direct benefit to subjects who participate in this research. This test can be used to evaluate your response to exercise at a range of sub-maximal intensities. This may allow you to tailor your training and racing according to your own physiological responses.

5. Inquires

Any questions about the procedures used in the exercise test or the results of your test are encouraged. If you have any concerns or questions, please ask us for further explanations.

6. Out-of-Study Contact

If you have any questions or concerns regarding the study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Fairview Research Helpline at telephone number 612-672-7692 or toll free at 866-508-6961. You may also contact this office in writing or in person at Fairview Research Administration, 2344 Energy Park Drive, St. Paul 55108.

7. Freedom of Consent

I hereby consent to voluntarily engage in an exercise test to determine my exercise capacity and state of cardiovascular health. My permission to perform this exercise test is given voluntarily. I understand that I am free to stop the test at any point if I so desire.

I have read this form, and I understand the test procedures that I will perform and the attendant risks and discomforts. Knowing these risks and discomforts, and having had an opportunity to ask questions that have been answered to my satisfaction, I consent to participate in this test.

Date Signature of Patient

Date Signature of Witness

8.3 Recruitment emails

Plyometric vs. Core Training Study recruitment email

PE 1262 Students:

Researchers from the School of Kinesiology at the University of Minnesota-Twin Cities are recruiting participants from PE 1262 in a study that will examine the effect of plyometric versus core training programs on running performance, anaerobic (sprint, jump, cycle) performance, running economy, muscle damage, injury, soreness, perceived effort and readiness for training sessions and the marathon. This study is optional and participation has no bearing on grading for the class.

The study involves a 12-week training program with one session of 15-20 minutes per week. Participants will be randomly assigned to either the plyometric group or the core group and will stay with that group throughout the 12 weeks. Pre- and post-testing will be done on a number of performance and physiological variables to assess changes that occur over the 12 weeks. Pre-testing will be done in late January and early February, and post-testing will occur in the last two weeks prior to the completion of the marathon on May 4, 2014.

The following tests will be done both pre- and post-training:

- Running economy (a 33-minute, sub-maximal treadmill run)
- Anaerobic field tests (10-bound, standing long jump, flying 30-m run, 60-m run, and 200-m run)
- Anaerobic lab tests (vertical jump and Wingate cycle test)

A capillary blood draw for assessment of muscle damage will be done 3 times throughout the semester, the first prior to the start of the training, the second in the 24-48 hours after a long run, and the last in the 24-48 hours after the marathon.

In addition, training logs will be accessed to evaluate injury/pain/soreness variables, readiness for training and the marathon, and rate of perceived exertion on long runs and other selected workouts. Class data from the 2-mile time trials and marathon finish time will also be used.

Study participants will be entered into a drawing for gift certificates to TC Running Company, a local running shoe store.

An info session will be held after class tomorrow. The Consent Form, which includes more details and information, is attached for you to look over as well. Contact Morgan Betker (Study Coordinator) if you have any questions or are interested:

betke015@umn.edu

563-210-2543

Running economy study recruitment email

Running a marathon? Pretty fast?

The Human and Sports Performance Laboratory (HSPL) at the University of Minnesota is seeking participants with an expected marathon finish time of 3:00 or faster for men, and 3:30 or faster for women. The study will examine the relationship between running economy and other metabolic factors and marathon finish time.

The study involves a 33-minute, sub-maximal treadmill run, with a short warm-up and six incremental stages of 5 minutes each at paces ranging from 75% of 10k pace to 10k race pace. Participants will wear a facemask so that gas analysis can be done throughout the test. This will be used to determine oxygen utilization and other factors related to running economy and the individual's metabolic response to sub-maximal exercise.

A recent (last two months) race finish time at 5k, 8k, 10k or another common road race distance is needed in order to calculate the paces for your stages. The treadmill test will be scheduled 1-2 weeks prior to your marathon and will be conducted at the HSPL on the University of Minnesota Twin Cities campus.

Contact Chris Lundstrom if you have any questions or are interested:
lund0982@umn.edu

8.4 Pre-test instructions**UNIVERSITY OF MINNESOTA**APPOINTMENT

DATE: _____ TIME: _____
 NAME: _____

Your exercise test is scheduled at the above time. Please be prompt and prepare for this test as indicated below. Please plan on this appointment lasting between 45 and 60 minutes.

In order to ensure the utmost in accuracy we ask that you comply with the following:

Pre-Test Instructions:

Be sure that you are rested. If you exercise the day before the test, be sure it is of light to moderate intensity an relatively short duration. You should not exercise within 12 hours of your test.

In the 24 hours prior to your test, eat and drink as you would in preparation for your marathon to ensure a metabolic state that is similar to what you will experience on marathon day.

Wear clothing that is comfortable for running in warm weather and footwear that is similar to what you will run the marathon in.

Additional Preparation and Instructions:

Upon your arrival, you will go over and turn in your forms to the research staff, and you will have an opportunity to ask any questions that you may have. Please be sure to have all necessary information available such as any pertinent medical information.

If you must cancel or reschedule your test, please do so at least 48 hours in advance. (contact Chris Lundstrom, lund0982@umn.edu)

I have read, understand, and agree to the above guidelines and policies.

Signature _____

Date _____

8.5 Testing Protocols

Lab Testing Protocol

Schedule:

- 1) Check in participant, confirm participant number and record number on testing sheet
- 2) Height and weight (for RE and Wingate tests)
- 3) 4 min walk/jog. Start @ 4 mph and progress according to subject preference
- 4) Vertical Jump (3xVJ w/ Vertec, 3xCMJ on FP, 3xSJ on FP, up to 3xVJ w/ Vertec)
- 5) Running Economy
- 6) 5 min. rec.
- 7) Wingate (for another study)

HEIGHT AND WEIGHT:

- 1) Subject should remove shoes for both height and weight
- 2) Extra layers of clothing should be removed for weight. Subject should wear what they will wear for running on the treadmill and for the Wingate test.

WARM-UP

- 1) Use either the Trackmaster or Incline Treadmill.
- 2) Begin with 1 minute at 4 mph, and increase either 1 mph per minute, or according to the subject's preferred warm-up pace.

VERTICAL JUMP

- 1) Subject should stand with heels flat and reaching arm fully extended.
- 2) Bottom of 6" (blue) tape mark should be moved to even with the tip of the furthest extended fingertip
- 3) Subject should take at least one submaximal practice jump, then be asked if they are ready to begin.
- 4) 3-6 jump attempts may be taken, with height vanes being cleared back to provide a goal for increasing on the next attempt. 3 jumps will be taken, then force plate countermovement jumps and squat jumps will be done. Additional attempts at increasing jump height on the Vertec may be taken after the force plate jumps.
- 5) No more attempts after failure to increase on two consecutive attempts, or after a maximum of 6 attempts.

JUMP MECHANOGRAPHY

- 1) Procedures followed according to John Fitzgerald protocol (see separate sheet)
- 2) 3 force plate countermovement jumps will be taken
- 3) 3 force plate squat jumps will be taken, with visual confirmation of no countermovement. In case of a detectable countermovement, trial will be discarded and an additional attempt taken.
- 4) additional attempts at increasing jump height on the Vertec may be taken

RUNNING ECONOMY

- 1) Subject should be fitted with heart rate monitor, wetted, and watch should be checked to confirm consistent signal
- 2) Fan should be turned on and pointed at treadmill.
- 3) Lundstrom RE protocol should be edited according to individual's specific paces, via "Open...Exercise Device Protocol"
- 4) Find subject according MAR2014 ID#, and add visit
- 5) Enter height and weight from data sheet, and select Lundstrom RE for test protocol.
- 6) Click on GX
- 7) Review protocol (a 3 min. warm-up stage and six stages of 5 min. starting very easy and finishing at slightly slower (93%) than 2 mile pace. Elevation remains @ 1.0% throughout
- 8) Confirm that subject knows what to do if they need to stop for any reason (step on rails, or hit stop, or raise their right hand above their head). Inform them that it is best not to try to talk during the test, as it won't be understandable and may affect data.
- 9) Fit subject with mask and connect to Medgraphics cart.
- 10) Click start and confirm HRM and gas data analysis working with 1 minute of standing on the treadmill.
- 11) Click begin exercise and adjust treadmill to reflect appropriate paces throughout the course of the 33-minutes of exercise, monitoring data collection and subject throughout.
- 12) At the conclusion of the 33-minutes, slow the treadmill to 3.0 mph and ask subject to walk for 1 minute.
- 13) Stop treadmill, remove mask, and instruct subject to keep HRM on for Wingate test.

WINGATE (for another study)

- 1) Allow 5 min. recovery after RE test, with access to fluids, bathroom.
- 2) Follow instructions on the white board for set-up and running test.

Field Testing Protocol

- 1) Check in participant and gather Consent if not already done.
- 2) Ask whether it is okay for Chris to be present for testing.
- 3) Find participant number if not already done, and record on testing sheet.
- 4) Testing data sheet should participant number only; no name.

Order of tests:

- 1) Flying-30m (1 attempt)
- 2) Standing long jump (3 attempts)
- 3) 60-m (1 attempt)
- 4) 10-bound (3 attempts)
- 5) 200-m (1 attempt)

Rest requirements:

- 1) At least 1 min between jump attempts
- 2) At least 3 min between tests
- 3) Participants will be scheduled up to 6 per hour and will go together from test to test

Warm-up:

- 1) 5+ min jog
- 2) Dynamic warmup including high knees, butt kicks, straight-leg shuffle, A-skip, B-skip, carioca, and fast feet
- 3) Accelerations 4x50m w/ 1 min rest.

Testing specifics:

- 1) **Flying 30m.** Set up timing gates 30m apart. Confirm distance w/ tape measure prior to testing session, and check timing gate placement before each test. Likewise, measure 20m acceleration zone and confirm w/ tape measure. Explain to subject that the goal is to cover the distance from one gate to the next as quickly as possible, and that they should be hitting full speed at the first timing gate, and not waiting until the gate to accelerate. When the subject is in position, start new test on the remote, and tell the subject to go whenever ready. Record time to hundredths of second on timing sheet immediately.
- 2) **Standing long jump.** Instruct subject to jump from a stationary position as close to the foul line as possible without touching it. Feet must not move prior to jump, however

subject may utilize all muscles and joints providing that feet remain stationary. Subjects may take practice jumps prior to measured jumps, and three jumps will be measured. Rotate through the test subjects to provide rest between jumps, or time 1 minute if necessary. Jump is measured from the outermost (furthest from the pit) edge of the foul line to the closest point of contact in the pit, whether it be where the feet, hands, or any other body part touches. If in question, measure multiple points of contact and choose the shortest distance. Record each jump immediately.

- 3) **60m.** Set timing gates at finish line. Place touch pad on the track behind the 60m start line. Instruct subject that the goal is to cover the distance from the start to the finish line as quickly as possible, and that they will start just behind the starting line and run as fast as possible through the finish line. Explain the 3-point stance start, and instruct subject to compress and hold the touch pad when ready, and to release only upon acceleration into the sprint. Explain that the start must occur within 5 seconds of compressing the touch pad and that the clock starts upon release. When the subject is in position, start new test on the remote, and tell the subject to go whenever ready. Record time to hundredths of second on timing sheet immediately.
- 4) **10-bound test.** Place tape marker that clearly establishing the 0' mark on the long/triple jump runway. Subjects will bound away from the pit and the runway distance markers will be utilized to measure distance to the nearest foot. A tape measure will be used to determine inches. Instruct subjects that the goal is to cover as much distance as possible in 10 bounds, and demonstrate the arm and leg action that is typically used, allowing them to practice. Instruct that a rock-step start is allowed (one foot may step backwards to initiate the first bound), but that the second foot must remain stationary. Three attempts will be measured. Rotate through the test subjects to provide rest between attempts, or time 1 minute if necessary. Jump is measured from back-most point of contact upon landing from the 10th bound. Two spotters should be used in order to determine point of landing. Tester should verbally count bounds for subject. Record each attempt immediately.
- 5) **200m.** Set up timing gates at finish line. Place touch pad on the track behind the 200m start line in the outside lane. Instruct subject that the goal is to cover the distance from the start to the finish line as quickly as possible, and that they will start just behind the starting line and run as fast as possible through the finish line. The 200m is one full lap, minus the stagger. Explain that they should stay in their lane for the whole run. The same touchpad starting procedure will be used as was used in the 60m. When the subject is in position, start new test on the remote, and tell the subject to go whenever ready. Record time to hundredths of second on timing sheet immediately.