

FACTORS AFFECTING RUNNING ECONOMY:
AN EXAMINATION OF THE VISUAL ASSESSMENT
OF RUNNING ECONOMY AND THE INFLUENCE OF FOOTWEAR

by

Robert G. Cochrum

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Dissertation Committee:

Dr. Jennifer L. Caputo, Chair

Dr. Don W. Morgan

Dr. John M. Coons

Dr. Dana K. Fuller

ABSTRACT

Persons with a good running economy (RE) consume less oxygen per unit of body mass than those with poor RE at the same velocity. While many factors affect RE, the extent footwear can affect RE remains elusive. Furthermore, the capability of distance running coaches to visually differentiate runners by RE is unknown. The first study compared RE and step frequency (SF) among recreational distance runners at 50% and 70% of velocity at $\text{VO}_{2\text{max}}$ ($\text{vVO}_{2\text{max}}$), while running barefoot, in minimal shoes, and in normal running shoes. The second study determined the ability of distance-running coaches to visually classify runners by RE and identify the criteria used to rank the runners.

In the first study, RE was not significantly altered by footwear at either 50% $\text{vVO}_{2\text{max}}$ ($p = .89$) or 70% $\text{vVO}_{2\text{max}}$ ($p = .13$). However, large individual variations in RE were seen in certain runners across footwear conditions. Running barefoot produced higher SF than running in the minimal condition at 50% $\text{vVO}_{2\text{max}}$ ($p = .007$). At 70% $\text{vVO}_{2\text{max}}$, SF was higher in the barefoot condition than both the minimal ($p < .001$) and standard conditions ($p < .001$). Furthermore, there was a higher SF in the minimal condition than the standard condition at 70% $\text{vVO}_{2\text{max}}$ ($p = .007$). In the second study, the coaches classified 17.9% of runners or less than 1 in 5 runners correctly. Neither years coaching ($r = .12$, $p = .184$) nor years in competitive running ($r = -.06$, $p = .484$) were related to the accuracy of classifying RE. Overall, footwear did not significantly affect RE despite individual variations and significant differences in step frequency among the shoe conditions. Runners should consider individual biomechanical and physiological

traits before making a footwear change in order to improve RE. Furthermore, the ability of distance running coaches to rank RE was not shown to be accurate or related to coaching characteristics. Consideration should be given to bridging the gap between coaching knowledge and the scientific literature.

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CHAPTER I

DISSERTATION INTRODUCTION

Running economy (RE) is generally defined as the steady-state oxygen consumption ($\dot{V}O_2$) at given submaximal speeds (Saunders, Pyne, Telford & Hawley, 2004a). When expressed relative to body mass (BM), individuals with good RE consume less oxygen per unit BM compared to persons with poor RE running at the same velocity. Because RE is a key predictor of distance-running performance, especially among endurance athletes relatively homogenous with respect to maximal aerobic power ($\dot{V}O_{2\max}$; Saunders et al., 2004a), gaining a better understanding of factors which underlie an economical running style could prove useful to sport scientists, coaches, and athletes seeking a means of improving training or racing performance (Saunders et al., 2004a).

Running economy is influenced by a number of physiological, biomechanical, and anthropometric characteristics. Physiological variables related to RE include, but are not limited to, fluctuations in heart rate (HR), ventilation ($\dot{V}_E$), muscle fiber type, and lactic acid (LA; Saunders et al., 2004a). Although research documenting HR and $\dot{V}_E$ disturbances and their link to RE are limited, both factors have been significantly and positively correlated with submaximal oxygen consumption, such that better RE is linked to lower HR and $\dot{V}_E$ values (Pate, Macera, Bartoli, & Maney, 1989). From a performance viewpoint, a decrease in steady-state HR and $\dot{V}_E$ coincides with findings indicating that more economical runners are able to incur a lower percentage of their $\dot{V}O_{2\max}$ while

running at a given speed, thereby decreasing reliance on fast-twitch, lactate-producing motor units (Conley & Krahenbuhl, 1980). Relative to muscle fiber composition, Williams and Cavanagh (1987) reported no difference in muscle fiber type among runners exhibiting good, medium, and poor RE, while Bosco et al. (1987) found a significant association between the percentage of fast-twitch fibers and net oxygen uptake per unit distance traveled. Slow-twitch muscle fibers, on the other hand, are more efficient per cross-bridge cycle and, hence, utilize less oxygen during oxidative phosphorylation (Bosco et al., 1987). Consequently, greater reliance on slow-twitch muscle fibers would result in less lactic acid accumulation and reduced disruption of the contractile process, leading to better distance running performance (Billat, Flechet, Petit, Gerard, & Koralsztein, 1999).

The aerobic demand of running is also influenced by a host of anthropometric variables (Saunders et al., 2004a). In considering height, shorter runners are more economical than taller runners in longer events (5,000 meters to marathon), whereas taller runners exhibit better RE in races less than 1500 meters in length (Bale, Bradbury, & Colley, 1986; Maldonado, Mujika, & Padilla, 2002). The effect of limb dimensions on RE remains largely unstudied, although some investigators have shown that more economical runners have longer legs (Steudel-Numbers, Weaver, & Wall-Scheffler, 2007), whereas other research has found no length difference among runners varying in economy (Lucia et al., 2006; Williams & Cavanagh, 1987). Conversely, the length of the lower leg (i.e., shank) does influence RE, in that athletes with longer shanks exhibit better RE (Lucia et al., 2006). Relative to limb mass and composition, the distribution of mass more proximally to the hip lowers the kinetic energy required to accelerate and decelerate

the limb, thus improving RE (Myers & Steudel, 1985). Lucia and colleagues (2006) also found that runners with a smaller lower-leg circumference were more economical runners. In addition, a number of research studies have shown that in adults, RE expressed as a function of total BM improves as body weight increases (Bergh, Sjodin, Forsberg, & Svenenahag, 1991; Pate, Macera, Bailey, Bartoli, & Powell, 1992; Williams & Cavanagh, 1987; Williams, Cavanagh, & Ziff, 1987).

Much interest has been focused on the biomechanical features of running and their potential association with RE. Lower-extremity gait variables which have been associated with a more economical running style include a lower vertical oscillation of the body center of mass (COM), a more acute knee angle during swing, greater maximum plantar flexion velocity during toe-off, and greater horizontal heel velocity at foot contact, faster rotation of the shoulders in the transverse plane, and greater angular excursion of the hips and shoulders about the polar axis in the transverse plane (Anderson, 1996; Saunders et al., 2004a). Conversely, biomechanical factors that have shown no significant relationship with RE include the amount of hip and shoulder rotation about the central axis, changes in the velocity of the COM in the anteroposterior and vertical directions during the support phase, the width between successive foot contact positions, and stride length (Williams & Cavanagh, 1987). Focusing specifically on upper-extremity movement, Williams and Cavanagh have suggested that more economical runner's exhibit less arm movement. Hinrichs (1990) has also noted that the movement of the arms during running tends to reduce the side-to-side motion of the body's COM, limit fluctuations in the velocity of the runner in the mediolateral (ML) and anteroposterior (AP) directions, and promote a more consistent forward velocity

(Hinrichs, 1990), all of which help to create a more stable running system that is correlated with improved RE (Dalleau, Belli, Bourdin, & Lacour, 1998).

A specific topic that has been studied frequently in distance runners is footwear (Burkett, Kohrt, & Buchbinder, 1985; Catlin & Dressendorfer, 1979; Divert, Mornieux, Mayer, & Belli, 2005a). The standard running shoe has been created to protect the human foot from traumatic injury and provide chronic injury prevention through cushioning and stabilization design characteristics (TenBroek, 2011). However, the cushioning properties of a standard shoe could result in added mass. Across a range of running speeds, VO_2 increases by $\sim 1\%$ for each 100 grams (g) of mass added to each shoe, thereby decreasing RE (Frederick, Daniels, & Hayes, 1984). Hence, shoe companies have managed to produce lighter-weight cushioned shoes to account for this detrimental effect of added mass. Aside from reduced mass, an additional benefit of traditional running shoes is the elastic return capabilities of cushioning materials, which have been demonstrated to reduce submaximal aerobic demand and improve RE (Craib, Miller, Mitchell, & Morgan, 1996; Saunders et al., 2004a). However, the energy return characteristics of standard running shoes are generally minimal, with most of the energy transferred to the shoe being dissipated through the heel at impact (Stefanyshyn & Nigg, 2000a).

Conversely, an alternative to running in a standard running shoe is to run in a minimal shoe. A minimal shoe is light and lacks the more traditional elevated heel, arch support, and narrow toe box, thereby causing most runners to switch from a rearfoot strike (RFS) in standard shoes to a midfoot (MFS) or forefoot strike (FFS) when running in minimal shoes (Divert et al., 2008; Squadrone & Gallozzi, 2009). Compared to a RFS, a FFS creates larger external dorsiflexion moments around the ankle that are countered

by an internal plantar flexor moment (Denoth, 1986; Williams, McClay, & Manal, 2000). Although higher external dorsiflexion moments result in greater triceps surae contraction, a more controlled dorsiflexion during a FFS could allow enhanced elastic energy storage and return because the heel could descend substantially under controlled dorsiflexion, thereby stretching the Achilles tendon while the triceps surae contracts eccentrically and isometrically (Hof, Zandwijk, & Bobbert, 2002).

Despite a growing scientific understanding of factors which can influence RE, surprisingly little is known regarding how to objectively evaluate runners to determine the extent to which they display an economical running pattern, average RE, or an uneconomical running gait. This disconnect in conveying scientific findings to members of the coaching profession may reflect both a delay in results from sport science research to reach coaches and clinicians and the fact that many coaches misunderstand how to apply basic physiological concepts to training schemes (Bosch, 2006). Moreover, while coaches believe in the value of sport science, they usually receive new or relevant information from other coaches, coaching clinics, or seminars, rather than reading scientific journals (Reade, Rodgers, & Hall, 2008).

To summarize, RE is generally considered the most important factor in distance-running performance (Saunders et al., 2004a). Consequently, it is important for coaches to be able to understand and visually identify characteristics associated with an economical running pattern and have a grasp of research-based recommendations for improving RE. Furthermore, a need exists to assess coaches' knowledge of RE concepts to determine the steps sport's scientist need to take in providing practical recommendations to coaches. An easily identified and modifiable factor that may be

associated with alteration of RE is footwear. However, the literature is inconclusive in determining which type of footwear is most useful for improving RE (Franz, Wierzbinski, & Kram, 2012; Perl, Daoud, & Lieberman, 2012). Also, little is known regarding the extent to which coaches can accurately classify runners along the RE continuum and the degree of congruence between coaches' descriptions of an economical running pattern and actual RE values.

Purpose

This dissertation project features two studies of RE. The purpose of the first study is to quantify differences in RE in recreational distance runners wearing a minimal shoe, a standard shoe, and running barefoot while running at two moderate exercise intensities. It is first hypothesized that running in a minimal shoe will increase step frequency and be more economical than running in a standard running shoe or barefooted at both 50 and 70% of velocity at VO_{2max} (vVO_{2max}). Next, running barefoot will increase step frequency and be more economical than running in a standard shoe at 50 and 70% of vVO_{2max} . The purpose of the second study is to determine the ability of distance running coaches to accurately classify runners varying in RE and identify the criteria used by coaches to classify runners along the economy continuum. It is hypothesized that the number of years spent coaching will be positively related to the accuracy with which coaches classify RE in a group of recreational runners. It is further hypothesized that the number of years spent as a competitive runner is positively related to the accuracy with which coaches classify RE in a group of recreational runners.

Significance of Studies

Although the literature is inconsistent regarding the myriad of factors that can potentially influence RE, it is important for coaches and clinicians to utilize the available scientific literature as a tool for improving running performance. Additionally, many coaches may not know how to best apply scientific knowledge or what to look for when applying research knowledge of RE. A characteristic that is easily identifiable, but inconclusive in its effect on RE, is footwear. As footwear is easily modifiable, an immediate and possibly sizeable improvement in RE can potentially be realized by simply changing shoe type. A clearer understanding of the type of shoe type most suitable for enhancing RE, combined with practical scientific RE recommendations, can help coaches create the most appropriate and successful training program for an endurance runner. It is also important to establish if coaches can correctly identify certain gait characteristics which are directly relevant to direct measures of RE, as coaches typically do not have the capability of performing metabolic testing of their athletes.

CHAPTER II

REVIEW OF LITERATURE

The current review of literature begins with an explanation of RE and the variation that exists within. Next, factors that affect RE are discussed including anthropometrics, performance level, training interventions, gait manipulation, biomechanics, and flexibility. An examination of the knowledge base and implementation strategies of endurance coaches and how each relates to running performance is also presented. The review then transitions to the importance of footwear as a factor that affects RE. Specifically, how the use of various types of footwear, including minimal footwear, affect RE compared to running barefoot. The review concludes by addressing the need for gross visual RE characteristic cues among endurance coaches. In addition, the need for consistency in finding the appropriate footwear for RE improvement is also addressed.

Running Economy

Running economy is generally defined as the oxygen cost of running at various submaximal speeds and determined by measuring steady-state oxygen consumption and respiratory exchange ratio (RER). Although VO_{2max} levels have been associated with better distance running performance (Conley & Krahenbuhl, 1980; Costill, 1967; Costill, Thomason, & Roberts, 1973; Saltin & Astrand, 1967), RE has been shown to be a stronger predictor of performance (Conley & Krahenbuhl, 1980; Morgan, Martin, & Krahenbuhl, 1989). Running economy at a given speed is often measured as a percentage

of $v\text{VO}_{2\text{max}}$ and/or the velocity at the onset of blood lactate accumulation (Billat et al., 1999). Essentially, runners with enhanced RE are able to perform at a relatively lower percentage of their $\text{VO}_{2\text{max}}$ for a given speed and duration. Lower oxygen costs will dampen the accumulation of lactic acid and reliance on fast twitch muscle fibers and also ‘spare’ glycogen stores by utilizing fat as the fuel of choice.

Validity and reliability of RE measures.

The most valid RE measures are assessed at an athlete’s training speed. In trained individuals, a marathoner is more economical at speeds elicited during a marathon race; whereas 800–1,500 meter trained individuals may prove more economical at faster speeds (Morgan et al., 1994). Additional findings from Maldonado et al. (2002) support this notion. In a comparison of elite level marathon, long middle distance, and short middle distance runners at five running speeds, as speeds increased the short middle distance group was significantly more economical than the long middle distance group (Maldonado et al., 2002).

In terms of variability of RE, within subject variation is minimal. Williams, Krahenbuhl, and Morgan (1991) studied the daily variation in RE of 10 moderately trained male runners who ran five times a week for 4 weeks. Each session consisted of 6 minute runs at speeds of 2.68, 3.13, and 3.58 $\text{m}\cdot\text{s}^{-1}$. After each 6 minute bout, the treadmill speed was immediately increased to the next pace. There were no significant differences in the coefficient of variation (CV) among the three running speeds, ranging from ~1-5%. In a similar study, Morgan et al. (1994) found low variation in RE among well-trained male and female distance runners. There was an insignificant ~1-2% CV in RE across speeds, indicating RE remained consistent at various speeds. Additionally, an

improvement was found in the CV of RE as speed increased in the females (statistically significant) and males (non-significant). An important finding from both the Williams et al. and the Morgan et al. research is two consecutive or non-consecutive days of testing accounted for ~90% of an individual's daily variation in RE. Therefore, relatively stable measurements of RE can be obtained based on the average of two measures per participant.

Reliability studies using moderate to well-trained athletes have shown intraindividual variations between ~1% to 5% (Saunders, Pyne, Telford, & Hawley, 2004b). However, technical error can also reduce the reliability of any measurement. From a RE perspective, Saunders et al. studied the typical error (TE) associated with equipment and testing, as well as the biological variation of RE in 11 elite, male distance runners. The authors also measured the between-athlete variation of 70 highly trained runners to determine the magnitude of the smallest worthwhile change (SWC) required for RE differences to be considered relevant. The results demonstrated measurement of RE is relatively stable with a TE of 2.4% observed during three 4-minute stages of running at 14, 16, and 18 km·h⁻¹. Additionally, the results indicated a SWC of 2.4% is needed in elite distance runners to be considered a relevant intervention effect. From an application perspective, an elite distance runner must improve his or her RE by >2.4% before a coach or scientist can be reasonably confident that a real change has occurred. These results are slightly lower, but similar to those of previous literature, indicating less than 10% of the total CV is accounted for by technological or measurement error (Morgan & Craib, 1992; Pereira & Freedson, 1997). Given the relatively minimal TE

found in Saunders et al. the expected amount of measurement error associated with RE in a well-controlled study is small.

In review, runners are most economical at distances at which they train or race. Variation in RE across submaximal speeds is minimal ($\sim 1\text{-}5\%$), with two consecutive or non-consecutive days of RE accounting for $\sim 90\%$ of individual daily variation in RE. Finally, technological error associated with the measurement of RE accounts for less than 10% of the total CV, but a change in RE of $> 2.4\%$ should be achieved before a coach can be confident an adaptation has been achieved. While individual variation in RE is minimal (Morgan et al., 1994), one factor that can influence RE between individuals could be anthropometric differences.

Anthropometrics and RE

Body-specific characteristics such as mass, height, limb length, and body fat percentage have been shown to be determinants of RE. As RE can be expressed as a ratio of a runner's VO_2 (L/min) divided by BM in kilograms (kg), BM can be a significant contributor to RE (Davies, Mahar, & Cunningham, 1997). Teunissen, Grabowski, and Kram (2007) examined the effects of independently altering body weight and BM on the metabolic cost of running. The researchers manipulated the body weight and BM of 10 recreational runners and measured their metabolic rates while they ran at 3 m s^{-1} . Weight was reduced using a harness system. Mass and weight were increased using lead strips attached to a padded belt wrapped tightly around the runner's waist. Mass alone was added by combining loading and simulated gravity, thereby keeping body weight constant and isolating the effects of added mass. Net metabolic rate decreased in less than direct proportion to reduced body weight, increased in slightly more than direct

proportion to added load (added mass and weight), and was not substantially different from normal running with added mass alone. These results are indicative of weight loss or weight gain being detrimental to RE.

Maldonado et al. (2002) examined the influence of body weight and height on the energy cost of running in highly trained middle- and long-distance runners. The authors compared RE at 5 running speeds in 38 national and international male athletes that specialized in marathon (M), long middle distance (LMD), or short middle distance competition (SMD). There was a negative correlation between RE and the height and weight of the runners in the SMD group; indicating the taller and heavier athletes were more economical. Further, there was a reduced RE and height and weight correlation as running distance increased. This finding supports the notion that as competition distance increases, runners with smaller builds could prove more economical (Anderson, 1996; Morgan et al., 1989).

The mechanisms through which BM can affect RE may relate to the thermodynamics of running. Heavier (lean BM unaccounted for) runners produce and store more heat at given submaximal running velocities (Marino, 2000). From a temperature standpoint, Nielsen et al. (1993) found that a core temperature of 39.5°C appears to be a threshold for fatigue for runners of various fitness levels. Fitter, leaner, or more physiologically gifted runners are able to run longer before meeting this thermoregulatory threshold. Heat production increases with BM without a concomitant increase in body surface area with which to dissipate the heat accumulation (Marino, 2000). However, thermoregulation as a limiting factor in RE is only relevant to specific longer events. The pace and distance a runner travels will ultimately determine how

quickly the runner reaches the thermoregulatory threshold and hence determine his or her RE and performance.

In contrast to the idea that runners who weigh less are more economical, other studies have shown that body weight itself is not as important as where the BM is distributed on the body. Aside from height and weight, many studies have shown an anatomical influence on RE. Lucia et al. (2006) found an inverse correlation between maximal circumference of the calf and VO_2 at a set running velocity (21 km/h) in a group of high level Spanish and Eritrean runners. Likewise, Scholz, Bobbert, Van Soest, Clark, and van Heerden (2008) found a strong correlation between a smaller moment arm of the Achilles tendon and RE. Scholz et al. measured the horizontal distance from the lateral and medial malleolus to the Achilles tendon and calculated the moment arm as the mean of these two distances. They indicated that the length of the moment arm explained 56% of the variance in RE. The authors theorized that the improved economy could be due to greater tendon energy storage and a reduced reliance on the contractile elements of the joint.

Additional anthropometrical and anatomical characteristics responsible for changes in RE include lower limb length, achilles tendon length, and smaller than average foot size. In a study examining the impact of the length of the lower limb on economy of running, Steudal-Numbers et al. (2007) found that those with longer legs were able to run at a lower oxygen cost than those with shorter legs. An additional interesting finding was that the lower oxygen costs were achieved without a concomitant increase in stride length. Lastly, in a review of literature by Anderson (1996) seeking to determine the interaction of biomechanics and RE, Anderson found that leg mass

distributed closer to the hip and a smaller than average foot were important factors for improved RE. These findings coincide with results indicating that mass distributed farther away from the trunk (e.g., closer to the feet) increases oxygen costs more than if it was carried on the trunk (Myers & Steudal, 1985). Jones, Knapik, and Daniels (1986) found an average VO_2 increase of 4.5% per kilogram of load carried on the feet. Another study found a 14% increase in VO_2 per kg carried on the feet, compared to only a 7% per kilogram increase when carried on the thigh (Martin, 1985). Additional authors have supported this notion by reporting a 1% increase in VO_2 across various running speeds for every 100 g added to a shoe (Franz et al., 2012; Frederick, 1984).

In summary, the influence of anthropometrical variables on RE are varied. Body weight and height appear to benefit RE in shorter middle distance events as long as weight is distributed closer to the COM. As the running event distance increases, both body weight and height are negatively related to RE. Lastly, smaller feet, shorter heels (in reference to Achilles tendon moment arm), and smaller calf circumference are all negatively related to RE. As discussed previously, performance in endurance-type running is highly influenced by RE (Saunders et al., 2004a). Therefore, differences in anthropometric measurements that affect RE, could also impact running performance.

Performance Level and RE

Many studies have found a correlation between performance and RE. In a comparison of elite distance runners ($\text{VO}_{2\text{max}} = 79 \text{ ml/kg/min}$) and good distance runners ($\text{VO}_{2\text{max}} = 69.2 \text{ ml/kg/min}$), Pollack, Jackson, and Pate (1980) found that the elite runners had better RE than the good runners. The investigation included 20 elite distance runners and 8 good distance runners. The two groups included 8 marathon (M) runners and 12

middle-long distance (M-LD) runners. The variables used for analysis included fat weight, lean weight, VO_2 during submaximal running, blood lactic acid concentration after submaximal work, and $\text{VO}_{2\text{max}}$. Discriminant analysis of the data indicated that a general physiological efficiency factor separated the elite from the good runners. Among other findings, the elite runners were found to be more economical than the good runners and the M runners were capable of utilizing a very large fraction of their $\text{VO}_{2\text{max}}$ for extended periods of time (i.e., better economy). Similarly, in a study examining 10 km and 16 km performance, Fay, Londeree, LaFontaine, and Volek (1989) found a significant correlation between running time and RE. Lastly, in a study comparing runners of comparable ability, Conley and Krahenbuhl (1980) found RE to be a good predictor of performance. The data showed significant correlations between submaximal VO_2 and performance at speeds of 14, 16, and 18 km/h.

To summarize, RE is a strong predictor of racing performance. Elite runners are more economical than good runners and marathon runners appear to be more economical than runners of shorter distances. It is general knowledge that elite athletes train a great deal in order to improve and/or maintain performance. Hence, if training is able to improve performance, then it might also influence RE.

Training Interventions and RE

Running economy is an important determinant of distance running performance and those with better times in specific events often train more than those with slower times. However, whether or not increased training volumes improve RE is inconclusive.

Run training.

In a study examining changes in the onset of blood lactate accumulation (OBLA) and muscle enzymes after 14 weeks of training at OBLA, Sjodin, Jacobs, and Svedenhag (1982) found an increase in the velocity at OBLA (V_{OBLA}) and the relative fraction of heart-specific lactate dehydrogenase (LDH). The activity of phosphofructokinase (PFK) and citrate synthase (CS) decreased after training indicating a reduction in lactate accumulation. Although, the authors did not measure RE directly, an improvement in V_{OBLA} has been shown to be an important factor in enhancing RE (Billat et al., 1999; Farrell, Wilmore, & Coyle, 1993).

In a shorter duration study, Denadai, Ortiz, Greco, and Mello (2006) examined the effects of interval training sessions of 95% and 100% of the vVO_{2max} on running performance. The experiment consisted of runners randomized into a 95% or 100% of vVO_{2max} training group. Each group performed two high-intensity interval training sessions per week, along with four submaximal run sessions per week. Significant improvements included vVO_{2max} , RE, and 1,500 meter (m) running performance in the 100% vVO_{2max} group. The V_{OBLA} and 5,000 m running performance were improved in both groups as well. Considering the vVO_{2max} of most runners is faster than 5,000 m race pace, it could be that both the 95% and 100% training were too intense to cause an improvement in 5,000 m RE. This notion is concurrent with previous research indicating better RE at paces similar to a specific race pace (Morgan et al., 1994).

From a recreational runner perspective, it appears that higher intensity interval training can also improve RE. Franch, Madsen, Djurhuus, and Pedersen (1997) compared the effects of three types of intensive run training on RE. The three groups were divided

into exhaustive distance training (DT), long-interval training (LIT), or short interval training (SIT) three times a week for 6 weeks. $\text{VO}_{2\text{max}}$ increased by 5.9%, 6%, and 3.6% in the DT, LIT, and SIT groups, respectively as did $\text{vVO}_{2\text{max}}$ by 9%, 10%, and 4%, respectively. RE improved by 3.1% in the DT group and 3.0% in the LIT group, but was not significantly different in the SIT group. The significant improvement seen in RE in the DT and LIT groups, but not the SIT group, could be a product of both volume (DT) and intensity (LIT). The average heart rates for the 3 training groups were not significantly different (93%, 94%, 92% of max HR in the DT, LIT, and SIT groups, respectively). However, although indicated as non-significant by the authors, it cannot be ignored that the DT (6,381m) and LIT (5,664m) groups traveled nearly twice as far in their training sessions than did the SIT group (3,049m). The increased volume over the course of a 6-week training regimen may explain why the DT and LIT groups improved RE, whereas the SIT group did not.

In contrast, in a study involving untrained male university students, Lake and Cavanagh (1996) found no change in RE over a 6 week training period. However, the participants did improve their $\text{VO}_{2\text{max}}$ and their running performance. The authors suggested that factors leading to improved RE, such as adjustments in movement patterns and ground reaction forces, may be influential after longer periods of training when physiological attributes such as $\text{VO}_{2\text{max}}$ have nearly peaked. This suggestion supports findings of a review by Morgan and Craib (1992) that training periods of 14 weeks to 5 years are needed for significant improvements in RE in non-high intensity training programs.

From a volume of training perspective, a few studies have indirectly examined the effects of volume of training on RE and the data are conflicting. Pate et al. (1992) found that training volume was not associated with better RE. However, Mayhew (1977) found that years of training was significantly correlated with RE in well-trained distance runners. The Morgan and Craib (1992) review supported the notion that the cumulative distance run over years rather than the most recent volume is most important. The review revealed no change or a slight decrease in RE following short training periods of 6-11 weeks, whereas training periods of 14 weeks to 5 years showed improvements in RE ranging from 3-18% (Morgan & Craib, 1992).

In other studies comparing the RE of runners of various training states, as well as various speeds, results support the notion that RE is not affected by training status. In a study examining well-trained distance runners, Helgerud, Storen, and Hoff (2009) sought to determine if differences existed in RE at different velocities in male and female distance runners. No significant differences in RE were found at velocities between 75% and 90% of VO_{2max} , supporting the findings of Di Pampero, Atchou, Bruckner, and Moia (1986) and Helgerud (1994). Finally, Slawinski and Billat (2004) found no significant differences in the cost of running between highly-, well-, and non-trained runners. Further, the range of intensities in the study ranged from 80-97% of vVO_{2max} , thereby providing support to the findings of Helgerud et al. (2009). However, the methods with which the runners in this study controlled their pace could have affected their economy. The highly-trained runners were paced by a cyclist traveling at a prescribed velocity. The well-trained and non-trained runners adopted the prescribed speed using an audio rhythm which determined the time to cover the next 25 meters. It could be that externally

controlling pace through various - and possibly distracting - means (cyclist, audio device) would inhibit the runner from developing his or her naturally selected stride rate, length, and RE. Additionally, the internal reliability of the study is affected due to running pace being controlled via two different protocols. In summary, higher training volumes have not been shown to increase RE. However, those who have accumulated more miles over the course of many years exhibit better RE than those with less years of training. Lastly, high intensity interval training >95% of $v\text{VO}_{2\text{max}}$ can improve RE in both trained and recreational runners.

Strength training and RE.

Endurance athletes must be able to maintain a high running velocity throughout the duration of a race (Saunders et al., 2004a). Subsequently, the role of neuromuscular factors in voluntary and reflex neural activation, muscle force and elasticity, running mechanics, and the anaerobic capacity of the athlete become highly important (Saunders et al., 2006). From a neuromuscular standpoint, Noakes (1991) proposed that runners with poor RE may have muscles that are less able to utilize the impact of energy produced as they eccentrically absorb the force of a landing. The ability to utilize this stored elastic energy depends on the relative stiffness of the various musculotendinous units. Arampatzis, DeMonte, Karamanidis, Klapsing, and Stafilidis (2006) in examining distance runners at submaximal speeds confirmed that runners with better RE exhibited enhanced levels of contractile strength and muscular stiffness. Resistance training has been shown to not only improve muscular strength, but also to potentially increase the stiffness of the muscle-tendon system, thereby increasing RE. Therefore, resistance

training could prove more consistent in improving RE, than run-type training which has only provided equivocal results (Midgley, McNaughton, & Jones, 2007).

Millet, Jaouen, Borrani, and Candau (2002) sought to investigate the influence of a concurrent heavy weight training (HWT) + endurance training program on RE and VO_2 kinetics in distance athletes. The researchers randomly assigned 15 well-trained participants who were randomly assigned to an endurance-strength (ES) training group or to an endurance only group (E). Before and after the 14 week training period, all participants performed field-and laboratory-based running and muscle function tests including a hopping test at a 2-Hz frequency to determine the maximal mechanical hopping power and lower-limb hopping stiffness. Training for the ES group consisted of two HWT sessions of lower-limb muscles per week that focused on the quadriceps, hamstring, and calf muscles. Workouts consisted of two warm-up sets followed by three to five sets to failure of 3 to 5 reps. The training program was periodized so that in each of these periods, the number of sets increased. The loads were progressively increased in order to maintain this range of repetitions per set. Results from the Millet et al. study were found to support the findings from previous research (Hoff, Helgerud, & Wisloff, 1999; Johnston, Quinn, Kertzer, & Vroman, 1997; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999) indicating an improvement of economy after a combined strength and endurance training program in endurance athletes. As for specific results, the E group maintained the same level of max strength, but showed a significant decrease in max hopping power and hop height. Whereas, the ES group increased max strength and maintained hopping power.

In line with the literature, significant relationships between max hopping power and max running velocity, average treadmill power, and hopping stiffness have been reported in young sprinters (Chelly & Denis, 2001). According to Millet et al. (2002) the correlation ($r = .55, p < .05$) between the change of RE and the change of hopping power during the training period suggests that the E group's decrease of muscular power may have affected RE. Millet et al. found no change in contact time or vertical stiffness while hopping in the ES group. However, Millet et al. suggested normal strength training (normal speed concentric contractions $> 90\%$ of 1RM) is associated with lower mean power and a slower rate of neural input than explosive-type strength training. Hence, the training performed in the Millet et al. study may not have been optimal for improving the stiffness in a maximal stretch shortening cycle (SSC) exercise like hopping; regardless of the increases in concentric strength and power. The ES group developed significant gains in lower body strength (25% in the half-squats and 17% in the calf raise) compared to no changes in the E group. The change in strength could have contributed to the 2.7% increase in $vV\dot{O}_{2\max}$ seen in the ES. However, Millet et al. found the correlation between change in $vV\dot{O}_{2\max}$ and change in RE was weak ($r = -.46, p = .09$), indicating that changes in RE are not explained to a great extent by the change in $vV\dot{O}_{2\max}$. In summary, the addition of HWT to endurance training of well-trained athletes was associated with a significant increase in running performance ($vV\dot{O}_{2\max}$) and an enhancement of RE. The improvements were suggested to be caused by an increase in maximal lower-limb power.

As indicated by Millet et al. (2002), HWT is a form of resistance training shown to improve RE and $vV\dot{O}_{2\max}$. Another form of resistance training that has shown promise in developing RE is explosive resistance training – also called plyometric

training. Plyometric training invokes specific neural adaptations such as an increased activation of the motor units, with less hypertrophy than typical heavy-resistance strength training (Saunders et al., 2006). Plyometric training enhances the muscles' ability to generate power by exaggerating the stretch-shortening cycle. An additional morphological change (as with most forms of resistance training) is the potential to increase the stiffness of the various muscle-tendon units. Consequently, RE could be improved by generating greater muscular force with less metabolic energy requirement (Saunders et al., 2004b).

Saunders et al. (2006) investigated a short-term plyometric training program in highly trained middle and long distance runners. The study consisted of 15 participants divided into a plyometric group (PLY) and a control group. Baseline and post testing included measures of RE at 3 running speeds (14, 16, and 18 km·h⁻¹), a maximal test to determine $\text{VO}_{2\text{max}}$, and strength and power parameters using a variety of jumping protocols. The PLY training lasted 9 weeks and consisted of three 30 minute sessions per week. The major finding from Saunders et al. is that the addition of 9 weeks of PLY to an endurance training program improved RE at 18 km·h⁻¹ by 4.1% when compared to a matched control group. The changes in economy occurred in spite of an absence of change of any cardiorespiratory measures including V_E , RER, HR, stride frequency, and LA. Saunders et al. suggested that improvements in RE are due to improved muscle power development and better use of stored elastic energy. The lack of improvements at the lower speeds of 14 and 16 km·h⁻¹ could be due to greater reliance on elastic machinery at increasing speeds, as shown by various literatures (Cavagna & Kaneko, 1977; Taylor, 1994).

The research appears to lend consistent support for various types of resistance training being beneficial to improving RE. However, to the competitive athlete, racing performance is likely more important than training. Few researches have investigated if racing performance is influenced by resistance training. Paavolainen et al. (1999) found that 9 weeks of explosive-strength training improved RE by 8% and 5km performance by 3% in spite of any significant change in $\text{VO}_{2\text{max}}$. Paavolainen et al. also measured various neuromuscular characteristics using a 20 m sprint test, the distance covered in five alternate forward leg jumps and the corresponding contact times, in addition to vertical and horizontal forces measured on a force plate during a 200 m run. The explosive-strength training group improved in all of these variables when compared to the control group (no strength training). The Paavolainen et al. results support the idea that RE is likely improved via resistance training due to enhanced neuromuscular function.

Additional research involving racing performance and plyometric training was conducted by Turner, Owings, and Schwane (2003), who found a 6% improvement in RE across three running speeds ($9.65 \text{ km}\cdot\text{h}^{-1}$, $11.27 \text{ km}\cdot\text{h}^{-1}$, and $12.89 \text{ km}\cdot\text{h}^{-1}$) and a 3% increase in 3 km run performance. Interestingly, the results from Turner et al. (2003) were not indicative of enhanced neuromuscular characteristics as the PLY training did not result in changes in jump height or various other neuromuscular variables. As for a time frame for improvements to occur, it appears that Turner et al. and Spurrs, Murphy, and Watsford (2003) have found improvements in RE due to PLY training in as little as 6 weeks.

Overall, resistance training of various types appears to benefit RE through both increased muscle power characteristics, and enhanced neuromuscular function. Coaches

and clinicians seeking to improve RE in athletes should consider utilizing resistance training and more specifically, explosive-type resistance training, as a non-running means of improvement. Improvements in neuromuscular function as well muscular and connective tissue strength could, in turn, lead to improvements in individual biomechanical characteristics. As a significant portion ($R^2 = .54$) of the variation in RE can be explained by biomechanical characteristics (Williams & Cavanagh, 1987) the addition of strength training to RE could be a worthwhile training endeavor.

Biomechanics and RE

Many of the often measured factors affecting RE are biomechanical characteristics including joint angle, ground reaction force, tendon elasticity, and stride length. These factors are generally referred to as kinematic and kinetic data. Whereas kinematics is a description of movements that do not consider the forces that cause the movement, kinetics attempts to explain these movements. Correspondingly, running involves the conversion of muscular forces (kinetics) trans-located through complex movement patterns (kinematics) that utilize all the major joints in the body (Saunders et al., 2004a). These forces and movement patterns are influenced by many anthropometrical characteristics including height, weight, and limb length and the impact of these variables on RE were discussed previously. High performance running is reliant on skill and precise timing in which all movements have purpose and function (Anderson, 1996) and various biomechanical characteristics play a crucial role.

In studies both collaboratively and individually, Williams and Cavanaugh (1987) have examined the relationship between biomechanics and RE. In an extensive study, Williams and Cavanaugh measured the effects of separate mechanical factors thought to

influence RE in 31 actively training runners in three RE groups (low, medium, high). The authors divided the results into three categories including: variables significantly different between groups; variables showing consistent trends between groups; and variables showing no significant differences or trends. In the significantly different between groups category, the vertical component of the ground reaction force as a function of time was smaller in the high RE group than in the low RE group. The high RE group exhibited a greater angle of the shank with the vertical at foot strike than the low RE group, smaller maximal plantar flexion angle following toe off than either the medium or low RE groups, more forward trunk lean during the running cycle than the low RE group, and lower minimum velocity of a point on the knee during contact than either the medium or low RE groups.

Of the energy and power variables measured, the low RE group showed significantly less transfer between the legs and the trunk than the other two groups. Although exhibiting no significance, many variables did trend toward that direction. The high RE group showed lower mechanical power (net positive power, total mechanical power), greater between segment energy transfer, smaller peak anteroposterior and vertical peak forces, a tendency towards a more “rear foot” strike, greater knee flexion during support, less arm movement, and less oscillation of the center of mass than both the medium and low RE groups.

In spite of these significant characteristics, Williams and Cavanagh (1987) found many exceptions indicating a large interindividual variation in RE. For example, the more physiologically efficient group of runners had a significantly greater forward lean compared with the least efficient group; nevertheless there were still individuals who

exhibited high RE and very little forward lean and runners who had low RE values and a large forward lean.

Still yet, as previously mentioned (Williams & Cavanagh, 1987), a substantial amount of variation in RE ($R^2 = .54$) can be contributed to biomechanical aspects. Of the many biomechanical characteristics shown to impact RE, vertical ground reaction forces (GRF), stride frequency, and stride length appear to be the most studied and consistently consequential.

RE and Vertical Ground Reaction Force

The spring-mass model of locomotion proposed by Dalleau, Belli, Bourdin, and Lacour (1998) dictates that the bounce of the body on the ground is counteracted by the spring behavior of the support leg. During the eccentric phase of contact, mechanical energy is stored in the muscles, tendons, and ligaments acting across joints. Recovery during the eccentric phase of the stored elastic energy reduces energy expenditure (Saunders et al., 2004a). In relation, an oscillating system is characterized by a resonant frequency with resonant frequency being the frequency at which a system freely vibrates after a mechanical impulse. Therefore, a more stable system, with less oscillation or resonant frequency, would theoretically result in greater economy.

Consequently, oscillation in any plane that does not contribute to forward momentum could be detrimental to RE. However, oscillation in the vertical plane via various GRF characteristics appears to be particularly unfavorable for advancing RE. Specifically, Cavagna and colleagues (Cavagna, 2006; Cavagna, Franzetti, Heglund, & Williams, 1988; Cavagna, Willems, Franzetti, & Detrembleur, 1991; Cavagna, Mantovani, & Willems, 1997) found and proposed that an increase in relative vertical

force (RF_v) leads to an asymmetrical rebound during high-velocity running. As running speed increases, the asymmetry becomes greater, thus leading to a decrease in push-average power (i.e., the work done divided by the duration of positive work production), and a decrease in maximum running velocity.

In a study that specifically manipulated vertical components and the subsequent influence on RE, Tseh, Caputo, and Morgan (2008) manipulated various running patterns in 9 female distance runners. All participants completed 2 sessions in which standing VO_2 was measured and participants ran for 6 minutes at $3.35 \text{ m}\cdot\text{s}^{-1}$ under 4 randomly selected conditions including: 1) normal running (NL); 2) hands behind back (BK); 3) hands on head (HD); and 4) running with exaggerated vertical oscillation (VOSC). Oxygen uptake measures were taken during the last 2 minutes of each running session. VOSC and HD created significantly higher VO_2 values compared to BK and NL. VO_2 measured during VOSC was also higher compared to HD. A perhaps more interesting finding is that no significant difference in gross VO_2 was observed between the BK and NL conditions. These results differ from the findings by Egbuonu, Cavanagh, and Miller (1990) who found a significant 4.0% increase in submax VO_2 in female distance runners who ran with a similar BK condition. Additionally, the runners in the Tseh et al. study exhibited a 19% increase in submax VO_2 (decrease in RE) compared to only 4.6% in Egbuonu et al. (1990) when VOSC was deliberately increased. However, the Tseh et al. study did employ a slightly higher vertical oscillation than the Egbuonu et al. investigation which could have contributed to this variation.

A limitation to the Tseh et al. (2008) investigation could have affected the overall outcomes of the variables measured. As shown by the Hinrichs (1990) study, upper body

muscular activity increases as running speed increases. Tseh et al. only measured one speed ($3.35 \text{ m}\cdot\text{s}^{-1}$). It could be that placing the arms behind the back only affects oxygen costs once a certain percentage of one's max speed is reached. In summary, derivation from normal running patterns via increased VOSC or by severely altering upper body mechanics (e.g., hands on the head while running) will cause significant decreases in RE.

In contrast to the Tseh et al. (2008) and Egbunu et al. (1990) studies, Bourdin, Belli, Arsac, Bosco, and Lacour (1995) sought to reduce vertical oscillations through loading the trunk via weight vest. The authors studied 10 male runners to determine the effect of vertical loading during level treadmill running at a velocity of 5 m/s. The net energy cost of running (Cr) and the external work of the center of mass of the body (Wext) were measured. When the participants ran with a vertical load of 9.3% of their BM, Cr and Wext were significantly reduced. The variations in the Cr and the Wext due to vertical loading were significantly correlated ($r = .75, p < .01$). The authors concluded that the reduction in the Cr with the added load was mainly due to the significant decrease in Wext . Therefore, reducing many of the unnecessary vertical components of running in favor of more horizontal momentum could promote better RE.

Brughelli, Cronin, and Chaouachi (2011) investigated the relationship of vertical and horizontal forces to running velocity (up to maximum) on a variety of kinematic and kinetic variables in Australian-Rules football players. Additionally, the authors investigated the relationships between maximum running velocity and various mechanical variables. A randomized crossover design was used to assess vertical force, relative vertical force, horizontal force, RF_v , contact times, stride length, stride frequency, and COM displacement over a range of velocities (40, 60, 80, and 100% of

maximum running velocity). As running velocity increased from 40 to 60%, vertical force (F_v) significantly increased. However, as running velocity increased from 60% to maximum, F_v remained relatively constant. In contrast, horizontal force (F_h) significantly increased with increments from 40 to 60%, from 60 to 80%, and from 80% to maximum speed. Vertical COM displacement remained relatively constant as running velocity increased from 40 to 60%, but significantly decreased as velocity increased from 60 to 80% and from 80% to maximum.

Therefore, as running speeds increase, horizontal force production becomes more important than vertical force production. Runners who exhibit higher vertical GRF characteristics as speeds increase must work harder to achieve and/or maintain a certain speed, thereby reducing RE. In contrast, those able to apply greater horizontal (non-braking) forces, with a concomitant maintenance of vertical forces, should exhibit better RE. Moreover, as running speeds increase so too does stride frequency. Consequently, manipulation of stride frequency could theoretically benefit RE by increasing horizontal force production and reducing vertical displacement.

Control of step frequency and vertical oscillation.

As determined by previous literature, as running velocities increase, so does both stride length and frequency (Brughelli et al., 2011; Saunders et al., 2004a). However, at stable speeds, there is generally a negative and interchangeable relationship between stride length and frequency (Saunders et al., 2004a). An additional variable relationship can be found with VOSC or displacement. As stride length is increased, stride frequency is relatively reduced, which leads to an increase in vertical displacement (Bourdin et al., 1995) which has been found to be less in those exhibiting better RE (Oyvind, Helgerud,

& Hoff, 2011; Williams & Cavanagh, 1987). At stable speeds, this relationship is reversed if stride length is shortened (Eriksson, Halvorsen, & Gullstrand, 2011).

Similarly, stride frequency has been shown to be positively correlated with leg stiffness (Farley & Gonzalez, 1996). Subsequently, according to work by Dalleau et al. (1998), RE is significantly correlated with muscle stiffness ($r = .80$) and resonant frequency ($r = .79$) of the propulsive leg, with stiffer muscles exhibiting lower working resonant frequencies. Hence, increasing stride frequency could indirectly lead to an increase in RE through reducing unnecessary VOSC.

However, the research suggests that most runners will freely develop running patterns that are the most economical for them (Williams & Cavanagh, 1987). Therefore, a conflict exists in whether to manipulate various biomechanical running factors in order to improve physiological variables (e.g., RE). Although Williams and Cavanagh (1987) suggested that over time runners will develop their most economical running patterns, it could be that manipulation of specific variables through various forms of feedback might lead to improvements of RE.

Eriksson et al. (2011) studied the possibility of controlling step frequency and vertical displacement using visual and auditory feedback. It was hypothesized that 1) by means of visual and verbal auditory feedback, a runner would be able to immediately reduce the product of step frequency and vertical displacement by a significant amount; and 2) when a runner received feedback on the product of step frequency and vertical displacement only, he or she would be more likely to reduce vertical displacement than step frequency to achieve the target. Recreational runners and orienteers ($N = 18$), completed 11 runs at $16 \text{ km} \cdot \text{h}^{-1}$ using either auditory or visual feedback. The visual

feedback was displayed on a TV-monitor in front of the runner using three vertical bars. The left bar represented the vertical displacement, the middle bar represented step length, and the right bar showed the mechanical power consumption. In each bar, a mark was shown indicating the target level set by the researchers. The auditory feedback was given through a wireless headset that the participant wore during the trials. The information was presented as pre-recorded verbal instructions on how to correct technique. The volume of the recordings was proportional to the error of the runner in relation to the target and represented the amount of correction needed.

Participants were more willing to compromise vertical displacement than stride frequency to achieve the target mechanical power. Further, although non-randomized and therefore not conclusive, the auditory feedback appeared to be more influential than the visual feedback. Eriksson et al. (2011) suggested that auditory feedback may have been more useful for dictating running parameters due to it being presented continuously rather than intermittently (every 2 seconds) as was the visual feedback. Additionally, the auditory feedback could not be readily ignored, whereas the visual could easily be disregarded by the runner looking away either purposely or by distraction. Third, because the runners did not have to focus on a screen in the auditory trial, they may have been able to concentrate on other environmental and inherent feedback to help achieve the desired running characteristics.

In summary, the findings of Eriksson et al. (2011) demonstrate that stride frequency and vertical displacement can be controlled in order to improve the mechanical cost of running. Practically, these results indicate that both an auditory and visual training program can be used by a runner to alter his or her technique in order to find a

comfortable stride frequency/VOSC that reduces overall mechanical work. Though the relationship between the mechanical cost of running and RE has been inconclusive mechanical power output could be an indirect measure of muscular effort (Martin & Morgan, 1992). Hence, a reduction muscular effort would reduce the oxygen cost of running and improve RE. Eriksson et al. (2011) demonstrated an improvement in the mechanical cost of running through stride frequency and vertical oscillation manipulation. However, little research has sought to determine how biomechanical training can influence RE. The literature suggests that runners will gradually develop or choose running patterns (e.g., stride length) that are the most economical for them (Williams & Cavanagh, 1987); however, not all runners seem to do so.

Control of stride length.

Morgan & Martin et al. (1994) examined whether distance runners displaying uneconomical freely chosen step lengths (FCSL) could be trained to shift FCSL toward a more optimal setting. Runners ($N = 9$) exhibiting an uneconomical FCSL completed 15 treadmill sessions of optimal step length (OSL) training at individually determined running velocities. The training sessions featured alternating 5-minute periods of combined audio and visual feedback matching OSL and no feedback. Compared with the control group, the experimental group demonstrated a significantly greater shift in FCSL toward OSL. These results suggest that at least through audiovisual feedback training, RE can be improved through step length perturbation.

In contrast, using a verbal and visual feedback system on running technique, Messier and Cirillo (2007) found no significant difference in RE after 5 weeks of training. However, the authors did find that they were able to influence changes in

relative stride lengths, shorter support time, and greater ankle dorsiflexion during support and greater knee flexion during support and non-support. Notably, the runners in the Messier and Cirillo study were of novice training status, but it was not mentioned if they exhibited an uneconomical FCSL to begin with. In addition, although not addressed specifically, changes in running mechanics could take longer than 5 weeks to manifest physiological (i.e., RE, V_E) adaptations as demonstrated in previous literature (Saunders et al., 2006).

As can be seen, it may be possible to introduce interventions to running patterns (e.g., stride length) in order to improve RE. However, this concept currently remains inconclusive. Perhaps more important than controlling a runner's stride length or frequency could be the time and force of impact with which the runner strikes the ground per stride. As such, the reverberations sent through the body as the foot makes contact with the ground could prove highly influential on RE.

Ground contact/support time and RE.

During ground contact, a runner activates muscles for the purposes of stability and for the maintenance of forward momentum. These functional and mechanical requirements during stance are reflected in the characteristics of the ground reaction force GRF. Excessive changes in momentum produced by runners in the vertical, AP, and ML directions could be considered wasteful motions in terms of metabolic energy requirements (Heise & Martin, 2001).

Heise and Martin (2001) hypothesized that less economical runners would exhibit greater support requirements during foot contact, as indicated by higher total vertical impulse (TVI) values. It also was hypothesized that higher magnitudes of the net vertical

impulse (NVI) and absolute medial-lateral impulse (MLI) would be associated with less economical running. The authors measured a group of 16 men with 10-km run times between 38-45 minutes. The stated hypotheses were examined by computing the associations between RE and the normalized GRF characteristics. Only two of the GRF characteristics, measured TVI and NVI, were found to exhibit significant positive correlations with RE. The results indicate that those with better RE exhibit less total and net vertical impulses. It was suggested that the TVI-RE relationship explained nearly 40% of the variability found in RE.

Additional studies have investigated the influence of running velocity on running mechanics in endurance and sprint athletes and each has reported similar findings to Brughelli et al. (2011). Kyrolainen, Belli, and Komi (2001) reported that relative vertical force (RF_v) increased only slightly (non-significant) as running velocity increased beyond 6.0m/s^{-1} . Nummela, Keranen, and Mikkelsen (2007) studied the effects of running at velocities from 4.5m/s^{-1} to maximum in 25 male endurance runners. Results indicated the RF_v remained relatively constant after the athletes attained a running velocity of 6.5m/s^{-1} .

In a more recent study, Oyvind et al. (2011) studied the effect of running stride peak forces on the RE of elite runners. The authors studied step length and frequency, contact time, and the peak horizontal and vertical forces of each step. The sum of the horizontal and vertical peak forces revealed a significant inverse correlation both with 3,000 meter performance ($r = .71$) and RE ($r = .66$) indicating that avoiding vertical movements and high horizontal braking force could be important for improved RE.

Similarly, Kram and Taylor (1990) suggested that the cost of running involves little work against the environment, but instead is done by muscles and tendons to lift and accelerate the body and limbs. The authors hypothesized and confirmed an inverse relationship between the rate of energy used for running and the time the foot applies force to the ground during each stride. These findings are at least somewhat supported by various works (Heglund, Fedak, Taylor, & Cavagna, 1982; Heglund & Taylor, 1988; Kram & Taylor, 1990) in which it was found that the metabolic demand of running is comparative to the force developed by the muscles. The force produced by the muscles is a product of supporting the weight of the body and the rate at which these forces are developed. If a greater amount of time is needed to develop force during each stride, more active muscle activity is needed; hence, increasing the cost of running (Heglund et al., 1982; Heglund & Taylor, 1988). Additional support for more economical runners exhibiting less ground contact time is found in a study by Nummela et al. (2006). The authors concluded that short contact times are required in both economical and high speed running indicating the importance of fast force production for each.

In summary, GRF characteristics are important considerations when assessing RE. Runners with better RE exhibit less vertical GRF characteristics and less horizontal braking forces. In relation to less braking force, runners with shorter ground contact times also exhibit better RE, thereby relying on greater restitution of elastic energy and less muscular effort. Correspondingly, as speeds increase, horizontal force production becomes more important than vertical force production.

Indices of various GRF variables represent important factors in describing variations in RE. However, factors aside from stride kinematics and kinetics could

influence movements in various GRF planes; namely, the sometimes drastic movements of the upper body. Although rarely researched, if movements of the arms, and hence upper body, affect GRF characteristics, then RE could also be affected.

Upper body biomechanics.

Very little literature has been written on the function of the arms in running. As previously addressed, Tseh et al. (2008) found a significant decrease in RE when runners' hands were placed on their heads while running at $3.35 \text{ m}\cdot\text{s}^{-1}$. However, Tseh et al. also found no difference when the runners' hands were placed behind them while running. Hence, the importance of upper body action, and/or arm movements, while running is equivocal. In general, the research that has been conducted on the upper body's contribution to running has focused on three major aspects: 1) electromyography (*EMG*) and net joint moment consideration (Hinrichs, 1985); 2) center of mass and propulsion considerations (Hinrichs, Cavanagh, & Williams, 1983); and 3) angular momentum considerations (Hinrichs, 1987; Hinrichs et al., 1983).

Hinrichs (1990) studied 10 recreational distance runners and filmed them three-dimensionally using four cameras while each ran on a treadmill at three speeds (3.8 m/s, 4.5 m/s, and 5.4 m/s). Simultaneous EMGs were recorded from eight upper extremity and trunk muscles with half of the participants wearing the electrodes on the right side and half on the left side. The first main finding was that the arms contribute little to angular momentum of the body about the ML and anteroposterior AP axes. Contrary to previous literature (Mann, 1981; Mann & Herman, 1985), the authors found that nothing indicated that the arms are able to balance the legs in any way about the ML and AP axes.

However, about the vertical axis, angular momentum in the upper body was found to offset the angular momentum of the lower body, leaving only a small amount of total-body angular momentum about this axis. Hinrichs (1987) suggested that the upper body helped create an angular impulse that allows the legs to more readily change their vertical angular momentum during the airborne phase. Subsequently, the arms were found to make a meaningful contribution of 5 to 10% to the vertical linear impulse on the body during each contact phase and consequently provide lift. The contribution of the arms to lift was found to increase as running speeds increased. The forward propulsion (drive) was not affected by arm movement. However, the arms were found to reduce fluctuations in the velocity of the runner in both the ML and AP directions. An interesting finding was that the arms were found to cross over slightly in front of the body, rather than swinging forward and backward. Although traditionally thought of as poor running mechanics, Hinrichs found it to be beneficial, in that it tended to reduce the side-to-side motion of the body center of mass, thus promoting more consistent forward velocity.

Finally, in reference to EMG activity, Hinrichs (1987) found moderate to strong activity in all the musculature sampled (deltoids, latissimus dorsi, triceps, pectoralis major, biceps, and brachioradialis). The activity of these muscles increased as running speed increased. The posterior deltoid showed the strongest activity and reached a peak of 60% of maximum voluntary contraction (MVC) at the fastest running speed. Considering the increased activity with increased running efforts, it would appear that the arms do serve a force application purpose and contribute to the ability to increase running velocity.

Additional research on the mechanics of arm action in running or RE is sparse. Williams & Cavanagh (1987) reported a relationship between arm action and energy cost in distance running. Williams found that those runners who were more economical showed less wrist excursion over the running cycle than those runners who were less economical. In another study assessing energy cost, Claremont and Hall (1988) examined the use of hand and ankle weights in running. The authors reported that carrying hand weights significantly reduced peak angular velocities and excursions of the upper arm and forearm compared to a no weight condition. In agreement, Hinrichs (1990) suggested that larger arms would not have to swing as vigorously to generate an equal amount of angular momentum about the vertical axis.

In summary, the action of the arms while running appears to add lift to the body, thus making it easier for the legs to transition from stride to stride. How this interaction affects VOSC demands more research. In addition, running with the arms crossing in front of the body could actually benefit RE in contradiction to what has been previously thought. However, running with the arms in a drastically altered position (i.e., behind the back) and thereby limiting arm movement does not seem to affect RE. Considering the stark contrast of these two findings, determination of the effect of the arms and upper body on RE remains elusive.

Overall, the biomechanical aspects related to RE are highly influential in describing individual variations in RE. To varying degrees, stride length, stride frequency, and vertical displacement appear to be the most influential biomechanical characteristics. Stride frequency, length, and vertical oscillation are inter-related at steady state speeds, in that as stride length increases, stride frequency decreases, leading to an

increase in vertical oscillation (Bourdin et al., 1995; Dalleau et al., 1998; Eriksson et al., 2011; Farley & Gonzalez, 1996). Other biomechanical factors influencing RE are ground contact time and the movements of the upper body. Runners exhibiting better economy exhibit shorter ground contact time and greater horizontal force development (Heise & Martin, 2001). The movements of the upper body work to balance the actions of the lower body in the vertical axis and also provide lift to the runner as one step transitions to the next (Hinrichs, 1987). However, research essentially subtracting the movement influence of the arms (Tseh et al., 2008) found no differences in RE. Finally, researchers attempting to manipulate characteristics of RE in order to improve RE have found various degrees of success (Eriksson et al., 2011; Morgan et al., 1994). However, runners also tend to develop metabolically appropriate running patterns over time (Williams & Cavanagh, 1987). Therefore, the usefulness of RE training remains questionable.

Flexibility and RE

Stretching through various means has been traditionally used as means to improve flexibility in hopes of improving performance and/or preventing injury (Nelson, Kokkonen, Eldridge, Cornwell, & Glickman-Weiss, 2001). However, the research supporting the relationship between flexibility and RE is equivocal, with the majority of research pointing to more flexible runners being less economical.

A few studies have been conducted supporting the theory that stretching can improve RE. Godges, Macrae, Longdon, Tinberg, and Macrae (1989) compared two commonly practiced stretching techniques to determine which was most effective for improving hip range of motion. The authors evaluated the effect of these stretching techniques on RE over a 3 week period in 7 moderately trained, male college students.

Goniometric measurements of hip range of motion (ROM) and RE were taken before and after a static stretching or soft tissue mobilization with proprioceptive neuromuscular facilitation (STM/PNF) stretching routine. The static stretching routine resulted in significant improvements in ROM for hip extension and hip flexion. The STM/PNF also resulted in significant improvements in hip extension ROM and hip flexion ROM. A significant improvement in RE at 40%, 60%, and 80% of VO_2 max were found following the static stretching procedure. The STM/PNF procedure improved RE only at 60% of $\text{VO}_{2\text{max}}$. The results suggest that static and STM/PNF stretching are useful for improving hip ROM, however, static stretching is best for improving RE.

In contrast, various studies have found either no influence of stretching on RE or an inverse relationship. In a study involving a 10-week program of stretching exercises and its effect on RE, Nelson et al. (2001) found that a stretching routine did not result in a significant change in RE. The researchers investigated 32 college aged students who reported running consistently for at least 6 months, 3 to 5 days a week, and not performing a stretching routine. RE and sit-and-reach scores were assessed both before and after a 10-week stretching program. Post testing revealed a significant improvement in sit-and-reach scores, but no significant change in RE. Some limitations can be deduced from this study. Although the stretching routine involved 15 different exercises involving both active and passive stretching, the only measurement taken to assess flexibility was the sit-and-reach test.

More recent findings involving RE and sit-and-reach scores by Jones (2002) found an inverse relationship between flexibility and RE. However, the runners in the Jones investigation were of international caliber, whereas the Nelson et al. (2001)

participants were recreational runners. It is important to note that the sit-and-reach test assesses the flexibility of the lower back and hamstring muscles (Baechle & Earle, 2008) and therefore does not accurately assess general ROM in joints such as the hip, knee, and ankle. In consequence, the results by Nelson et al. cannot be directly compared to the work by Godges et al. (1989) who used a goniometer to measure hip joint ROM.

In a now classic study examining the association between flexibility and RE in sub-elite level male distance runners, Craib et al. (1996) found the least flexible runners to be more economical. The purpose of the study was to examine the association between nine measures of limb and trunk flexibility and RE in 19 competitive distance runners with 10-km race times under 40 minutes. The nine flexibility assessments included (1) trunk rotation, (2) side bend, (3) heel-to-buttocks, (4) standing external rotation of the hip with hip flexion at 90°, (5) sit-and-reach, (6) hip flexion, (7) straight leg raise, (8) dorsiflexion of the foot and, (9) plantarflexion of the foot. Of the nine stretch routine variables administered, only standing external hip rotation and dorsiflexion were significantly correlated (negative) with RE. The forward stepwise regression model included the two significant variables and resulted in an R^2 of 0.47, indicating 47% of the variance observed in the RE measures was predicted by the dorsiflexion and standing external hip rotation flexibility measures.

Likewise, Gleim, Stachenfield, and Nicholas (1990) found that untrained participants who exhibited the lowest flexibility were the most economical when running at speeds ranging from 3-11 km/h. This finding coincides with the findings of Craib et al. (1996) in that less flexibility in the transverse and frontal planes of the trunk and hip regions of the body stabilize the pelvis at the time of foot impact with the ground. Less

flexibility can help to reduce the need for muscular forces to reduce excessive ROM, instead relying on the stiffness of the musculature and connective tissue to do so (Gleim et al., 1990). In summary, enhanced flexibility via training or otherwise does not appear to be beneficial for RE. However, the extent to which RE is affected may depend on the performance level of the runner (recreational vs. sub-elite to elite). One possible reason for better RE in the less flexible runners could be due to a tighter musculotendinous (MTU) which could reduce the muscular effort via increased restitution of elastic energy.

Musculotendinous unit activity and RE.

Flexibility research appears to suggest that less flexibility, particularly in the hip and ankle areas, helps to reduce the oxygen cost of running. The mechanisms responsible are suggested to be the activity of various musculotendinous units and activation of the stretch-shortening cycle (SSC) and various stretch reflex responses (Saunders et al., 2004b). The physiology of the SSC has been well documented in the sports training literature (Baechle & Earle, 2008; McArdle, Katch, & Katch, 2007). The mechanical model of the stretch reflex involves three components including the series elastic component (SEC), contractile component (CC), and the parallel elastic component (PEC).

While the SEC includes some muscular components, it is the tendons that constitute the majority of the SEC. When the musculotendinous unit is stretched, as in an eccentric muscle action, the SEC acts as a spring and is lengthened; as it lengthens, elastic energy is stored. If a concentric action begins immediately after the eccentric action, the stored energy is released, allowing the SEC to contribute to total force production (Baechle & Earle, 2008). The SSC utilizes the energy storage capabilities of

the SEC as well as stimulation of the stretch reflex to aid in a maximal increase in muscle recruitment over a minimal amount of time (Baechle & Earle, 2008). The SSC is can be divided into three phases: 1) eccentric – with a stretch of the agonist muscle; 2) amortization – a delay between the end of the eccentric phase and the beginning of the next phase; 3) concentric phase – shortening of the agonist fibers (Baechle & Earle, 2008). These phases, characteristic of musculotendinous activity, form the basis of previous results involving GRF (Boudin et al., 1995; Brughelli et al., 2011; Kram & Taylor, 1990; Kyrolainen et al., 2000; Nummela et al., 2006; Oyvind et al., 2011) flexibility (Craib et al., 1996; Gleim et al., 2005; Godges et al., 1989; Jones, 2002; Nelson et al., 2001), and the contributions of each to RE. Previous research indicates a more efficient MTU has the ability to store and release elastic energy and therefore contribute to locomotion via a reduction in the muscular effort needed to propel the body forward or to control unwanted movements. Less active musculature will decrease oxygen costs via reduced substrate utilization. As speeds increase, enhanced RE will also decrease reliance on type 2 muscular fibers thereby reducing lactate accumulation.

A quality example of the major contribution of the musculotendinous structures to movement can be found in the work of Ker, Bennett, Bibby, Kester, & Alexander (1987). The authors estimated that the Achilles tendon and tendons in the arch of the foot can store 35% and 17%, respectively, of the kinetic and potential energy gained and dissipated in a step while running at moderate speeds. As speeds increase, elastic recovery of energy prevails over the contractile machinery and accounts for most of the work (Cavagna, Saibene, & Margaria, 1964; Cavagna & Kaneko, 1977; Ker et al., 1987; Taylor, 1994). The extent of elastic capabilities is influenced by the rate and magnitude

of stretch, the level of activation and stiffness of the muscle tendon unit, muscle length at completion of the stretch, and the time lag between completion of the stretch and initiation of the succeeding concentric contraction (Aruin & Prilutski, 1985; Aruin, Prilutski, & Raitsin, Savelev, & Cheloveka, 1979; Cavagna & Kaneko, 1977). Therefore, the major role of the musculature during running is to modulate the stiffness of these springs to maximize the exploitation of elastic energy (Alexander, 1991; Cavagna et al., 1988; Taylor, 1994).

The Achilles tendon and arch of the foot are not the only structures to store and release elastic energy. Sasaki and Neptune (2006) examined muscle mechanical work and elastic energy utilization during walking and running near the preferred gait transition speed. The authors quantified the mechanical work done by individual muscle fibers and series elastic elements (SEE) in a group of young adults walking and running above and below the preferred walk-run transition speed (PTS). Potential advantages related with the muscle fiber–SEE interactions at various speeds were also assessed. It was hypothesized that (1) muscle fiber mechanical work is greater in running than walking below the PTS, and inversely, fiber work is greater in walking than running above the PTS, and (2) SEE utilization is greater in running above than below the PTS. Major findings included less muscle fiber work in walking below the PTS, than in running, but higher in walking than running above the PTS. Thus, walking below the PTS is more metabolically economical, whereas running is more suitable above the PTS due to less muscle fiber work and greater SEE utilization. It was estimated that energy stored in the tendon and aponeurosis of the triceps surae and quadriceps accounted for 75% of the energy stored in all the tendons active in running.

In addition to the general capacity of a MTU to produce non-metabolic force, it has been suggested that an MTU with a longer tendon should have more potential for stretch, storage of elastic energy, and ultimately, more force generation during the subsequent concentric muscle action (McCarthy et al., 2006). Thinner tendons (smaller cross sections) will store and return less mechanical energy for the same stretch. However, thinner tendons have more stress, strain, and stretch for any given force, favoring increased elastic energy storage when force is held constant (Biewener & Roberts, 2000). The muscles around the ankle and knee joints contribute > 70% of the total mechanical work during running as indicated by Kumagai et al. (2000) and in line with the work of Sasaki and Neptune (2006). Likewise, Hunter et al. (2011) suggested that these two muscle tendon complexes could be of particular importance for generation of SSC potentiation during running.

Considering the apparent importance of these two muscle tendon complexes for force generation during running, Hunter et al. (2011) investigated the independent relationships of knee/ankle flexibility, quadriceps/patella tendon length, and Achilles tendon length and thickness with walking economy and RE. It was hypothesized that tendon length and thickness, as well as joint flexibility, would be positively related to walking economy and RE. The study involved 21 male recreational distance runners who had completed either a 10-km or marathon race in the last 6 months. Quadriceps/patella and Achilles tendon length were measured by magnetic resonance imaging (MRI) and economy of locomotion was measured at a walking speed of 3 miles per hour (mph), and running speeds of 6 and 7 mph (NVOWK, NVO6, and NVO7 respectively). Knee and ankle joint flexibility were measured by goniometry, and leg lengths were measured by

anthropometry while seated. Achilles tendon length was positively related to NVOWK, NVOW6, and NVOW7. Achilles tendon cross section (thickness) area was unrelated to any walking or running oxygen uptake. Quadriceps/patella tendon length was positively related to NVO7 and significance was approached for a relationship between quadriceps/patella tendon length and NVO6 ($r = .38, p = .06$). Plantar flexion flexibility was significantly related to NVO7 and correlations between plantarflexion flexibility and NVO6 ($r = .31, p = .09$) and NVOW ($r = .33, p = .08$) approached significance. However, after examining the independent relationship of each of the variables to RE, Hunter et al. found that only longer Achilles tendon and reduced flexibility of the plantar flexors achieved significance.

These results could imply that individuals who have longer and less flexible tendons have a more compliant ankle plantar flexor MTU, therefore increasing SSC activity and RE. A surprising finding was the lack of a significant relationship between walking economy or RE and Achilles tendon cross section. Overall, Hunter et al. (2011) found a coefficient of determination for two different statistical models indicating that over 50% of the variance in RE was explained by Achilles tendon length and either plantar flexor or knee extensor flexibility. The findings from Hunter et al. support the need to account for tendon length and flexibility of the plantar flexors when determining differences in RE. Considering the length of tendons is likely genetic and unchangeable, it could be inferred that at least a portion of RE is pre-determined and unlikely to be affected by training.

Finally, Arampatzis et al. (2006) tested the hypothesis that runners having different running economies would show differences in the mechanical and morphological properties of their MTU in the lower extremities. Long distance runners ($N = 28$) ran on a treadmill at velocities of 3.0, 3.5, and 4.0 m s⁻¹ for 15 min each. Along with kinematics of the left leg during running, measurements of isometric maximal voluntary plantarflexion and knee extension contractions at 11 different MTU lengths of the left leg were measured with a dynamometer. A cluster analysis was used to classify the participants into three groups according to their RE at the three velocities. The most economical runners exhibited higher contractile strength of the triceps surae muscle tendon unit, a higher compliance of the quadriceps tendon and aponeurosis at low level forces (< 45% of MVC), and higher energy storage capacity during MVC in both the triceps surae and the quadriceps MTU. Clearly, the findings from Arampatzis et al. (2006) add to the majority of research indicating morphological MTU differences between runners of various RE calibers.

In summary, flexibility and the activity of the MTU appear to be inter-related. Less flexible runners are able to rely on the MTU for storage and restitution of elastic energy, thereby reducing muscular effort and improving RE. Beyond flexibility, the ability to rely on the MTU for elastic return could be at least partially related to tendon morphological properties. Thinner tendons and longer Achilles tendon, quadriceps, and patellar tendon lengths are both related to better RE at various speeds. Although flexibility can be enhanced, it is difficult to become “more” inflexible. Similarly, aside from growth or extreme flexibility gains, it is likewise difficult to increase tendon length. Therefore, a portion of RE appears to be genetically pre-determined.

The literature concerning factors that influence RE is expansive and varied. Perhaps more problematic is that most factors appear to be inconclusive. For example Godges et al. (1989) found greater flexibility to be beneficial for RE, whereas Gleim et al. (1990) found those less flexible to be more economical while running. Yet still, the ability for flexibility training to be useful for RE could be dependent on the treatment and treatment group. Godges et al. used a stretching treatment and then measured RE whereas the Gleim et al. participants were only assessed for flexibility in various positions before RE was assessed. As for the type of sample used, the Godges et al. and Gleim et al. participants were recreationally fit, whereas Craib et al. (1996) used sub-elite level distance runners. From a coaching standpoint, dissemination of the scientific literature could depend on which source of literature the coach consults. One coach may deem poor hip flexibility as characteristic of good RE, whereas another may see poor hip flexibility as an area that can be targeted to improve RE. For the coaches and clinicians in the field, applying up-to-date scientific principles can be more difficult when the literature is unclear as to what constitutes positive and negative RE characteristics. More importantly, due to limited access to equipment and resources needed to assess RE, a coach must be able to visually determine that a runner may exhibit poor RE before an attempt to correct running patterns is made. Therefore, a need exists to assess coaches' knowledge in visually determining the qualities of excellent or poor RE.

Knowledge of RE Characteristics

Reade, Rodgers, & Hall (2008) sought to determine how high performance coaches access the knowledge of sport scientists. The purpose of the study was to answer the questions: 1) How do coaches perceive sport science research, 2) What sources do

coaches consult when looking for new ideas, and 3) What barriers do coaches encounter when trying to access new information? Reade et al. (2008) found that coaches believe that sport science makes an important contribution to high-performance sport. Coaches are most likely to consult other coaches or attend coaching conferences to get new information (Reade et al.) In addition, sports scientists and their publications were ranked very low by the coaches as likely sources of sport science information. According to Reade et al., the barriers to the coaches' access to sport science are the time required to find and read scientific journals, and lack of reasonable access to sport scientists. Therefore, a need exists for an avenue whereby scientific knowledge can be made readily available to coaches for more immediate use.

Similarly, Williams and Kendall (2007) sought to determine how elite coaches and sports scientists perceive the research needs of elite coaching practice. Surveys were administered to coaches representing 19 sports of whom over 90% reported having more than 10 years' experience as a coach and 51.7% held a bachelor degree or higher. The survey consisted of 88 items designed to gather information about elite coaches' and sports scientists' perceptions of the research needs of elite coaches. Four areas of focus were identified for the study: application of sport science research, qualities valued in coaches/researchers, information-seeking/dissemination strategies, and coaching education and knowledge.

Williams and Kendall (2007) found that both coaches and researchers agreed that it is the role of the researcher to inform coaches of pertinent developments within various sports science disciplines. Among the qualities valued in coaches and researchers, there were significant differences between the responses of the researchers and coaches. The

coaches placed more emphasis on the “success of athletes” and “many years of coaching experience,” whereas the researchers placed more emphasis on “keeping up to date with the latest developments” and “having good rapport with the support personnel.” The findings of Williams and Kendall and Reade et al. (2008) express the need for sports scientists to somehow disseminate recent scientific findings to coaches in ways coaches can both easily understand and apply. Suggestions for appropriation of scientific findings to coaches include participation in coaching clinics and reporting in sports-specific magazines. An interesting, but logical finding is that both coaches and researchers agreed that coaches need more research that is based in “natural” settings (Williams & Kendall, 2007). Thus, as the laboratory cannot replace that which takes place in the field of play, a need exists for scientists to present practical and cost-effective means to coaches for both evaluating and improving RE.

As discussed previously (Reade et al., 2008; Williams & Kendall, 2007), coaches appear to value scientific knowledge, but find it either impractical or not readily accessible. Coaches also prefer to gain new knowledge from other coaches or coaching seminars and clinics rather than academic publications (Reade et al., 2008). Therefore, the development of knowledge, and hence success, within coaching circles could be somewhat inhibited by a divide between science and practice. However, effective coaching is a mixture of pedagogy, science, and sociology (Nash & Collins, 2006) and can therefore be affected by various factors.

Gilbert, Lichtenwaldt, Gilbert, Zelezny, and Cote (2009) conducted an exploratory study to compare the developmental profiles of successful high-school coaches to determine if portions of a coach’s developmental profile were associated with

successful coaching. The findings suggested that more successful coaches had accumulated extensive experience as an athlete and were better than average athletes in relation to their peers. These findings are not surprising given research has shown that many coaches attribute their development of coaching knowledge to their own experience and observing experienced coaches (Nash & Collins, 2006). Similarly, coaching can be somewhat thought of as the education of the athlete and, as such, coaches are teachers. Berliner (1994) suggested that the expert teacher with 10 years' experience will have spent a minimum of 10,000 hours in the classroom as a teacher, preceded by about 15,000 hours in the classroom as a student. Therefore, appropriate knowledge and application of current scientific research, as well as experience as both a coach and athlete, may help determine successful coaching.

In reference to endurance sports specifically, coaching success not only depends on knowledge and application of current scientific knowledge, but also more common physiological variables (e.g., $\text{VO}_{2\text{max}}$). However, research suggests that many coaches who work with endurance athletes do not have a solid grasp on basic physiological concepts. Bosch (2006) found that many coaches who work with endurance athletes still believe in old concepts that are no longer considered correct. The most common misunderstandings related to the concepts of $\text{VO}_{2\text{max}}$, lactate threshold (LT), training heart rate, and dehydration and fluid requirements during prolonged exercise. These findings support the previously discussed work of Reade et al. (2008) and Williams and Kendall (2007) in which the most current and/or useful scientific information is not being appropriately relayed to the coaching population.

In summary, coaches and scientists appear to share a similar vision as to the importance of sports science in the field of play. However, a lack of an appropriate funnel whereby recent scientific findings can be transferred to coaches exists. Most coaches do not have the equipment necessary to measure RE and/or in the case of recruiting, the time, to pull in a runner and test them in a lab. From a recruiting standpoint, an exceptional runner who exhibits poor RE could possess the most potential for improvement and therefore, be valuable to a potential team. The ability to quickly and effectively identify potential RE problem areas is a valuable and necessary skill to a coach or clinician. However, this ability could be lacking as evidenced by the findings that many endurance coaches lack a true understanding of how to apply many basic physiological mechanisms. An inability to correctly apply certain physiological concepts could also lead to a poor ability to visually identify potential areas for improvement. In essence, a coach's breadth of knowledge of a sport should expand beyond the dissemination of raw physiological numbers. Coaches should also be able to identify problems or potential areas of improvement through visual inspection of the athlete in action.

A potential area of improvement that coaches can assess visually and scientifically is the influence of footwear on a runner's economy. Given that footwear is the runner's only true piece of equipment, choosing the right type of shoe is of great importance. A coach's knowledge should be such that he/she is able to identify if a runner can improve their economy simply by changing the type of shoe they are wearing.

Footwear and RE

Storage and return of energy via footwear.

One factor that has consistently shown to influence RE is footwear (Saunders et al., 2004a). Williams and Cavanagh (1987) suggested that though many physiological and biomechanical factors contribute to RE, the most economical runners have identifiable characteristics in their running patterns. Williams and Cavanagh suggested that these characteristics affect muscular demands both before and during support, with forefoot strikers relying on musculature to assist with cushioning, making them less economical. In contrast, rear foot strikers tend to rely on footwear and skeletal structures to take the load and are more economical (Williams & Cavanagh, 1987). In lieu of the fact that > 75% of shod runners typically rear RFS and most running footwear is designed to absorb the load in this area, RFS are likely to be most affected by the cushioning properties of a shoe. Indeed, some well cushioned shoes have been found to reduce oxygen costs by up to 2.8% over stiffer shoes of the same weight (Frederick, 1983; Frederick, Clarke, Larsen, & Cooper, 1983). The reduction in oxygen costs due to footwear could be due to the energy return characteristics of the shoe.

Shorten (1989) investigated the possibility of energy return from footwear. The investigator noted that the energy return ability of the footwear compared to the passive elastic properties of the body is minimal. Most of the energy transferred to the shoe is dissipated through the heel at impact. Later, Stefanyshyn and Nigg (2000a) estimated that only 10-15 joules (J) of energy is stored and recovered during a running step. The actual amount of elastic recoil depends on the specific material used in making the shoe. For energy return from footwear to be useful, it must occur directly over or anterior to the

COM of the support leg, thereby allowing the athlete to be propelled forward. However, in contrast to the majority of shod runners who are RFS, the bulk of the heel of the footwear is not in contact with the ground as propulsion begins. Thus, Stefanyshyn and Nigg estimated even lower amounts of energy (4 to 6 J) are available for return to the stride cycle. It was also estimated that 30% of energy transferred to the shoe is dissipated as heat and the remaining energy is only useful if the timing, frequency, location, and direction of impact are ideal (Stefanyshyn & Nigg, 2000a).

Considering the apparent lack of energy return elicited from a standard shoe, the importance of wearing a shoe appears to be primarily for protective purposes. Modern running shoes are designed to make running more comfortable and less injurious by using elastic materials in a large heel to absorb some of the transient force and spread the impulse over more time (Nigg, 1986). The pad of the human heel is also able to provide some protection from impact forces. Two types of injuries often occur due to various amounts of running: 1) traumatic injuries and 2) overuse injuries. Traumatic injuries occur quickly and often without prior cause/influence. Traumatic injuries can include stepping on dangerous objects and sprains and strains of joint structures. Traumatic injuries are capable of occurring no matter the type of footwear. Overuse injuries are related to a tissue or bone structure being repeatedly stressed, leading to breakdown of that tissue. Stress fractures of the tibia and lower leg are a classic example of overuse injuries in runners. Shoe companies have responded to these potential injury mechanisms by providing shoes with ample cushioning, as well as motion control soles to help minimize or correct certain joint abnormalities. Additionally, physicians and podiatrists

often prescribe cushioned and soft athletic footwear or soft insoles as a means to treat those with stress fractures or lower leg injuries (Gillespie & Grant, 2000).

The storage and return of energy via standard running shoe materials is limited (Shorten, 1989). Specifically, the bulk of the cushion in standard running shoes is relegated to the heel of the shoe. Considering that energy return is most useful when it occurs directly over or anterior to the COM of the support leg, the construction of standard running shoes is not optimally designed for energy return. An additional problem with running shoes with a large amount of cushion could be the mass of the shoe. Cushioning materials throughout the sole could add economy reducing mass to the shoe, without a concomitant increase in energy return.

Shoe mass.

Conversely, the addition of materials and structures (arch, midsole) to help protect the foot via cushioning or overcome structural deficiencies (e.g., over pronation) could lead to a heavier shoe. From a mass and RE standpoint, less mass on the distal extremities is more economical (Catlin & Dressendorfer, 1979; Jones et al., 1986; Martin, 1985; Myers & Steudal, 1985). More specifically, Frederick et al. (1984) demonstrated that across a range of running speeds, VO_2 increases by $\sim 1\%$ for each 100 grams of mass added to each shoe. Considering mass alone, it would appear that a lighter shoe would be more beneficial for RE and likely subsequent performance. In a study of various shoe types and weights, Burkett et al. (1985) examined 21 habitually shod runners at $3.35 \text{ m}\cdot\text{s}^{-1}$ without controlling for shoe type, shoe weight, or strike type. Runners were 1-2% more economical when running barefoot compared to the usual shod condition. The difference

was attributed to the extra mass of the shod running. Inherently, it seems logical that lighter footwear is more economical than heavier footwear.

A potential explanation for a mass effect on RE could be lower leg stiffness. Divert et al. (2008) found that leg stiffness varied when mass was applied to the shoe. Peak GRF did not change between mass conditions when shod, but vertical stiffness did. Consequently, VOSC increased with additional mass on the footwear. Stride frequency was also shown to be reduced when mass was added as has been seen with previous literature (Erikson et al., 2011).

In a study specifically examining differences between running shod versus barefoot, Franz et al. (2012) found running shod to be more economical than running barefoot. Franz et al. studied the effects of adding mass to both the feet and footwear in measuring the metabolic cost of running barefoot versus shod and strike type and RE. The authors studied 12 participants with the following study inclusion criteria: mid-foot strike preference both barefoot and with shoes, ran at least 25 km/week total, including at least 8 km/week barefoot or in minimal running footwear for at least 3 months out of the last year, and a self-reported ability to sustain a $3.3 \text{ m}\cdot\text{s}^{-1}$ running pace for at least 60 minutes. Participants completed four “barefoot” running conditions: barefoot, barefoot with ~150 g, ~300 g, and ~450 g of mass added per foot. The same procedure was conducted in the “shod” condition as shoes weighing ~150 g and 300 g per shoe were worn.

Franz et al. (2012) found that adding mass to the feet significantly increased oxygen uptake whether running barefoot or shod. Linear regressions of the data indicated that for each 100 g of mass added per foot, VO_2 increased by 0.92% and 1.19% during

barefoot and shod running, respectively. Although non-significant, without added mass, RE was 2.1% lower when running in shoes compared to barefoot. For 8 of the 12 participants, running in lightweight, cushioned shoes was more economical than running barefoot, despite the greater mass. Additionally, stride length was 3.3% longer during shod running and apparently was an outcome of footwear and not of added mass. In footwear conditions matched for equal mass, all but the heaviest condition (300 g added per foot to the shoe vs. 450 g added per foot for barefoot) showed that running shod was more economical than running barefoot. However, although non-significant, even the heaviest condition showed the shod condition to be 2.6% more economical than the barefoot condition. Although the bulk of shoe cushioning tends to reside in the heel and is significant source of mass, many shoes have cushioning that runs continuously from the heel to the midsole. Thus, the midsole can also affect the mass characteristics of a shoe. Similarly, the midsole often has its own stiffness properties that can either increase or decrease RE.

Midsole cushioning.

Just as in the heel, greater midsole cushioning would seem to reduce peak impact forces. However, the effect of midsole cushioning on GRF and vertical impact has been equivocal. Nigg (1983) tested shoes with varying degrees of hardness (i.e., cushioning characteristics) and found the hardness of the midsole was not correlated to peak impact magnitudes. The participants appeared to adjust their running patterns to the material properties of the footwear in order to avoid substantive footfall forces. In line with this research and overall cushioning characteristics, Kong, Candelaria, & Smith (2009) suggested that runners should choose shoes for reasons other than cushioning. The

authors studied the effects of shoe degradation on running biomechanics by comparing the kinetics and kinematics of running in new and worn shoes. The results indicated that as shoe cushioning decreased, runners modified their patterns to maintain impact pressure.

As has been previously mentioned, increased vertical oscillation and ground contact time appear to hinder RE (Williams & Cavanagh, 1987). In an examination of the effects of shoe cushioning upon GRF in running, Clarke, Frederick, and Cooper (1983) found that softer and more cushioned shoes caused a greater vertical force impact peak (VFIP) compared to a harder soled shoe. In terms of ground contact time, an increase in VFIP could cause the foot to be on the ground longer and hence reduce RE. In relation to the Nigg (1983) work, Hennig, Valient, and Lui (1996) found peak impact to be reduced when runners wore firm footwear. The runners appeared to attempt to compensate for the perception of reduced cushioning with more forefoot landing.

As shown, the effects of midsole cushioning on RE is equivocal. On one hand, the research points to midsole cushioning as having a negative effect on RE (Clarke et al., 1983). Whereas, other research indicates the cushioning characteristics of the midsole are unimportant because runners will adapt their stride characteristics according to the shoe's cushioning (Kong et al., 2009). Perhaps more important than the cushioning properties of the midsole is the thickness of that cushioning and the extent to which it alters natural stride patterns.

Midsole thickness.

There is limited research on midsole thickness and the potential impact on running parameters. TenBroek, Umberger, and Hinrichs (2006) showed that a thicker

midsole produced greater inversion during cutting movements. In addition, balance has been shown to suffer with footwear that is both thick and soft (Robbins & Waked, 1997). Robbins and Waked (1997) utilized a balance beam to measure balance in various shoe types and found a thin, hard midsole lead to improved balance scores. Lastly, the soles of running shoes are intended to provide both support and protection and are comprised of materials designed to help reduce the force of vertical impact (Robbins & Waked, 1997). However, Robbins and Waked found shoes with soft materials like those used in most running shoes (ethyl-vinyl acetate-EVA) increased vertical impact through behavior aimed at optimizing stability. The pattern continued through the most destabilizing condition (the softest material). The authors suggested that when runners land on an unfamiliar surface, the amplitude of vertical impact is higher than on any subsequent footfall. Thus, humans protect against instability by landing harder in an attempt to compress spongy materials and gain stability. Thus, aside from heel cushion, a thicker and softer midsole could lead to stability, balance, and impact issues. Although meant to reduce impact shock, it could be that shoes that lack a significant midsole could actually benefit the runner by causing an ensuing reliance on the body's natural landing mechanics.

To summarize, many factors including elastic return capabilities, mass, and cushioning properties can contribute to the influence a shoe can have on RE. Standard running shoes are made of materials that are intended to promote energy storage and return (Frederick et al., 1983) yet, most of the energy transferred to the shoe is dissipated as heat or only useful if the timing, frequency, location, and direction of impact are ideal (Stefanyshyn & Nigg, 2000a). The bulk of cushioning in shoes is generally located in the

heel; however the midsole can also contribute a significant amount of cushioning mass and thickness to the shoe. Numerous studies indicate that mass added to the extremities can decrease RE (Catlin & Dressendorfer, 1986; Jones et al. 1986; Martin, 1985; Myers & Steudal, 1985). Therefore, impact characteristics aside, lighter footwear is more beneficial to RE than heavier footwear.

The impact of the midsole on RE is equivocal and the literature is limited. On one hand, the midsole could help to provide impact cushioning and propulsion through elastic energy return. On the other hand, runners tend to develop strike patterns that are reflective of the cushioning properties of the shoe (Kong et al., 2009). Although a more cushioned shoe may feel more comfortable and also provide protection from traumatic injury, the research regarding this shoe type and RE is inconclusive. Altogether, research supports the idea of a minimal-type shoe that is lighter, slightly cushioned, and yet able to take advantage of the bodies' own storage and elastic energy return capability.

Minimal Footwear

In spite of the oxygen consumption conserving and benefits of lightweight cushioned shoes, ever growing research points to heavily cushioned shoes actually being a perpetrator in some overuse (non-traumatic) injuries (Daoud et al., 2012; Robbins & Hanna, 1987; Utz-Meagher, Nulty, & Holt, 2011). In response, some shoe companies have developed various minimal-type shoes. Minimal shoes are designed to work with the foot naturally, while providing protection against some traumatic-type injuries caused by directly exposing the foot to the elements. The footwear industry defines minimal footwear as a shoe with a thin, flexible midsole and outsole with a light, basic upper with

little or no heel counter (TenBroek, 2011). These differences in shoe characteristics create various adaptations to running patterns; particularly stride length and frequency.

Running in a minimal type shoe creates a more vertical leg position at contact than in a standard shoe (De Wit, Clercq, & Aertz, 2000); thereby reducing stride length. Therefore, in order to maintain constant speed, an increase in stride frequency is needed. Stride frequency has been shown to be significantly greater for barefoot running compared to running in standard running shoes (Divert et al., 2005b). Divert et al. (2005a) also found that flight time is less in barefoot running when compared to standard shod running in agreement with findings by Squadrone and Gallozzi (2009). Intuitively, taking larger strides could increase impact and braking forces thereby increasing the runner's discomfort with ground contact. Runners could inherently develop a shorter stride length in order to attenuate this discomfort.

As can be seen, wearing minimal-type shoes can affect stride kinematics and kinetics in terms of stride length, frequency, and ground contract time. In terms of literature examining the effects of minimal footwear and performance, little published research exist exclusively examining a manufactured "true minimal" shoe. Hamill, Freedson, Boda, and Reichsman (1988) compared a traditional-type running shoe with a racing flat which often resembles a minimal shoe in heel counter design and mass, but has slightly more cushioning. The authors studied recreationally active females who ran at speed corresponding to 90% of their VO_{2max} . The participants were required to run at this speed for 15 minutes in each shoe on separate days. A major difference was seen in the rear foot motion between footwear conditions. The racing flat condition had a 42% greater maximum rear foot angle than the traditional training footwear. Considering the

work of Cavanagh (1981), these results seem appropriate as it was suggested that footwear with a firmer midsole, wider heel base, and stiffer heel counter should better control pronation. The racing shoe in the Hamill et al. study exhibited none of these features.

Although inherently different in their design, most minimal shoe research has used combinations of various minimal-type shoes including those of the “toe-shoe” variety in comparisons with standard shod conditions. These 5-finger-type shoes are not only an attempt to reduce weight in a shoe, but to also mimic the action of the foot as it strikes the ground. Five-finger or “toe-shoes” are manufactured by various companies with the most prominent being the Vibram 5-finger shoe. These shoes are designed to imitate the spreading and splaying of the toes as the foot touches down and pushes off during each stride sequence. Displaying even less cushioning than most minimal shoes, the finger-like shoes are expected to be the most “life-like” of all minimal shoes. How these shoes compare to running barefoot and a regular shod condition has only knowingly been examined by one set of authors.

Squadrone and Gallozzi (2009) sought to assess how changes in the mechanical characteristics of the foot/shoe ground interface affect spatio-temporal variables, ground pressure distribution, sagittal plane kinematics, and RE in 8 experienced barefoot runners. The second aim was to evaluate if the 5-finger shoe (Vibram) was successful in imitating barefoot running. Squadrone and Gallozzi found that compared to the standard shod condition, when running barefoot the athletes landed in a more plantar-flexed position at the ankle. This created a shorter stride length and ground contact time as well as a higher stride frequency. Compared to the standard shod condition, RE was higher (better) and

peak impact forces lower in the Vibram shoe. Interestingly, although non-significant, the thrust peak vertical forces were higher with the Vibram compared to barefoot running indicating that the Vibram shoe allowed the runners to push off more intensely than the barefoot runners. Squadrone and Gallozzi suggested that this small difference could be due to the thin rubber sole of the Vibram shoe that might have reduced some of the discomfort associated from running strictly barefoot. In summary, the Vibram shoe was able to appropriately mimic the characteristics of the barefoot condition while allowing runners to improve upon various running parameters (RE) compared to a standard shod condition.

The work by Squadrone and Gallozzi (2009) prompted many researches to lump all minimal-type footwear together along with “true” barefoot runners in comparisons with standard shod (cushioned elevated heel, arch supports, stiff sole) conditions. A study meeting this description was conducted by Perl et al. (2012), who studied the effects of footwear and strike type on RE. The authors’ purpose was to assess if RE differed in minimal shoes versus standard running shoes with cushioned elevated heels and arch supports and in FFS versus RFS. Each participant ran in either a standard running shoe (Asics Gel-Cumulus 10) or in a Vibram 5-finger shoe. The Vibram shoes were used in the minimally shod condition to help prevent injuries to the foot due to the treadmill impact. As predicted, Perl et al. found that running in minimal shoes was less costly (2.41%-3.32%) than running in standard shoes after accounting for the effects of shoe mass, strike type, habitual footwear usage, and stride frequency. An interesting finding was that no significant difference in RE was found between FFS and RFS running styles when controlling for footwear type. Considering most research has found that those

running in minimal shoes tend to FFS or MFS (Divert et al., 2008; Hamil et al., 2011; Squadrone & Gallozzi, 2009) these findings need to be addressed more fully through additional research. Ultimately, aside from differences in the amount of environmental protection provided by a standard-type running shoe, wearing a minimal type shoe should improve performance. As endurance running performance is highly linked to RE (Saunders et al., 2004a), understanding the impact of wearing minimal shoes over standard shoes when measuring RE is paramount.

Effect of minimal footwear on RE.

As shown previously, the answer as to whether RE is improved by running barefoot or in a minimal shoe compared to a standard running shoe remains elusive. Squadrone and Gallozzi (2009) found running in a barefoot-type shoe (Vibram 5-fingers) to be more economical than a standard running shoe and even slightly more (non-significant) than running barefoot. Similarly, Perl et al. (2012) found that minimally shod runners were modestly, but significantly more economical than traditionally shod runners regardless of strike type, after controlling for shoe mass and stride frequency. In contrast, Franz et al. (2012) found that running in lightweight cushioned shoes was more economical than running barefoot (when matched for mass). Similarly, Divert et al. (2008) found that for conditions of equal mass, barefoot and shod running showed equivalent values for RE.

Reasons for improved RE in barefoot or minimal-type footwear compared to standard shoes (when controlling for mass) are most often explained by differences in biomechanical characteristics. Barefoot/minimal running generally necessitates mid-foot or forefoot strike patterns, which have different mass-spring mechanics than a RFS

pattern (Perl et al., 2012). Tendons, ligaments, and muscles of the lower extremity store elastic energy during the first half of the stance phase and then recoil during the second half, helping to push the body's COM upward and forward (Perl et al., 2012). The benefit of utilizing a more FFS pattern is due to more elastic energy storage in the Achilles tendon, which can recover approximately 35% of the mechanical energy that the body generates each step (Perl et al., 2012). The initial GRF is lower in a FFS than in a RFS; however, it creates a larger external dorsiflexion moment around the ankle that is countered by an internal plantar flexor moment (Denoth, 1986; Williams et al., 2000). Greater control of dorsiflexion during FFS could allow more elastic energy restitution because the heel is able to descend substantially more, thereby stretching the Achilles tendon while the triceps surae contracts eccentrically or isometrically (Hof et al., 2002)

From a RFS position, an elevated heel can limit ankle dorsiflexion which may decrease Achilles tendon strain compared to a minimal shoe or barefoot running in which there is no heel counter. Therefore, the Achilles tendon could store more elastic energy in a FFS than in a RFS and possibly more in those that FFS when running minimally (Perl et al., 2012). Energy storage in the arch is another potential difference between those who run in standard shod footwear or minimally. The arch has been estimated to recover ~17% of the mechanical energy generated per step (Ker et al., 1987). Considering most standard running shoes are made with arch supports that decrease vertical arch compression during stance, the amount of elastic recoil could be less than in those who run wearing minimalist shoes. As for foot strike, a RFS runner experiences little or no arch compression at impact because the arch is subject to a GRF below or slightly posterior to the ankle where it is opposed by the downward force of the body's mass (Perl

et al., 2012). These forces likely stiffen the arch until the foot is flat, thereby preventing storing and subsequent restitution of elastic energy.

Lastly, foot strength could prove to be a factor. Individuals who wear stiff-soled shoes with arch supports possibly have weaker foot muscles than individuals who perpetually run minimally (Bruggemann, Potthast, Braunstein, & Niehoff, 2005). The strength of the muscles in one's feet could affect elastic energy storage in the arch due to increased SSC activation and hence reduce RE.

To summarize, the research regarding the potential benefits of wearing minimal shoes rather than traditional shoes appears promising, but inconclusive. The potential mechanisms by which RE could be improved through minimal shoes appear to be related to MTU interactions and weight reductions. Increased stretch of various MTU complexes, specifically the Achilles tendon/ triceps surae, can help to reduce overall muscular effort and subsequently enhance RE. Weight that is distributed farther away from the trunk can increase the cost of running. Minimal shoes are lighter than traditional running shoes and can therefore help to enhance RE through carriage of less distal weight.

Conclusions

Running economy is a measure of steady state submaximal oxygen consumption at various running speeds (Saunders et al., 2004a). RE has also been suggested to be the greatest contributor to distance running performance (Saunders et al., 2004a). The measurement of RE is a simple measurement for those experienced in operating metabolic equipment and software. However, many factors affect RE, therefore the process of improving or reforming it can be confounding (Morgan & Craib, 1992;

Williams & Cavanagh, 1987). Additionally, although many characteristics have been identified in those demonstrating better or worse RE, many others remain inconclusive (Morgan & Craib, 1992; Williams & Cavanagh, 1987). Further, much of the analysis of a runner's economy has been performed in a laboratory setting by discipline-specific scientists. Coaches may or may not have access to facilities or equipment needed to appropriately analyze the RE of the athletes they coach.

The scientific literature is dense with information regarding RE. However, a gap exists between the current scientific findings and subsequent application by coaches and clinicians (Reade et al., 2008). Further, many endurance coaches appear to misinterpret many physiological concepts (Bosch, 2006). These findings, along with the complicated nature of both reviewing and improving RE, call for a need for more practical information and suggestions for concepts involving RE. If sport scientists are to assist coaches in developing more practical methods for improving RE, then a starting point must be established for what coaches currently know. In order to determine if an athlete qualifies for an attempt at improving RE, coaches must first be able to identify runners exhibiting poor RE. To date, no research exists regarding whether coaches are able to accurately discriminate between runners of good and poor RE when controlling for performance indicators. Therefore, once scientists have a sense of coaching knowledge in regards to RE, then practical recommendations can be made.

From a coaching practice standpoint, most physiological and biomechanical changes targeted at improving RE take time to develop (McArdle et al., 2007). However, the footwear an athlete wears is a variable that can be easily adjusted if the need is warranted. Hence, determination of footwear that could prove most beneficial for RE is a

highly intriguing and imminently useful concept. Currently, runners tend to employ three different footwear options for advancing their running practice including the traditional running shoe, minimal shoes, and barefoot running. The research concerning which footwear most practically benefits RE is inconclusive. Hence, additional recommendations are needed to help clarify the type of footwear most beneficial for runners seeking a more economical running experience and improvement in performance.

CHAPTER III

COMPARISON OF RUNNING ECONOMY VALUES WHILE WEARING NO SHOES, MINIMAL SHOES, AND NORMAL RUNNING SHOES

Introduction

Running economy (RE) is generally defined as a measure of steady-state oxygen consumption ($\dot{V}O_2$) per unit body mass (BM) at various submaximal running speeds (Saunders, Pyne, Telford, & Hawley, 2004). Compared to persons with poor RE, individuals with good RE consume less oxygen per unit body mass, exhibit greater reliance on aerobic means of energy production, display an enhanced ability to utilize fat as a fuel, rely less on fast-twitch muscle fiber contribution, and accumulate lower concentrations of lactic acid while running at the same velocity (Saunders et al., 2004). Many factors have been shown to affect RE including muscle fiber type, training status, gait mechanics, muscle stiffness, tendon length, and flexibility (Saunders et al., 2004).

Another variable which has been shown to influence RE is footwear. Multiple studies have found that for every 100 grams of mass added to a shoe, $\dot{V}O_2$ increases by approximately 1% across a range of submaximal running speeds (Franz, Wierzbinski, & Kram, 2012; Frederick, Daniels, & Hayes, 1984). In addition, well-cushioned shoes have been reported to lower the aerobic demand of running by up to 2.8% when compared to less-cushioned shoes (Franz et al., 2012; Frederick, Clark, Larsen, & Cooper, 1983). Taken together, these findings provide support for athletes to use lightweight, cushioned shoes to improve RE.

Many athletic shoe companies have taken advantage of recent advances in shoe material technology to create lightweight shoes of varying cushioning characteristics. Recent advances in shoe design have also led to the development and marketing of minimal shoes, which are extremely lightweight and lack a cushioned elevated heel, arch support, and a stiff sole. The recent popularity of running in minimal shoes (i.e., minimal or natural running) can be attributed to the training practices of the Tarahumara Indians, who run in thin sandals with little material (McDougall, 2009). Also, shoe companies have begun manufacturing lightweight low-cushioned minimalist shoes that mimic running barefoot.

While advocates of minimalist running believe that this form of locomotion may aid in decreasing the incidence of chronic running injuries (Lieberman et al., 2010; Robbins & Hanna, 1987), the effect of wearing minimalist shoes on RE is sparse and inconclusive. Hanson, Berg, Deka, Meendering, and Ryan (2011), for instance, demonstrated that while running at 70% of velocity at VO_{2max} (vVO_{2max}), barefoot running was more economical than running shod during both overground and treadmill conditions. Conversely, Franz et al. (2012) found that running barefoot at $3.35 \text{ m}\cdot\text{s}^{-1}$ offered no energetic advantage over running shod, when energy usage was assessed from a metabolic power perspective. Moreover, these authors reported that running shod provided metabolic savings of 3% to 4% compared to running barefoot.

Given the ambiguity of previous research on this topic, the purpose of this study was to quantify differences in RE at 50% and 70% of vVO_{2max} , while running in three different footwear conditions (barefoot, minimal shoes, and normal running shoes) among recreational distance runners. It was hypothesized that running in a minimal shoe

would increase step frequency and lead to better RE than in a standard running shoe or barefoot at speeds of 50% and 70% of $v\text{VO}_{2\text{max}}$. We also hypothesized that running barefoot would increase step frequency and produce a lower aerobic demand of running compared to running in a standard shoe.

Methods

Participants

Participants were healthy, injury-free males ($N = 9$) aged 18 to 40 years (age 26.8 ± 6.8 years, body mass 81.2 ± 11.9 kg, and height 177.6 ± 7.0 centimeters) who ran between 15-20 miles per week. Before testing began, university Institutional Review Board approval was obtained and all participants were provided written informed consent. Participants completed four laboratory testing sessions and refrained from liquids (aside from water), food, and caffeine 4 hours prior to testing. Furthermore, the subjects were told not to engage in strenuous exercise the previous 24 hours, and general aerobic work the previous 8 hours of each visit. To control for potential circadian variation in oxygen consumption, all participants were asked to complete each session at roughly the same time of day. To account for any confounding effects from wearing minimal shoes for the first time, participants were required to have worn and trained (≥ 5 miles a week) in a minimal-type shoe for a minimum of 3 months prior to the start of this investigation (Robbins & Hanna, 1987)

Instrumentation

Maximal and submaximal oxygen consumption. Maximal oxygen consumption and submaximal VO_2 were measured using a metabolic cart with an open-circuit spirometry gas collection system (MOXUS Modular VO_2 System; AEI Technologies,

Pittsburgh, PA). Concentrations of expired oxygen and carbon dioxide were determined using an S-3AOxygen Analyzer sensor and CD-3A Carbon Dioxide analyzer, respectively. Inspired volumes were measured by a turbine attached to a Hans Rudolph mouthpiece and the turbine was calibrated prior to each testing session using a certified 3-L calibration syringe. Gas analyzers were calibrated prior to each treadmill test to room air (20.93% O₂ and 0.03% CO₂) and known standard gas concentrations (4.03% CO₂ and 16.02% O₂; NexAir, Memphis, TN). All running bouts were conducted on a FITNEX high speed treadmill (Dallas, TX).

Step frequency. Step frequency was obtained from a video recording using a Sony® Handy Cam with 16 GB internal memory. A large digital clock (Big Time Clocks Model #116, New York, NY) with a stopwatch function was placed in view of the video camera in order to determine the number of steps taken during each 5-minute RE trial. Step frequency was determined from the video recording by manually counting the number of steps taken between minute 4 and 5 of each RE trial. Each step frequency measurement was conducted twice. In the instance that two measures were greater than two steps apart, a third measure was conducted, and the average of the closest two measures were recorded.

Anthropometric measures. Height and body mass were measured twice in minimal clothing and barefoot, to the nearest tenth of a cm (SECA 222-stadiometer) and tenth of a kg (Health O' Meter mass scale), respectively. If height or body mass varied by more than two tenths of a cm or kg, respectively, an additional measure was taken and the nearest two measures were averaged.

Footwear. Minimal shoes are described as lacking those features found in standard running shoe (a cushioned elevated heel, arch supports, and a stiff sole). As minimal type shoes often vary between manufacturers, a heel-to-toe drop of less than 4 millimeters (mm), a mass of less than 255.1 g, and stack height of less than 20 mm (Winn, 2013) were required for each pair of minimal shoes. Stack height (shoe heel height) was determined by measuring the participant's height in each of the two respective shoe conditions (standard shod, minimal) and subtracting the participant's barefoot height, with the calculated difference deemed as each shoe's respective heel height. In cases when stack height varied by more than two tenths of a mm, an additional measure was taken and the nearest two measures were averaged. Shoe mass for the standard and minimal shoes assessments was measured using a scientific grade gram (g) scale (American Weigh Scales, Norcross, GA). Standard running shoes are defined as having a cushioned elevated heel, arch supports, and a stiff sole (Perl, Daoud, & Lieberman, 2012).

Heart rate. Heart rate (HR) was recorded using a Polar Electro® (Model #N2965) heart rate strap and sensor synced to the metabolic cart and measured throughout the $\text{VO}_{2\text{max}}$ test and each RE trial.

Procedures

Maximal oxygen consumption. Maximal oxygen uptake was measured during the first laboratory visit utilizing procedures employed by Hanson et al. (2011), and each participant ran in his respective standard shoe. The testing protocol began at a speed of $80.5 \text{ m} \cdot \text{min}^{-1}$ and increased by $26.8 \text{ m} \cdot \text{min}^{-1}$ every 2 minutes until HR reached 170 beats per minute (bpm). Once a HR of 170 bpm was attained, running velocity was increased

by $13.4 \text{ m}\cdot\text{min}^{-1}$ every minute until volitional exhaustion occurred. Maximal oxygen consumption was deemed to have been met if participants satisfied two of three criteria, which include a plateau in oxygen consumption with an increase in workload, an RER of 1.10 or higher, or attainment of a HR value within 10 beats of age predicted max ($220 - \text{age}$). A protocol designed by Hanson and colleagues (2011) was used to determine velocity at $\text{VO}_{2\text{max}}$. Velocity at $\text{VO}_{2\text{max}}$ is the speed at which the athlete is running when $\text{VO}_{2\text{max}}$ occurs, as long as this speed is sustained for at least 1 minute. If an athlete achieved a $\text{VO}_{2\text{max}}$ during a workload that was not sustained for 1 minute, the speed of the previous workload was recorded as $\text{vVO}_{2\text{max}}$.

Running economy trials. Within 5 days of the assessment of $\text{VO}_{2\text{max}}$, participants completed the first of three footwear specific RE trials (barefoot, minimal shoe, and standard running shoe) in the participant's own footwear (i.e., footwear not provided by researchers). Each laboratory visit began with the measurement of body mass and was followed by a treadmill accommodation period of 6 minutes at a self-selected pace in the randomly assigned footwear condition (Lavcanska, Taylor, & Schache, 2005). Following the accommodation period, runners were then prepared for the RE assessment which consisted of a 5-minute trial at a speed of 50% and also at 70% of $\text{vVO}_{2\text{max}}$. Additionally, to simulate over ground running, the treadmill was set at 1% grade for each trial (Jones & Doust, 2007). Running economy was calculated as the average VO_2 over minutes 3 to 5 of each trial with a steady state condition confirmed as maintenance of an RER of less than 1.0. Utilizing a procedure followed by Hardin, Bogert, and Hamil (2004), a 5-minute standing rest period was provided in which HR was required to fall to below 120 bpm prior to beginning the second RE trial. Heart rate was measured as the average bpm

during minutes 3 to 5 of each RE trial, while rate of perceived exertion (RPE) was measured using the Borg scale (6-20) during the last 15 seconds (4:45–5:00) of each trial.

Statistical Analysis

Data analysis was performed using the International Business Machines Corporation Statistical Packages for the Social Sciences (version 19.0) software. Descriptive statistics for participants and shoe characteristics (e.g., mass, stack height) are expressed as mean $\pm$ standard deviation. A two-way repeated measures MANOVA was used to evaluate RE and step frequency under three footwear conditions (barefoot, minimal shoe, standard running shoe) and two running speeds (50% and 70% of vVO_{2max}) as within-subjects factors and statistical significance defined with an alpha level of $p < .05$. If a significant multivariate effect was detected, separate univariate ANOVAs were employed to identify group differences (alpha level of $p < .025$) for each dependent variable (RE, step frequency). Intraclass correlations were calculated to evaluate the test-retest reliability of the dependent variables and can be found in Table 1.

Results

Descriptive statistics for participants, including shoe characteristics, can be found in Table 2. Intra-class correlation coefficients between speeds for footwear and step frequency can be found in table 2. The two-way repeated measures MANOVA indicated a significant multivariate effect for footwear (*Pillai's F* [4, 32] = 7.79, $p < .001$, *partial* η^2 = .49), intensity (*Pillai's F* [2, 7] = 188.67, $p < .001$, *partial* η^2 = .98), as well as the interaction between footwear and intensity (*Pillai's F* [4, 32] = 4.96, $p = .003$, *partial* η^2 = .38). Due to the significant interaction effect, each level of intensity (50%, 70%) was

Table 1

Intraclass Correlations between Speeds for Footwear and Step Frequency

Variable	50% $\dot{V}O_{2\max}$	70% $\dot{V}O_{2\max}$
Footwear	0.76	0.90
Step frequency	0.96	0.98

analyzed separately via one-way repeated measures MANOVAs using an adjusted alpha level of .025. The effect of footwear was significant at both 50% of vVO_{2max} (*Pillai's F* [4, 32] = 3.91, $p = .01$, *partial* $\eta^2 = .33$) and 70% of vVO_{2max} (*Pillai's F* [4, 32] = 10.02, $p < .001$, *partial* $\eta^2 = .56$). When results for RE and step frequency were considered separately, step frequency was statistically significant at both 50% (*G-G F* [1.5, 12.1] = 14.78, $p = .001$, *partial* $\eta^2 = .65$) and 70% of vVO_{2max} (*G-G F* [1.6, 12.6] = 65.29, $p = .001$, *partial* $\eta^2 = .89$). Running economy was not significant at 50% vVO_{2max} (*G-G F* [1.6, 12.4] = .07, $p = .89$, *partial* $\eta^2 = .01$) or 70% vVO_{2max} (*G-G F* [1.7, 13.9] = 2.50, $p = .126$, *partial* $\eta^2 = .24$). Descriptive statistics for RE and step frequency measures can be found in Table 3. At 50% of vVO_{2max} , step frequency was higher when running barefoot than when running in the minimally shod condition ($p = .007$). At 70% of vVO_{2max} , step frequency was also higher in the barefoot condition than in the minimal ($p < .001$) and standard conditions ($p < .001$), with the minimal condition also exhibiting significantly higher step frequency than the standard condition at 70% vVO_{2max} ($p = .007$).

Discussion

The current study was conducted to determine the effect of footwear on RE at two submaximal running speeds in recreational distance runners. The hypothesis that running in a minimal shoe would be more economical than running barefoot or in a standard shoe was not supported at either speed. However, the second hypothesis was partially supported in that running in minimal footwear significantly increased step frequency compared to running in the standard shoe condition at a speed of 70% vVO_{2max} , but not at 50% vVO_{2max} . Moreover, while running barefoot, step frequency was significantly higher when compared to running in the minimal and standard shoe conditions at both speeds.

Table 2

Participant and Footwear Descriptive Statistics

Participant characteristics	<i>M</i>	<i>SD</i>
Age (years)	26.8	6.8
Height (cm)	177.6	7.0
Body mass (kg)	81.2	11.9
VO _{2max} (ml · kg ⁻¹ · min ⁻¹)	51.9	4.9
Minimal stack height (mm)	7.7	2.7
Standard stack height (mm)	26.9	4.0
Minimal shoe mass (g)	179.7	29.3
Standard shoe mass (g)	301.2	41.2

Table 3

Step Frequency and RE across Footwear and Speed Conditions

	<u>50% vVO_{2max}</u>		<u>70% vVO_{2max}</u>	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Step frequency (Steps per minute)				
Barefoot	164*	9	175**	11
Minimal	161	8	170***	11
Standard	160	8	166	9
Running economy (mL · kg ⁻¹ · min ⁻¹)				
Barefoot	32.9	2.1	43.1	3.4
Minimal	33.1	3.1	44.2	4.3
Standard	33.1	2.4	43.3	3.1

Note. Steps per minute and RE calculated as means of minutes 3 - 5. *Significantly different than minimally shod condition ($p = .007$). **Significantly different from minimally shod ($p < .001$) and standard ($p < .001$) conditions. ***Significantly different from standard condition ($p = .007$).

Despite these differences in step frequency, however, RE did not vary significantly across footwear conditions at 50% and 70% vVO_{2max} .

The results support the notion that the association between gait descriptors and the aerobic demand of running is complex and multifaceted (Frederick, 1983; Frederick et al., 1984; Squadrone & Gallozzi, 2009). At stable speeds, step frequency and step length exhibit a negative and interchangeable relationship, such that, as stride length is increased, stride frequency is relatively reduced and the opposite is also true (Saunders et al., 2004). Though not statistically measured, conversion of step frequency to a step length measure (Meters per minute $\div$ number of steps taken per minute) yielded worthwhile information when comparing means. For instance, at 50% of vVO_{2max} , running in minimally-shod shoes led to a 2.1% longer step length compared to running barefoot, while running in standard shoes resulted in a 2.4% longer step length compared to the barefoot running condition. At 70% of vVO_{2max} , minimally shod runners adopted a step length that was 3.2% longer than barefoot runners, while running in standard shoes produced a 2.3% greater step length than running in the minimally-shod condition and a 5.6% longer step length than barefoot running. Previous research (De Wit, De Clercq, & Aerts, 2000; Divert, Mornieux, Baur, Mayer, & Belli, 2005; Franz et al., 2012) has also indicated an increase in stride length from barefoot to a standard shoe running conditions among recreationally fit runners with significant barefoot running experience. Similarly, in a group of highly trained runners, Bonacci et al. (2014) demonstrated that stride length and stride frequency were significantly longer and slower, respectively, while running in minimal shoes compared to running barefoot. In the current study running in the shod

condition yielded a significantly longer stride length and lower step frequency than running in both the minimal and barefoot conditions.

Though step frequency varied across footwear conditions, no significant changes were observed in RE at either speed. In a small number of published studies, reductions in the aerobic demand of running have been demonstrated when running barefoot or in a barefoot-similar condition (e.g., thin diving sock or Vibram 5-finger shoe) versus shod running (Divert et al., 2005; Flaherty, 1993; Hanson et al., 2011; Squadrone & Gallozzi, 2009), while other research has indicated that running barefoot is less economical than running shod (Franz et al., 2012). While no single explanation can be offered as to why RE has been shown to vary among different footwear conditions, variations in shoe mass may provide some insight relative to this question.

In this regard, multiple authors have reported that the oxygen demand of running is increased by approximately 1% per 100 g of mass added per shoe (Franz et al., 2012; Frederick et al., 1984). Current literature suggests that a threshold mass may exist, beyond which RE becomes worse. A number of studies, for instance, have shown that a mass of ~ 350g or greater may induce statistically significant changes in RE. Specifically, Divert et al. (2005) assessed oxygen consumption in runners wearing a thin diving sock loaded with either 150g or 350g and in standard running shoes weighing either 150g or 350g. The authors found that RE in the 150g barefoot conditions (diving sock and completely barefoot) did not significantly vary from either the unweighted diving sock or un-weighted barefoot conditions. However, both 350g conditions (diving socks loaded with 350g and 350g standard running shoes) exhibited higher oxygen costs compared to the 150g conditions (diving socks loaded with 150g and 150g standard

running shoes). Similarly, Flaherty (1993) reported that running in shoes with a mass of 356g (per shoe) resulted in 4.6% greater oxygen consumption compared to running barefoot. In contrast, Franz et al. (2012) found that adding 300g to a lightweight cushioned shoe (~450g per foot) was only 1.2% less economical when compared to running barefoot. In our study, two subjects ran in standard running shoes with a mass of greater than 350g (362 and 381 grams) with one subject exhibiting his lowest oxygen consumption and the other subject exhibiting his highest oxygen consumption when compared to running in the barefoot and minimal conditions. Therefore, a certain shoe mass may indeed lead to a noticeable alteration in oxygen consumption while running, but the extent of the change is likely to vary on an individual basis.

Though shoe mass has been proven to be inconclusive in explaining variations in RE, shoe design and/or cushioning characteristics, particularly shoes with a more elastic and viscous heel, may help explain the fluctuation in energy demands caused by running in different types of footwear (Hamill, Russell, Gruber, & Miller, 2011; Nigg, Stefanyshyn, Stergiou, & Miller, 2002; Kong, Candelaria, & Smith, 2009).

Previous studies (Divert et al., 2005; Hamill et al., 2011) indicate runners will ultimately rely on the running patterns that are most economical for them. Additionally, numerous studies have demonstrated that aerobic demand is increased at a constant speed when stride length is either lengthened or shortened beyond that which is the freely chosen for an individual (Martin & Morgan, 1992). Indeed, Cavanagh and Williams (1982) suggested freely chosen stride length is at or near optimal RE. Therefore, as suggested by Nigg and Enders (2013), runners may automatically adapt to a change in

running condition or strike pattern in order to maintain the most economical running performance.

Significant differences in RE across footwear conditions were not found, yet individual RE between footwear conditions sometimes varied substantially. For example, one runner exhibited a 3% difference in RE among footwear conditions at 50% of vVO_{2max} , while another exhibited a 12% difference in RE across footwear conditions. At 70% vVO_{2max} , one runner exhibited a 2% difference in RE across footwear conditions, while another exhibited a 12% difference across footwear conditions. The implications of these differences may be more valuable when considering their influence on running performance. Burkett, Kohrt, and Buchbinder (1985) demonstrated that a 1.7% increase in absolute VO_2 is equal to roughly a $5 \text{ m}\cdot\text{min}^{-1}$ decrease in speed. Using the findings of Burkett et al. (1985) and Hanson et al. (2011), a 1.0% increase in VO_2 would result in a $2.94 \text{ m}\cdot\text{min}^{-1}$ decrease in running speed. Based on these data, a 3% to 12% difference in VO_2 would translate to a speed increase of approximately 8 to $35 \text{ m}\cdot\text{min}^{-1}$ or 0.30 to $1.31 \text{ m}\cdot\text{hr}^{-1}$. In regards to performance, a change of $1 \text{ m}\cdot\text{hr}^{-1}$ could potentially improve performance by ~ 3 minutes and 25 seconds over the course of a 5 kilometer race. Therefore, a change in footwear (or running barefoot) could prove useful for a given individual in terms of improving RE, subsequent training, and/or racing performance.

The results of the current study support the theory that runners ultimately adapt and are most economical in conditions specific to that individuals characteristics. Though RE was relatively constant among shoe conditions, large interindividual differences in RE could be readily distinguished. At 50% of vVO_{2max} , for instance, 4 of the 9 runners exhibited their highest oxygen consumption (i.e., least economical) while running in a

minimal shoe. Alternatively, another 4 subjects were most economical in the standard shod condition. At 70% of vVO_{2max} , 5 of the 9 subjects exhibited their highest oxygen consumption in the minimal shoe condition, whereas another four of the nine participants were most economical while engaged in barefoot running. One potential explanation for these disparate findings could be related to the comfort level experienced by each participant while running under each shoe condition. These findings are similar to those of Luo, Stergiou, Worobets, Nigg, and Stefanyshyn (2009) who demonstrated that RE was significantly improved when running in a shoe deemed most comfortable compared to shoes that were labeled less comfortable.

Future research considerations should include determining the impact of shoe heel-to-toe drop on RE, as well as the possibility of a mass threshold at which RE may be significantly affected. In addition, researchers may wish to test RE at speeds greater than 50% of vVO_{2max} for a low-end speed, as many runners found it to feel very slow. Only runners on the lower end of the vVO_{2max} continuum seemed to be affected by the slower running speed, but analysis of RE at speeds of greater than 60% of vVO_{2max} may improve external validity. Finally, although comparable to other research in this area in terms of participant number (Perl, Daoud, & Liebermann, 2012) researchers may wish to strengthen statistical power by increasing the number of participants utilized in similar experimentation.

In conclusion, RE was not significantly different across barefoot, minimally-shod, and standard shoe conditions in a group of recreational distance runners while running at low and moderate intensities. Stride length and step frequency differences were observed between footwear conditions, thereby providing a possible explanation for the

mechanisms responsible for maintenance of RE in spite of footwear differences. Finally, these findings suggest the presence of a potential individual physiological preference for a particular running condition which could ultimately determine metabolic effort, rather than the presence of an actual barefoot or shoe effect on running economy.

CHAPTER III REFERENCES

- Bonacci, J., Saunders, P., Hicks, A., Rantalainen, T., Vicenzino, B. T., Spratfor, W. (2014). Running in minimalist and lightweight shoe is not the same as running barefoot: A biomechanical study. *British Journal of Sports Medicine*, 47, 387-392. Doi: 10.1136/bjsports-2012-091837
- Burkett, L. N., Kohrt, W. M., & Buchbinder, R. (1985). Effects of shoes and foot orthotics on VO_2 and selected frontal plane knee kinematics. *Medicine and Science in Sports and Exercise*, 17(1), 158-163.
- Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine & Science in Sports & Exercise*, 14, 30-35.
- De Wit, B., De Clercq, D., & Aerts, P. 2000. Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics*, 33, 269-278.
- Divert, C., Mornieux, G., Baur, H., Mayer, F., & Belli, A. (2005). Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine*, 26(7), 593-598.
- Flaherty, R. F. (1993). *Running economy and kinematic differences among running with the foot shod, with the foot bare, and with the bare foot equated for weight* (Unpublished doctoral dissertation) Springfield College, Springfield, MA.
- Franz, C., Wierzbinski, C. M., & Kram, R. (2012). Metabolic cost of running barefoot versus shod: Is lighter better? *Medicine & Science in Sports & Exercise*, 44(8), 1519-1525. doi:10.1249/MSS.0b013e3182514a88

- Frederick, E. C., Daniels, J. T., & Hayes, J. W. (1984). The effect of shoe weight on the aerobic demands of running. In N. Bachl & L. Prokop (Eds.) *Current topics in sports medicine* (616-625). Vienna: Urban & Schwarzenberg.
- Frederick, E. C. (1983). Measuring the effects of shoes and surfaces on the economy of locomotion. In B. M. Nigg & B. A. Kerr (Eds.). *Biomechanical aspects of sport shoes and playing surfaces* (93-106). Calgary: University of Calgary.
- Frederick, E. C., Clark, T.E., Larsen, J. L., & Cooper, L. B. (1983). The effect of shoe cushioning on oxygen demands of running. In B. M. Nigg & B. A. Kerr (Eds.), *Biomechanical aspects of sport shoes and playing surfaces* (104-114). Calgary: University of Calgary
- Hamill, J., Russell, E. M., Gruber, A. H., & Miller, R. (2011). Impact characteristics in shod and barefoot running. *Footwear Science*, 3(1), 33-40.
- Hanson, N. J., Berg, K, Deka, P., Meendering, J. R., & Ryan, C. (2011). Oxygen cost of running barefoot vs. running shod. *International Journal of Sports Medicine*, 32, 401-406. doi:10.1055/s-0030-1265203
- Hardin, E. C., Bogert, A. J., & Hamill, J. (2004). Kinematic adaptations during running effects of footwear, surface, and duration. *Medicine and Science in Sports and Exercise*, 36(5), 838-844. doi:10.1249/01.MSS.0000126605.65966.40
- Jones, A. M., & Doust, J. H. (2007). A 1% treadmill grade most accurately reflects the energetic cost of running. *Journal of Sports Sciences*, 14(4), 321-327.
- Kong, P. W., Candelaria, N. G., & Smith, D. R. (2009). Running in new and worn shoes: A comparison of three types of cushioning footwear. *British Journal of Sports Medicine*, 43, 745-749. doi:10.1136/bjsm.2008.047761

- Lavcanska, V., Taylor, N. F., & Schache, A. G. (2005). Familiarization to treadmill running in young unimpaired adults. *Human Movement Science*, 24, 544-557. doi:10.1016/j.humov.2005.08.001
- Lieberman, D. E., Venkadesan, M., Werbal, W. A., Daoud, A. I., D'Andrea, S., Davis, I., & Pitsiladis, Y. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature*, 463(28), 531-535. doi:10.1038/nature08723
- Luo, G. Stergiou, P., Worobets, J., Nigg, B., & Stefanyshyn, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science*, 1(1), 25-29. doi:10.1080/19424280902993001
- Martin, P. E., & Morgan, D. W. (1992). Biomechanical considerations for economical walking and running. *Medicine & Science in Sports & Exercise*, 24 (4), 467-474.
- McDougall, C. (2009). *Born to run: A hidden tribe, super athletes, and the greatest race the world has never seen*. New York, NY: Alfred A. Knopf.
- Nigg, B., & Enders, H. (2013). Barefoot running—some critical considerations. *Footwear Science*, 5(1), 1-7.
- Nigg, B.M., Stefanyshyn, G. Stergiou, P., & Miller, J. (2002). The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. *Journal of Biomechanics*, 36, 569-575. doi:10.1016/S0021-9290(02)00428-1
- Perl, D. P., Daoud, A. I., & Liebermann, D. E. (2012). Effects of footwear and strike type on running economy. *Medicine & Science in Sports & Exercise*, 44(7), 1335-1343.

- Robbins, S. E., & Hanna, A. M. (1987). Running-related injury prevention through barefoot adaptations. *Medicine & Science in Sports & Exercise*, 19(2), 148-156.
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34(7), 465-485.
- Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of Sports Medicine and Physical Fitness*, 49(1), 6-13.
- Winn, Y. (2013). *Barefoot/minimalist running shoes: How to choose*. Retrieved from <http://www.rei.com/learn/expert-advice/how-to-choose-barefoot-minimalist-running-shoes.html>

APPENDIX FOR STUDY I

APPENDIX A

IRB Letter of Approval

July 30, 2013

Robbie Cochrum

Department of Health and Human Performance

rgc2r@mtmail.mtsu.edu, john.coons@mtsu.edu

Protocol Title: "Effect of footwear type and velocity on running economy""

Protocol Number: **13-015**

Dear Investigator(s),

I have reviewed your research proposal identified above and your request for continuation and your requested changes. Approval for continuation is granted for one (1) year from the date of this letter. Any changes to the originally approved protocol must be provided to and approved by the research compliance office.

You will need to submit an end-of-project report to the Office of Compliance upon completion of your research. Should the research not be complete by the expiration date, **July 30, 2014**, please submit a Progress Report for continued review prior to the expiration date.

According to MTSU Policy and Procedure, a researcher is defined as anyone who works with data or has contact with participants. Therefore, should **any individuals be added to the protocol that would constitute them as being a researcher, please identify them and provide their certificate of training to the Office of Compliance.** Any change to the protocol must be submitted to the IRB before implementing this change.

Please note that any unanticipated harms to subjects or adverse events must be reported to the Office of Compliance at (615) 494-8918. Also, all research materials must be retained in a secure location by the PI or **faculty advisor (if the PI is a student) for at least three (3) years** after study completion. Should you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,

Kellie Hilker

Compliance Officer

Research Compliance

CHAPTER IV

ACCURACY OF VISUAL CLASSIFICATION OF RUNNING ECONOMY BY COACHES

Introduction

Running economy (RE) is defined as the oxygen cost per unit body mass for a given velocity of submaximal running and is assessed by measurement of steady-state oxygen (VO_2) consumption (Anderson, 1996; Conley & Krahenbuhl, 1980; Conley, Krahenbuhl, and Burkett, & Millar, 1984; Morgan & Craib, 1992). Running economy is considered an important component of distance-running performance, especially among athletes who display similar levels of maximal aerobic power (Saunders, Pyne, Telford, & Hawley, 2004) and is a product of many physiological and biomechanical factors (Lucia et al., 2006; Saunders et al., 2004). A runner exhibiting a metabolically-economical running style is able to incur a lower percentage of maximal oxygen consumption ($\text{VO}_{2\text{max}}$) at a given velocity compared to a runner who is less economical. Sustaining a low rate of oxygen consumption during submaximal exercise can also diminish reliance upon fast-twitch muscle fibers, spare muscle glycogen usage, and lead to less lactic acid production and accumulation (Saunders et al., 2004).

Whereas endurance running performance is generally measured on the road or track, measurement of RE is a time-intensive, laboratory-based assessment requiring specialized and expensive instrumentation and trained technicians. For coaches working with distance runners, access to a well-equipped exercise physiology laboratory outfitted

for metabolic testing may be limited or unavailable. Hence, the extent to which coaches or other talent assessors can visually differentiate runners based on economy profiles would be advantageous in strategically recruiting and deploying athletes in events reflecting their individual RE profiles and evaluating the success of economy-based training programs.

The extent to which coaches are able to visually distinguish problem areas in an athlete's running mechanics or factors related to RE may be associated with their experience as a coach or athlete. Characteristics of successful coaches include a greater number of years of coaching experience, becoming a coach at a young age, having received more mentoring throughout their coaching career, and attending more coaching courses, workshops, and/or symposia (Young, Jemczyk, Brophy, & Cote, 2009). Successful coaches have also participated in the sport they coach, although success as an athlete does not appear to be as important to coaching success (Young et al., 2009). Gaining a better understanding of the visual skills of coaches in classifying and ranking runners on RE and the criteria used in classifying athletes with respect to RE, may be useful in the development of practical RE assessments and recommendations for coaches of all levels. Hence, the purpose of this study was to determine the ability of distance-running coaches to accurately classify runners varying in RE and identify the criteria used by coaches to classify runners along the economy continuum. It was hypothesized that the number of years spent coaching would be positively related to the accuracy with which coaches classify RE in a group of recreational distance runners. It was further hypothesized that the number of years spent as a competitive runner would be positively related to the accuracy with which coaches classify RE in a group of recreational runners.

Methods

Participants

Study participants were recreational runners from the mid-south region of the United States recruited through local running and triathlon clubs and area road races. Running participants were healthy, injury-free males ($N = 5$), who had run regularly for an average of at least 15 miles a week for the past year and had recorded a 5-km race time of between 16 to 28 minutes during this period. Descriptive characteristics of the running participants are presented in Table 1. Inclusion criteria for the coaching participants ($N = 121$) included serving as a designated distance coach, head cross-country coach, or triathlon coach for male athletes at the junior high school, high school, college, national, or international level. Coaches were recruited through high school and collegiate programs throughout the nation via a survey link that was distributed through coaching email list-serves and the message board (LetsRun.com) of the website.

Instrumentation

Maximal and submaximal oxygen consumption. Measurement of $\text{VO}_{2\text{max}}$, submaximal oxygen consumption, and respiratory exchange ratio (RER) was obtained using a metabolic cart with an open-circuit spirometry gas collection system (MOXUS Modular VO_2 System, AEI Technologies, Pittsburgh, PA). Concentrations of expired oxygen and carbon dioxide were determined using an S-3A oxygen analyzer sensor and CD-3A carbon dioxide analyzer sensor, respectively. Inspired volumes were measured by a turbine attached to a Hans-Rudolph mouthpiece which was calibrated prior to each testing session using a certified 3-L calibration syringe.

Table 1

Descriptive Statistics for Running Participants (N = 5)

	Minimum	Maximum	<i>M</i>	<i>SD</i>
Age (years)	19.0	28.0	23.4	3.6
Height (cm)	174.0	182.0	176.8	3.3
Body mass (kg)	59.4	92.0	74.8	13.4
Body fat (%)	9.6	20.0	12.6	4.2
RE (ml·kg ⁻¹ ·min ⁻¹)	40.2	49.4	44.7	3.7
VO _{2max} (mlkg ⁻¹ ·min ⁻¹)	45.7	65.8	57.4	7.8

Note. RE = running economy; VO_{2max} = maximal oxygen consumption.

The gas analyzers were calibrated prior to each treadmill test with room air (20.93% O₂ and 0.03% CO₂) and known standard gas concentrations (16.02% O₂ and 4.03% CO₂; NexAir, Memphis, TN).

A test protocol designed by Morgan, Martin, Baldini, and Krahenbuhl (1990) was used to determine VO_{2max}. Participants began running at 2.68 m·s⁻¹ and at 0% grade for three minutes. Treadmill speed was then increased by 0.22 m·s⁻¹ every three minutes until a speed of 3.80 m·s⁻¹ was reached. At this point, treadmill grade was increased 2.5% every two minutes until volitional fatigue ensued. Maximal oxygen consumption was deemed to have been met if participants satisfied two of three criteria, plateau in oxygen consumption with an increase in workload, an RER of ≥ 1.10 , or attainment of a heart rate (HR) value within 10 beats of age predicted max (220-age) (Astorino, Robergs, Ghiasvand, Marks, & Burns, 2000).

Assessment of RE (submaximal oxygen consumption) was conducted while each participant ran at 3.57 m·s⁻¹ for 6 minutes during each of 2 to 3 (if needed) RE trials. Running economy was calculated by taking the average of the VO₂ measures every 10 seconds from minutes four through six of each trial. Criteria for achieving a steady-state condition included maintenance of an RER of less than 1.0 from minutes 4 to 6. Measures of VO₂ and RER were recorded during all runs.

Anthropometric measures. Height and body mass were measured twice each to the nearest tenth of a cm (SECA stadiometer) and tenth of a kg (Health O' Meter mass scale), respectively, and averaged. In cases where height or mass varied by more than a tenth of a cm or kg respectively, an additional measure was secured and the mean of the nearest two values were taken as indicative of height and body mass, respectively.

Body composition. Body composition (body fat percentage) was determined using a calibrated Harpenden skinfold caliper (Baty International, West Sussex, England) and a three-site (chest, abdomen, thigh) skinfold protocol (Jackson & Pollock, 1978). Each site was measured twice by a certified ACSM health and fitness specialist. If the skinfold measures differed by two or more millimeters, a third measure was obtained and the average of the nearest two closest values was taken as representative of the skinfold thickness of each body site.

Heart rate. Heart rate was recorded using a Polar ® Electro (Model #N2965) heart rate strap and receiver synced to the metabolic cart and measured throughout the $\text{VO}_{2\text{max}}$ test and RE trials.

Video analysis. Runners ran unencumbered by all metabolic testing equipment while being filmed from the front, right, and rear sides during the final minute of a 3-minute treadmill run at a speed of $3.57 \text{ m}\cdot\text{s}^{-1}$. All filming was conducted using three Sony ® Handy Cam cameras with 16 GB internal memory. All three running perspectives were edited and combined (Adobe Final Cut Pro®) into a single video that allowed the coaches to view the three camera angles on one screen.

Coaches ranking of RE. Qualtrics® research software, Research Suite, 2013 was utilized to collect each coach's ranking of each runner's RE, as well as to garner descriptive information from each coach. Qualtrics® research software allows researchers to upload large surveys with video attachments, in addition to collecting and tabulating user responses. Participants received an email from the researcher with a link to the Qualtrics® survey management software website. Each email included the procedures necessary to complete the survey along with providing a detailed definition of the

meaning of RE, as well as how to appropriately rank each runner's economy. Upon agreeing to participate in the study, the Qualtrics® software directed each coach to complete a questionnaire (see Appendix A) regarding coaching and athletic background and current/past educational experiences. Along with the questionnaire, each survey contained 1-minute videos of the five runners performing RE trials at a speed of $3.57 \text{ m}\cdot\text{s}^{-1}$ for a total of five videos. Coaches were prompted to view all five 1-minute videos in a single session before viewing each again and assigning a RE ranking for each participant from 1 to 5 (best = 1; worst = 5). Each video could be viewed as many times as the coach felt necessary before assigning a RE ranking. Lastly, coaches provided a list of characteristics used in determining their ranking of each runner's economy (see Table 6).

Procedures

Before testing commenced, university Institutional Review Board approval was obtained (see Appendix C). All running participants provided written informed consent and coaches provided consent when agreeing to complete the online questionnaire. The experimental protocol required the participants to visit the laboratory two to three times and to refrain from liquid (aside from water), food, and caffeine intake for at least 4 hours and strenuous exercise for a minimum of 24 hours prior to testing. Each runner's initial visit was used as part of a screening process in which runners were included or eliminated from further participation based on his RE value at a speed of $3.57 \text{ m}\cdot\text{s}^{-1}$. All participants were tested during the mid-morning (i.e., 10:00-11:00 a.m.) and each visit occurred within 1 week of the last. Participants were expected to maintain current running and fitness regimens between laboratory visits.

During the first RE visit, anthropometric and body composition measurements were taken (three-site skinfold) for each participant. All participants were accommodated to level treadmill running by completing two, 3-minute treadmill bouts at $3.35 \text{ m}\cdot\text{s}^{-1}$ and $3.8 \text{ m}\cdot\text{s}^{-1}$, respectively followed by a 6-minute level treadmill run at $3.57 \text{ m}\cdot\text{s}^{-1}$. A 5-minute rest period was allotted to runners between the accommodation trial and RE trial. Identifying runners with a minimal difference in RE of $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ is important for displaying significant statistical differences between runners of low, medium, and high RE (Williams & Cavanagh, 1987). Thus, a total of 33 participants were tested in order to find 5 participants whose RE values varied by a minimum difference of $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ between each runner.

It has been found that two consecutive or non-consecutive days of testing provides acceptably stable measures of RE and accounts for daily variation in the aerobic demand of running (Morgan et al., 1994). Therefore, VO_2 values measured during the first and second laboratory visits were compared in order to obtain a reliable measure of RE. Running economy values found to vary by more than $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ for a given runner necessitated a third laboratory visit in which the two RE measures within $2 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ were averaged to derive the RE value for each screened participant. Thus, the final accepted RE value included an average from two of the three RE assessment visits. The second (and/or third visit, when needed) visit began with a measurement of body mass (needed for accurate oxygen consumption analysis) followed by a 6-minute treadmill warm-up period (3 minutes each at $3.35 \text{ m}\cdot\text{s}^{-1}$ and $3.8 \text{ m}\cdot\text{s}^{-1}$) and a 6-minute assessment of RE. Of the final 5 participants included in the study, none exhibited a daily RE value that varied by more than $1 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ and none needed a third visit to verify a reliable RE

measure. On the same day a reliable RE value (compared to either visit #1 or #2) was found, the breathing mask and headgear were removed and the participant ran unencumbered for 2 minutes, followed by an additional minute (3 minutes total) in which the participant was simultaneously filmed from three perspectives (front, right side, behind) for a total of 60 seconds from each perspective. Upon completion of the video recording, runners were asked to come back for one final laboratory visit (within 1 week) in which maximal oxygen consumption was assessed and completed. Videos of each runner were then edited as described earlier and integrated into the Qualtrics survey software. Once completed, the survey link was distributed electronically to the coaches.

Statistical Analysis

All data (descriptive characteristics, coaching classifications) were collected and sorted via Qualtrics. Data analysis was conducted using International Business Machines Corporation Statistical Packages for the Social Sciences (version 19.0) software. Descriptive statistics for coaching participants were expressed as mean $\pm$ standard deviation and statistical significance defined using an alpha level of $p < .05$. Frequencies were reported for descriptive characteristics of runners the coaches listed as useful in determining their RE rankings. Pearson correlation coefficients were used to determine whether years of coaching and years as a runner were related to accuracy of ranking RE, as measured by the percentage of runners correctly classified by each coach according to RE and by the average discrepancy between the actual runner's ranks and the coach's rank. A linear regression analysis was used to predict the accuracy with which the coaches ranked the runners by RE based on the coaching characteristics. Likewise, a linear regression analysis was used to predict the mean discrepancy (average of absolute

difference between actual runner's rank and coach's rank of the runner) between a participant's RE rank and the coach's rank of each participant's RE from the coaches' characteristics. Coaching characteristics in each linear regression analysis included the number of years spent coaching, the number of years competed as a distance/mid-distance runner, highest coaching level (junior high, high school, college, private/professional), highest education level (high school, bachelor's, master's, doctorate), whether or not a coach had obtained a sport or training certification (yes, no), a coach's primary competitive distance while he or she was a runner competitively (sprints, 800-1500, 1500-5000, 5000-10,000, marathon, triathlon), and the coach's highest competition level as a runner (high school, age group, collegiate, national, international).

Results

Surveys were completed by 347 coaches. Due to inconsistent and omitted responses, 121 completed questionnaires were included in the data analysis. Descriptive statistics for study independent variables can be found in Table 2. Pearson correlation coefficients among the study variables can be found in Table 3.

Due to the number of coaches who responded as coaching at more than one position and level (e.g., high school and junior high coach), only the highest coaching level was used for analysis of the coaching level variable. Furthermore, one of the questions posed to coaches referred to whether or not they had obtained a sports/fitness-certification. Many coaches listed a variety of sports and fitness training certifications that were not originally listed in the research questionnaire and no meaningful patterns

were discovered. Thus, this variable was coded as a 'yes' or 'no' response with yes indicative of having a certification and no indicative of not having a certification.

The hypothesis that the number of years spent coaching would be positively related to the number of runners correctly identified (less than 1 in 5 or 17.9% $\pm$ 16.7 accuracy percentage) with which coaches classified RE was not supported ($r = .12$, $p = .184$). The second hypothesis that the number of years spent as a competitive runner would be positively related to the accuracy with which coaches classified RE was also not supported ($r = -.06$, $p = .484$). Likewise, neither years spent coaching ($r = -.004$, $p = .968$) nor years spent as a competitive runner ($r = .02$, $p = .811$) were correlated with the mean discrepancy (1.8 $\pm$ 0.4) across RE rankings. Preliminary analyses were conducted to ensure no violation of the assumptions of normality, linearity, multicollinearity, and homoscedasticity prior to conducting the linear regression analyses. In terms of accuracy percentage, the full model containing all predictors (number of years coaching, number of years competed as a distance/mid-distance runner, highest coaching level, education level, certifications obtained, primary competitive distance as a runner, and highest competition level as a runner) was not statistically significant, $F(7, 113) = 0.85$, $MSE = 281.18$, $p = .550$, $R^2 = .05$ (see Table 4), and the full model for predicting mean discrepancy (average of absolute difference between actual runner's rank and coach's rank of the runner) was also nonsignificant, $F(7, 113) = 0.65$, $MSE = 0.17$, $p = .713$, $R^2 = .04$ (see Table 5). Therefore, none of the coaching characteristics were useful for predicting accuracy percentage or the mean discrepancy between actual rank and coach's rank.

Table 2

Descriptive Statistics for Coaching Characteristics (N = 121)

Coach characteristic	%	Min	Max	<i>M</i>	<i>SD</i>
Number of years coaching		1	41	8.0	6.7
Years competed as a distance/mid-distance runner		1	50	11.9	9.2
<i>Highest coaching level</i>					
Junior high	13.2				
High school	40.5				
College	34.7				
Private/Professional	11.6				
<i>Highest education level</i>					
High school	19.0				
College	41.3				
Master's level	28.9				
Doctorate	10.7				
<i>Certifications</i>					
No	76.9				
Yes	23.1				
<i>Primary competitive distance as runner</i>					
Sprints	0.8				
800-1,500 m	16.5				
1,500-5,000 m	36.4				
5,000-10,000 m	31.4				
Marathon	12.4				
Triathlon	2.5				
<i>Highest competition level as runner</i>					
High school	19.0				
Age group	14.0				
Collegiate	51.2				
National	11.6				
International	4.1				

Table 3
Pearson Correlations Coefficients among Study Variables (N = 121)

Variable	1	2	3	4	5	6	7	8
1. Accuracy percentage								
2. Mean discrepancy	-.57*							
3. Highest coaching level	-.04	.08						
4. Number of years coaching	-.12	-.004	.05					
5. Number of years training/competing as a runner	-.06	.02	.39*	.21*				
6. Highest education level	.001	.004	.19*	-.08	.38*			
7. Certifications (1=Yes, 0=N0)	.09	-.12	.17	.07	.42*	.29*		
8. Primary competition distance as runner	.13	-.10	.12	-.01	.12	.25*	.14	
9. Highest competition level as runner	-.01	-.04	.22*	.08	.24*	.23*	.17	.08

Note. * $p < .05$

Table 4

Linear Regression Model for Predicting Accuracy Percentage

Variable	<i>B</i>	<i>SE</i>	β	95% CI for <i>B</i>	
				Lower bound	Upper bound
Constant	16.48	9.21		-1.76	34.73
Highest coaching level	-0.55	1.95	-0.03	-4.40	3.31
Number of years coaching	-0.28	0.24	-0.11	-0.75	0.19
Number of years training/competing as runner	-0.16	0.21	-0.09	-0.57	0.26
Highest education level	-0.78	1.94	-0.04	-4.62	3.07
Certification	5.44	4.05	0.14	-2.59	13.46
Primary competition distance	2.14	1.56	0.13	-0.96	5.24
Highest competition level as runner	-0.004	1.55	0.00	-3.08	3.07

Note. Accuracy percentage = coach's ranking accuracy. Certification was coded as 1 = Yes, 0 = No.

Table 5

Linear Regression Model for Predicting Mean Discrepancy

Variable	<i>B</i>	<i>SE</i>	β	95% CI for <i>B</i>	
				Lower bound	Upper bound
Constant	1.85	0.23		1.39	2.30
Highest coaching level	0.05	0.05	0.10	-0.05	0.14
Number of years coaching	0.000	0.006	-0.004	-0.01	0.01
Number of years training/competing as a runner	0.002	0.005	0.05	0.008	0.01
Highest education level	0.02	0.05	0.04	-0.08	0.12
Certifications	-0.14	0.10	-0.15	-0.34	0.06
Primary competition distance	-0.04	0.04	-0.10	-0.12	0.04
Highest competition level as runner	-0.02	0.04	-0.05	-0.10	0.06

Note. Mean discrepancy = average of absolute difference between actual runner's rank and coach's rank of the runner. Certification was coded as 1 = Yes, 0 = No.

Discussion

The current study evaluated the ability of distance-running coaches to correctly rank runners on RE through video observation of distance runners during treadmill running. The coaches in this study were not able to accurately rank the runners by RE, regardless of years spent coaching or years spent competing as a runner. For instance, coaches were able to identify less than one in five runners correctly (17.9%). Furthermore, coaching level (junior high, high school, college, private/professional), highest level of education (high school, college, master's, doctorate), and the primary competition event the coach associated himself with during his running career (sprints, 800-1,500m, 1,500-5,000m, 5,000-10,000m, marathon, triathlon) were not significant predictors of RE ranking accuracy or the mean discrepancy between true and predicted ranking scores.

Previous research has shown that the number of years spent coaching and competing as a distance runner are reflective of coaching success (Gilbert, Lichtenwaltdt, Gilbert, Zelezny, & Cote, 2009; Young et al., 2009). However, success in terms of visually ranking RE was not supported by either years of coaching experience or the number of years a coach had competed as a distance runner. Likewise, Raunig (1989) found that the number of years of coaching experience did not significantly relate to the ability of coaches to correctly identify runners of varying RE. Taken together, these results highlight the difficulty involved in visually assessing RE by coaches at any level of experience or expertise. Additionally, results from the present investigation are consistent with the notion that success in distance-running sports is dependent on many factors support the findings by Morgan et al. (1995) that economical and uneconomical

runners can be found in all performance categories (e.g., elite, sub-elite, good, untrained). Although speculative, it is possible that uncertainty as to how certain gait characteristics affect RE and a lack of familiarity with findings in the scientific literature related to biomechanical influences on running economy may have contributed to the relatively poor ability of coaches to visually identify RE. It could be further speculated that other coaching characteristics not specified in the current study may not improve the accuracy of the coaches' ranking, but rather the coaches' ability to predict the differences in accuracy among the coaches.

Although distinguishing runners of varying RE by sight is a challenging task, coaches appear more capable of distinguishing runners from other groups of athletes based on RE. For instance, Raunig (1989) quantified the ability of high-school running coaches to distinguish RE through visual observation in a group of 12 running participants separated by running performance times and sport (four elite runners, four good runners, four cyclists). Results from this study indicated that coaches were able to distinguish the two running groups from the cycling group (r_s of .74, for the Spearman-rho test), but not from each other in terms of oxygen consumption (RE) when running at $4.47 \text{ m}\cdot\text{s}^{-1}$. The two running groups differed in terms of oxygen consumption at $4.47 \text{ m}\cdot\text{s}^{-1}$ by an average of $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ with the elite runner exhibiting better RE. Conversely, the cyclists VO_2 measures varied by nearly $8 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$ from the elite runners and nearly $6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ from the good runners. The current study also utilized a $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ VO_2 range between runners and also found coaches were not successful in correctly discerning the runners' actual rank. Thus, as suggested by Raunig, a $2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ criterion may be too small to separate runners by economy rank.

Overall, the coaches' ranking of running economy was poor. As seen in Figure 1, the ranking accuracy of RE values ranged from 0 to 60%, with nearly half the coaches only being able to identify 20% of runners correctly. Furthermore, roughly 58% of coaches were able to accurately rank the two least economical runners in order (based on accuracy percentage) compared to roughly 21% who were able to accurately rank the two most economical runners (see figure 2). These findings suggest that it is perhaps easier to identify less-metabolically optimal running styles than it is to identify runners displaying economical running pattern. It is not known if common running patterns were found in the 4th and/or 5th most economical runners that made it easier for coaches to correctly identify these runners compared to the other three runners in relation to RE. However, Raunig (1989) did find coaches were able to accurately distinguish fit cyclists with poor RE from runners with better RE when both were assessed in an RE trial. Collectively, these findings suggest that visual identification of RE may be easier in less economical runners.

Although not an exhaustive list, many biomechanical and anthropomorphic descriptors that are beneficial for RE have been previously quantified by various authors and are shown in Table 6. Consequently, in addition to ranking runners according to RE, coaches were asked to report the visual identifiers used in determination of their RE rankings. Coaches' familiarity with evidence-based concepts relating to RE (see Table 6) was apparent by the characteristics that coaches listed as being influential in their RE rankings (see Table 7).

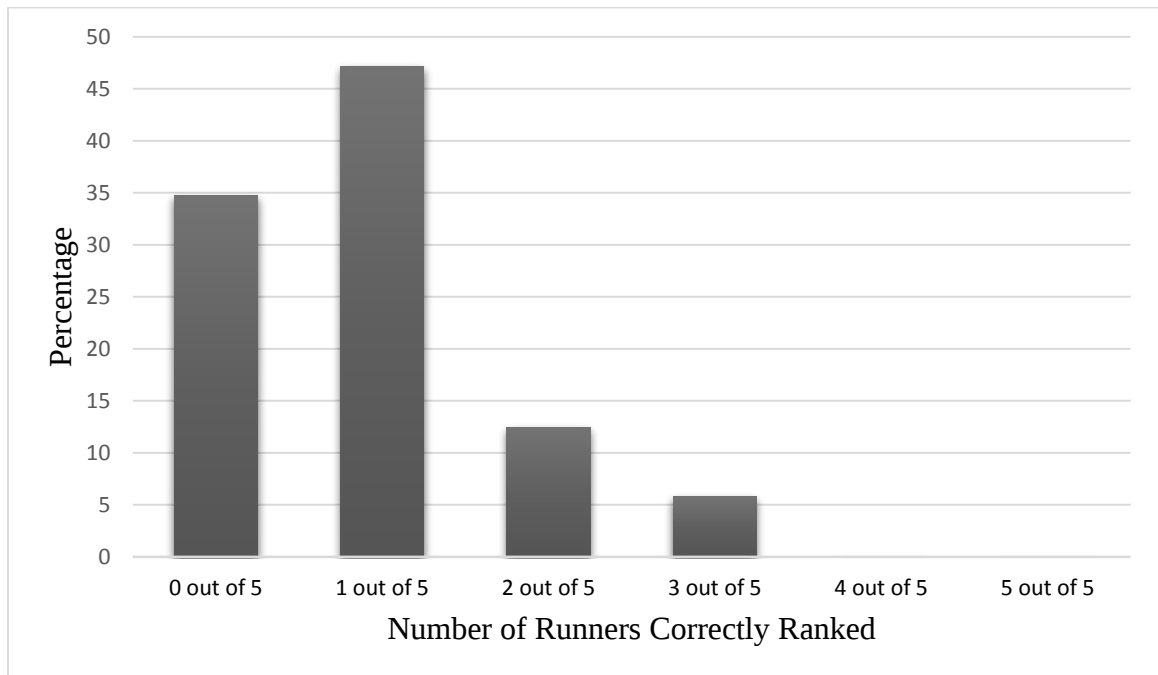


Figure 1. Number of Correctly Ranked Runners by Coaches. Identification of 4 out of 5 runners is not measurably possible based on an uneven sample number (5).

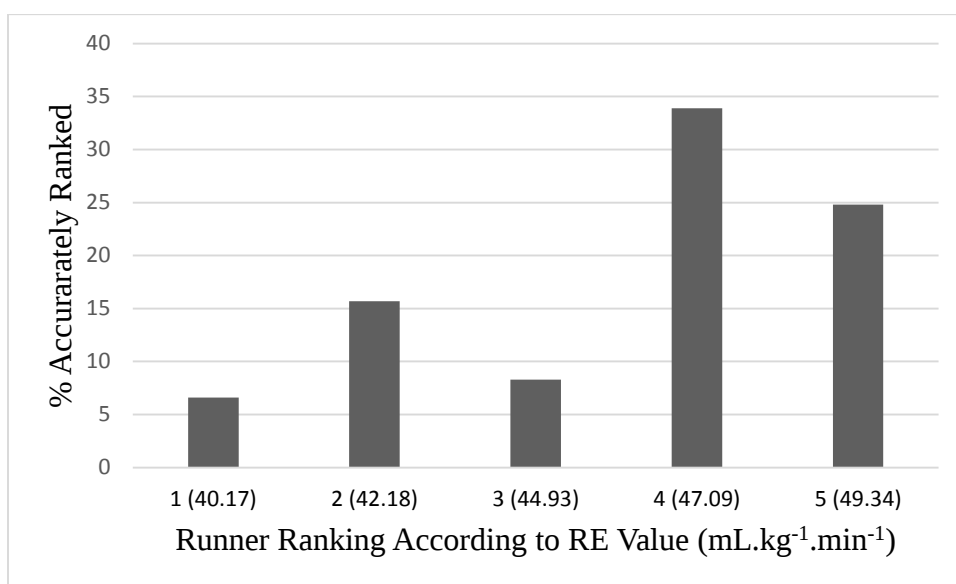


Figure 2. Accuracy of Coaches in Correctly Ranking each Runner on RE. RE values for each runner in parentheses (mL.kg⁻¹.min⁻¹). 1 = most economical runner. 5 = least economical runner.

However, on many occasions, the application of the identifier was misused in relation to the documented impact of the factor on RE. For instance, Williams and Cavanagh (1987) found more economical runners exhibited a greater forward lean than less economical runners. Yet, many coaches listed an excessive forward lean as being detrimental to RE. Although speculative, this inconsistency in response may be associated with coaches consulting with other coaches or attending coaching conferences to obtain training information rather than searching out evidence published in the scientific literature (Reade et al., 2008).

From a performance standpoint, the ability to visually distinguish certain potential problematic areas in running patterns could prove useful for coaches at all levels. Specifically, coaches who can distinguish even minor RE inconsistencies could initiate adjustments earlier-on in a runner's training program and potentially improve long-term performance outcomes. The majority of comments/identifiers listed by coaches as being influential in ranking RE are mentioned in the related scientific literature (see Table 6). However, many of these variables were referred to in a manner that was in contrast to the findings suggested by scientific research. For example, while nearly 11% of coaches mentioned a heel-striking footfall pattern as being detrimental to RE, this factor has not been proven to be detrimental and some research even indicates that it may be beneficial for RE (Williams & Cavanagh, 1987). In contrast, many coaches also listed body mass as being a factor that can affect RE, implying runners with a heavier body mass are not as economical when compared to runners with a lower body mass. Indeed, the majority of the related scientific literature indicates more economical runners have a lower body mass and less body fat compared to less economical runners (Saunders et al., 2004).

Table 6

Factors Related to Better Economy in Runners

Factor	Description for better running economy	Author
Height	Average or slightly shorter than average for males	Anderson, 1996
Ponderal index	High index and ectomorphic or mesomorphic physique	Anderson, 1996
Body fat	Low percentage	Anderson, 1996
Leg measures	Mass distributed closer to the hip joint, smaller calf circumference	Anderson, 1996; Lucia et al., 2006
Pelvis	Narrow	Anderson, 1996
Feet	Smaller than average	Anderson, 1996
Flexibility	Less flexibility in the transverse and frontal planes of the trunk and hip regions and less calf flexibility	Craib et al., 1996; Gleim et al., 1990
Stride length	Freely chosen over considerable training time and/or shorter given similar fitness level	Anderson, 1996; Cavanagh et al., 1977

Table 6 (continued)

Factors Related to Better Economy in Runners

Factor	Description for better RE	Corresponding author
Kinematics	More acute knee angles during swing	Anderson, 1996
	Low vertical oscillation of body center of mass	Anderson, 1996
	Greater forward trunk lean	Williams & Cavanagh, 1987
	Less plantar flexion	Williams & Cavanagh, 1987
	Arm motion that is not excessive	Anderson, 1996
	Faster rotation of shoulders in the transverse plane	Anderson, 1996
	Greater angular excursion of the hips and shoulders about the polar axis in the transverse plane	Anderson, 1996
Kinetics	(less impact at footfall (Low peak ground reaction forces)	Anderson, 1996
Footstrike patterns	Rearfoot strike	Ogueta-Alday, 2014

Table 7

Identifier Listed by Coaches as Being Helpful in Visually Ranking RE

Listed as good for RE	Percentage of total responses	Listed as bad for RE	Percentage of total responses
Higher stride rate/shorter stride length	13.6%	Greater vertical displacement/Bounce	13.2%
Midfoot/forefoot strike footfall pattern	9.1%	Heel striking footfall pattern	10.7%
Footfall under center of gravity	5.0%	High body mass	9.1%
Greater forward lean	2.4%	Lateral/transverse movement of arms across body	7.0%
		High arm carriage	6.6%
		Lateral/transverse rotation of lower body	6.5%
		Greater forward lean	6.2%
		Overstriding	6.1%
		Lateral/transverse rotation of torso	4.5%

Interestingly, the most economical runner in the current study also exhibited the highest body mass and body fat percentage. Hence, RE is affected by many factors and accurate visual differentiation between runners of varying RE likely cannot be determined by one lone factor

Results from the current investigation point out the need to provide coaches with evidence-based RE suggestions prior to assessment in order to determine if RE ranking scores can be improved. Furthermore, scientists and coaches may wish to work together to develop a research-based list of factors known to influence RE. The availability of such a listing may lead to reduced misinterpretation regarding the potential influence of a variable or set of variables on as well as improve the ability of a coach to distinguish among runners of varying RE and practically apply this information to training the athlete. However, given the ambiguity of some research findings and the hesitance of many coaches to take the time to read the relevant literature in this area, this task could prove difficult to accomplish.

With respect to potential limitations of this project, further consideration should be given to sampling a larger number of coaches. Although the coaching questionnaire was available to all coaches across the nation, 121 responses likely does not represent a true cross-sectional sampling of local, regional, and national distance-running coaches and coaching levels. A few coaches mentioned that they would have preferred to view the running videos in slow motion rather than in real-time speed, and it is possible that this constraint may have contributed to a lack of accuracy in evaluating RE. However, coaches were allowed to view the videos as many times as they liked, which may or may

not have compensated for the lack of slow-motion analysis. Finally, many coaches simply mentioned a few words relating to the identifiers used to rank each runner based on RE. On many occasions, it was unclear as to whether the coach meant an identifier was beneficial or detrimental to RE. Hence, many comments were left unaccounted for, due to lack of clarity from the researcher's standpoint. Therefore, future investigators should attempt to obtain more complete and meaningful comments from coaches regarding factors used to rank RE to avoid ambiguity on behalf of the researcher.

Conclusion

Running economy at a given speed is a prime indicator of endurance running performance and capability. However, assessment of RE in a laboratory setting can be a costly and time-intensive process that is not practical for distance running coaches at any level. Thus, the ability to visually identify RE flaws based on current evidence-based findings and make subsequent adjustments could prove useful for improving RE. However, findings from the current study illustrate the difficulty in assessing rank-order differences in RE by observational means alone. Moreover, neither coaching nor athletic experience improved ranking accuracy in the current sample. Analysis of specific identifiers that coaches use to assess running technique yielded characteristics similar to those which have been identified in the literature as being relevant to RE. However, many identifiers were misinterpreted concerning their actual influence on RE. Thus, coaches and scientist must work together to determine the most appropriate methods for relaying scientific findings to practitioners in the field.

CHAPTER IV REFERENCES

- Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine*, 22(2), 76-89.
- Astorino, T. A., Robergs, R. A., Ghiasvand, F., Marks, D., & Burns, S. (2000). Incidence of the oxygen plateau at VO_2max during exercise testing to volitional fatigue. *Journal of Exercise Physiology Online*, 3(4), 1-12.
- Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Medicine & Science in Sports & Exercise*, 12(5), 357-360.
- Conley, D. L., Krahenbuhl, G. S., Burkett, L. N., & Millar, A. L. (1984). Following Steve Scott: Physiological changes accompanying training. *The Physician & Sports Medicine*, 12, 103-106.
- Craig, M. W., Mitchell, V. A., Fields, K. B., Cooper, T. R., Hopewell, R., & Morgan, D. W. (1996). The association between flexibility and running economy in sub-elite male distance runners. *Medicine & Science in Sports & Exercise*, 28(6), 737-743.
- Gilbert, W., Lichtenwalder, L., Gilbert, J., Zelezny, L., & Cote, J. (2009). Developmental profiles of successful high school coaches. *International Journal of Sports Science and Coaching*, 4(3), 415-431.
- Gleim, G. W., Stachenfield, N. S., & Nicholas, J. A. (1990). The influence of flexibility on the economy of walking and jogging. *Journal of Orthopedic Research*, 8, 814-823.

- Jackson, A. S., & Pollock, M. L. (1978). Generalized equations for predicting body density of men. *British Journal of Nutrition*, 40(03), 497-504.
- Lucia, A., Esteve-Lanao, J., Olivan, J., Gomez-Gallago, F, San Juan, A. F., Santiago, C....Foster, C. (2006). Physiological characteristics of the best Eritrean runners' exceptional running economy. *Applied Journal of Nutrition & Metabolism*, 31, 530-540.
- Morgan, D. W., Bransford, D. R., Costill, D. L., Daniels, J. T., Howley, E. T., & Krahenbuhl, G. S. (1995). Variation in the aerobic demand of running among trained and untrained subjects. *Medicine and Science in Sports and Exercise*, 27(3), 404-409.
- Morgan, D. W., & Craib, M. (1992). Physiological aspects of running economy. *Medicine & Science in Sports & Exercise*, 24(4), 456-461.
- Morgan, D. W., Craib, M. W., Krahenbuhl, G. S., Woodall, K., Jordan, S., Filarski, K., ...Williams, T. (1994). Daily variability in running economy among well-trained male and female distance runners. *Research Quarterly for Exercise and Sport*, 65(1), 72-76.
- Morgan, D. W., Martin, P. E., Baldini, F. D., & Krahenbuhl, G. S. (1990). Effects of a prolonged maximal run on running economy and running mechanics. *Medicine & Science in Sports & Exercise*, 22(6), 834-840.
- Ogueta-Alday, A., Rodríguez-Marroyo, J. A., & García-López, J. (2014). Rearfoot striking runners are more economical than midfoot strikers. *Medicine & Science in Sports & Exercise*, 3(5), 451-455.

- Raunig, T. A. (1989). Prediction of RE based on observation. (Unpublished doctoral dissertation). University of Montana, Missoula, MT.
- Reade, I., Rodgers, W., & Hall, N. (2008). Knowledge transfer: How do high performance coaches access the knowledge of sports scientists? *International Journal of Sports Science and Coaching*, 3(3), 319-334.
doi:10.1260/174795408786238470
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34(7), 465-485.
- Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, 63(3), 1236-1245.
- Young, B. W., Jemczyk, K., Brophy, K., & Cote, J. (2009). Discriminating skilled coaching groups: Quantitative examination of developmental experiences and activities. *International Journal of Sports Science & Coaching*, 4(3), 397- 414.

APPENDICES FOR STUDY II

APPENDIX A

Coaching Descriptive Questionnaire

1. Please indicate the number of years you have been the primary HEAD COACH of distance runners? (i.e., cross country, track, and/or private coaching): _____
2. Please indicate the approximate age you became a distance running coach:
Head Coach _____ Assistant Coach _____
3. Please indicate your current coaching level or levels:
a. Junior high b. High school c. Collegiate
d. Professional/Private e. Currently not a coach
4. Please indicate the highest level of experience you have training/competing in running sports (cross country, track, road racing, and triathlon):
a. None b. Junior high c. High school d. Age group
e. Collegiate f. National g. International
5. If you chose an answer besides NONE in question #4, please circle your primary competition distance (outdoor track/ road, approximate triathlon distances)
a. Sprints b. 800 to 1,500 c. 5,000 to 10,000 d. Marathon +
e. Triathlon (list event)
6. If you have significant experience in another sport besides distance running please list the level and sport: Sport: _____; Level competed: _____
7. Please indicate the approximate number of TOTAL years you have competed/trained as a mid-distance/distance runner: _____
8. Please indicate the highest level of education you have CURRENTLY achieved:
a. High school b. College c. Masters level d. Doctorate
9. Please choose any of the following certifications that you CURRENTLY hold or have held within the last 6 months:
a. ACSM-CPT/HFS
b. NSCA-CPT/CSCS
c. NASM - CPT

- d. USAT level 1
- e. USAT level 2
- f. USAT level 3
- g. USATFCCCA (indicate specialty _____)
- h. Other (indicate _____)

10. Do you consider coaching runners to be your primary occupation?

- a. Yes
- b. No

APPENDIX B

Running Characteristics

Running Economy is defined as the oxygen cost (submaximal VO_2) of running a set steady state speed (e.g., 7 mph). Running economy is considered to be the most important predictor of distance running performance.

Directions:

- 1) Please view each of the 5 videos and then rank the runners from best to worst with respect to their running economy.
- 2) All videos are ~ 1 minute long and provide views of each runner at one speed and from three camera angles.
- 3) Please view videos as often as is needed in order to most accurately rank each runner.

Visual Assessment of Running Economy:

Please assign your rankings below:

1 = best running economy (most economical) and 5 = worst running economy (least economical)

Runner #1: Ranking _____

Runner #2: Ranking _____

Runner #3: Ranking _____

Runner #4: Ranking _____

Runner #5: Ranking _____

In making your running economy choices today, please type-in any major characteristics you VISUALLY considered in ranking the runners. Please be specific and include as many characteristics as you would like.

For example:

- 1) Runner #1 is ranked 5th because he exhibits poor running posture
- 2) I ranked the runners with a HIGH ARM CARRIAGE higher than others

APPENDIX C

IRB Letter of Approval

October 28, 2013

Robbie Cochrum

Protocol Title: **Accuracy of visual classification of running economy by coaches**

Protocol Number: 14-105

Dear Investigator(s),

The MTSU Institutional Review Board or its representative has reviewed the research proposal identified above. The MTSU IRB or its representative has determined that the study meets the criteria for approval under 45 CFR 46.110 and 21 CFR 56.110, and you have satisfactorily addressed all of the points brought up during the review.

Approval is granted for one (1) year from the date of this letter for 550 participants (500 coaches and 50 runners). Please use the version of the consent form with the compliance office stamp on it that will be emailed to you shortly.

Please note that any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918. Any change to the protocol must be submitted to the IRB before implementing this change.

You will need to submit an end-of-project report to the Office of Compliance upon completion of your research. Complete research means that you have finished collecting and analyzing data. Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date. Please allow time for review and requested revisions. Failure to submit a Progress Report and request for continuation will automatically result in cancellation of your research study. Therefore, you will NOT be able to use any data and/or collect any data.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to complete training (there is no need to include training certificates in your correspondence with the IRB). If you add researchers to an approved project, please forward an updated list of researchers to the Office of Compliance (compliance@mtsu.edu) before they begin to work on the project.

All paperwork, including consent forms, needs to be given to the faculty advisor for storage. All research materials must be retained by the PI or faculty advisor (if the PI is a student) for at least three (3) years after study completion and then destroyed in a manner that maintains confidentiality and anonymity.

Sincerely,

Paul S. Foster, Ph.D.
Associate Professor

CHAPTER V

OVERALL CONCLUSIONS

The central theme of this dissertation was running economy (RE), defined as the mass-related aerobic demand of running for a given submaximal running speed. In the first study, differences in RE when running barefoot, in minimal-type shoes, or in standard running shoes were identified in a group of recreational distance runners with experience running in minimal shoes. In the second study, the ability of distance-running coaches to correctly rank runners according to RE based on video observation was examined.

In Study 1, the effects of running under three footwear conditions (barefoot, minimal shoe, standard shoe) on RE was measured at two speeds (50 and 70% of vVO_{2max}) over the course of three days. Results from this study demonstrated that RE was not significantly different at either speed across all footwear conditions. However, at 50% of vVO_{2max} , running barefoot resulted in a significantly higher step frequency than running in a minimal shoe, whereas at 70% vVO_{2max} , running barefoot produced a significantly higher step frequency than running in both minimal and standard conditions. In addition, at 70% vVO_{2max} , participants running in a minimal shoe displayed a significantly higher step frequency compared to running in a standard running shoe. Although speculative, it is possible that step frequency may have been adjusted in order to maintain RE.

Previous studies which have compared the effects of running barefoot to running in various types of footwear on RE have yielded equivocal results (Saunders et al., 2004a). However, this study was unique in that two speeds were compared and all runners were experienced in running in both minimal and standard athletic footwear. When group findings are considered, results from Study 1 indicate that simply switching shoes or running barefoot will not lead to a meaningful change in RE. However, the influence of footwear choice on RE may vary from across individuals. For instance, some runners in the sample exhibited variations in RE exceeding 10% when running in one shoe versus another shoe. From a performance standpoint, a change in RE of this magnitude could potentially reduce 5k race time by more than three minutes.

Additional factors aside from footwear and speed are known to influence RE, including body mass, stride length, muscle fiber type, and various biomechanical variables (Saunders et al., 2004a). The extent to which distance coaches can visually differentiate runners based on RE would be beneficial in strategically evaluating the success of economy-based training programs. Thus, the second study of this dissertation was conducted to determine if distance coaches could visually differentiate RE among a group of runners.

Junior high, high school, collegiate, and professional distance-running coaches with various backgrounds and years of experience were asked a series of questions relating to their history as a coach and athlete (e.g., years spent coaching, highest training/racing level as athlete). Coaches were then asked to view video recordings of five recreational distance runners and rank them in order of perceived RE ability (1 = best

RE, 5 = worst RE). After ranking each runner, coaches were asked to provide a list of identifying characteristics they used in determining their RE rankings for each runner. Results from Study 2 indicated that the coaches were not able to rank runners of better economy (i.e., lower oxygen consumption) over runners with worse economy (i.e., higher oxygen consumption). Overall, no coach was correctly able to correctly rank all five runners with respect to RE, and only 5% of coaches were able to rank three of the five runners in the correct order. In addition, neither the number of years a coach has trained and competed as a runner, the highest coaching level attained, or the number of years spent coaching was a significant predictor of the ability to accurately rank runners on RE

In addition to ranking each runner, each coach provided a list of descriptors that were used in determining rank-order scores of RE. While many of these economy descriptors have been identified in the evidence-based scientific research as being influential to RE, coaches described their impact in a manner that was contradictory to that supported by the research literature. For example, while many coaches suggested that a runner displaying a heel-strike pattern would be less economical than a runner with a mid-or-forefoot strike, the majority of published research has shown the a heel-striking pattern results in a lower aerobic demand (Williams & Cavanagh, 1987). Practically speaking, these findings suggest a disconnect between coaches and scientists in terms of communicating training recommendations involving biomechanical factors associated with better RE. Currently, it is unknown how the ability to accurately rank a group of runners on RE is reflective of overall coaching success. Therefore, future consideration

should be given to bridging the gap between current scientific findings regarding RE and pragmatic recommendations made by coaches.

In conclusion, the overall results from Studies 1 and 2 highlight the diversity of factors related to RE and the difficulty in identifying runners with better or worse RE by video observation alone. This dissertation revealed that footwear choice does not substantially affect RE among a group of recreationally-trained runners, but that shoe selection can affect RE on an individual basis. From a coaching perspective, visual assessment of the biomechanical and anatomical features associated with better or worse RE remains a difficult task. Considered collectively, this dissertation sheds light on the need for practical dialogue between scientists and coaches regarding factors which influence RE.

DISSERTATION REFERENCES

- Alexander, R. M. (1991). Energy-saving mechanisms in walking and running. *Journal of Experimental Biology*, 160, 55-69.
- Anderson, T. (1996). Biomechanics and running economy. *Sports Medicine*, 22(2), 76-89.
- Arampatzis, A., De Monte, G. Karamanidis, K., Morey-Klapsing, G., Stafilidis, S., & Bruggemann, G. P. (2006). Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *Journal of Experimental Biology*, 209, 3345-3357.
- Aruin, A. S., Prilutski, B. I., Raitsin, L. M., Savelev, I. A., & Cheloveka, F. (1979). Biomechanical properties of muscles and efficiency of movement. *Human Physiology*, 5(4), 426-434.
- Aruin, A. S., & Prilutski, B. I. (1985). Relationship of the biomechanical properties of muscles to their ability to utilize elastic deformation energy. *Human Physiology*, 11(1), 8-12.
- Baechle, T. R., & Earle, R. W. (Eds.). (2008). *Essentials of strength training and conditioning*. Champaign, IL: Human Kinetics.
- Bale, P., Bradbury, D., & Colley, E. (1986). Anthropometric and training variables related to 10 km running performance. *British Journal of Sports Medicine*, 20, 170-173.

- Berliner, D. C. (1994). Expertise: The wonder of exemplary performances. In J. N. Mangieri & C. C. Block (Eds.), *Creating powerful thinking in teachers and students: Diverse perspectives* (pp. 161-186). Fort Worth, TX: Holt, Rinehart, & Winston.
- Biewener, A. A., & Roberts, T. J. (2000). Muscle and tendon contributions to force, work, and elastic savings: A comparative perspective. *Exercise and Sports Science Review*, 28(3), 99-107.
- Billat, V. L., Flechet, B., Petit, B., Gerard, M., & Koralsztejn, J. P. (1999). Interval training at VO₂ max: Effects on aerobic performance and overtraining markers. *Medicine & Science in Sports & Exercise*, 31(1), 156-163.
- Bosco, C., Montanari, G., Ribacchi, R., Giovenali, P., Latteri, F., Iachelli, G., . . . Saibene, F. (1987). Relationship between the efficiency of muscular work during jumping and the energetics of running. *European Journal of Applied Physiology and Occupational Physiology*, 56(2), 138-143.
- Bosch, A. N. (2006). Exercise science and coaching: Correcting common misunderstandings about endurance coaching. *International Journal of Sports Science & Coaching*, 1(1), 77-87.
- Bourdin, M., Belli, A., Arsac, L. M., Bosco, C., & Lacour, J. R. (1995). Effect of vertical loading on energy cost and kinematics of running in trained male subjects. *Journal of Applied Physiology*, 79(6), 2078-2085.

- Bruggemann, G. P., Potthast, W., Braunstein, B., & Niehoff, A. (2005). Effect of increased mechanical stimuli on foot muscles' functional capacity. In: *Proceedings of International Society for Biomechanics XXth Congress*, Cleveland, OH. American Society of Biomechanics, 552.
- Brughelli, M., Cronin, J., & Chaouachi, A. (2011). Effects of running velocity on running kinetics and kinematics. *Journal of Strength Conditioning Research*, 25(4), 933-939.
- Burkett, L. N., Kohrt, W. M., & Buchbinder, R. (1985). Effects of shoes and foot orthotics on VO_2 and selected frontal plane knee kinematics. *Medicine & Science in Sports & Exercise*, 17(1), 158-163.
- Bergh, U., Sjodin, B., Forsberg, A., & Svenenhag, J. (1991). The relationship between body mass and oxygen uptake during running in humans. *Medicine & Science in Sports & Exercise*, 23, 205-211.
- Catlin, M. E., & Dressendorfer, R. H. (1979). Effect of shoe weight on the energy cost of running. *Medicine & Science in Sports & Exercise*, 11, 80.
- Cavagna, G. A. (2006). The landing-take-off asymmetry in human running. *Journal of Experimental Biology*, 209, 4051-4060.
- Cavagna, G., Franzetti, P., Heglund, N., & Williams, P. (1988). The determinants of the step frequency in running, trotting, and hopping in man and other vertebrates. *Journal of Physiology*, 399, 81-92.
- Cavagna, G. A., & Kaneko, M. (1977). Mechanical work and efficiency in level walking and running. *Journal of Physiology*, 268, 647-681.

- Cavagna, G., Mantovani, M., & Willems, P. (1997). Effect of an increase in gravity on the power output and rebound of the body in human running. *European Journal of Physiology*, 437, 678-684.
- Cavagna, G. A., Saibene, F. P., & Margaria, R. (1964). Mechanical work in running. *Journal of Applied Physiology*, 18, 1-9.
- Cavagna, G., Willems, P., Franzetti, P., & Detrembleur, C. (1991). The two power limits conditioning step frequency in human running. *Journal of Physiology*, 437, 95-108.
- Cavanagh, P. R. (1981). *The running shoe book*. Palo Alto, CA: World Publications.
- Chelly, S. M., & Denis, C. (2001). Leg power and hopping stiffness: Relationship with sprint running performance. *Medicine & Science in Sports & Exercise*, 33, 326-333.
- Clarke, T. E., Frederick, E. C., & Cooper, L. B. (1983). Effects of shoe cushioning upon ground reaction forces in running. *International Journal of Sports Medicine*, 4(4), 247-251.
- Claremont, A. D., & Hall, S. J. (1988). Effects of extremity loading upon energy expenditure and running mechanics. *Medicine and science in sports and exercise*, 20(2), 167-171.
- Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Medicine & Science in Sports & Exercise*, 12(5), 357-360.

- Costill, D. L. (1967). The relationship between selected physiological variables and distance running performance. *Journal of Sports Medicine and Physical Fitness*, 7(2), 61-66.
- Costill, D. L., Thomason, H., & Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. *Medicine & Science in Sports & Exercise*, 5(4), 248-252.
- Craib, M. W., Mitchell, V. A., Fields, K. B., Cooper, T. R., Hopewell, R., & Morgan, D. W. (1996). The association between flexibility and running economy in sub-elite male distance runners. *Medicine & Science in Sports & Exercise*, 28(6), 737-743.
- Dalleau, G., Belli, A., Bourdin, M., & Lacour, J. R. (1998). The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology and Occupational Rehab*, 77(3), 257-263.
- Daoud, A. I., Geissler, G. J., Wang, F., Saretsky, J., Daoud, Y. A., & Lieberman, D. E. (2012). Foot strike and injury rates in endurance runners: A retrospective study. *Medicine & Science in Sports & Exercise*, 44(7), 1325-1334.
doi:10.1249/MSS.Ob013e3182465115
- Davies, M. J., Mahar, M. T., & Cunningham, L. N. (1997). Running economy: Comparison of body mass adjustment methods. *Research Quarterly for Exercise and Sport*, 68(2), 177-181.

- Denadai, B. S., Ortiz, M. J., Greco, C. C., & Mello, M. T. (2006). Interval training at 95% and 100% of the velocity at VO_2 max: Effects on aerobic physiological indexes and running performance. *Applied Physiology, Nutrition, and Metabolism*, 31, 737-743.
- Denoth, J. (1986). Load on the locomotor system and modeling. (1986). In B. M. Nigg (Ed.), *Biomechanics of running shoes* (pp. 65-116). Champaign IL: Human Kinetics.
- De Wit, B., De Clercq, D., & Aerts, P. (2000). Biomechanical analysis of the stance phase during barefoot and shod running. *Journal of Biomechanics*, 33(3), 269-278.
- Di Pampero, P. E., Atchou, G., Bruckner, J. C., & Moia, C. (1986). The energetics of endurance running. *European Journal of Applied Physiology*, 55, 259-266.
- Divert, C., Baur, H., Mornieux, G., Mayer, F., & Belli, A. (2005a). Stiffness adaptations in shod running. *Journal of Applied Biomechanics*, 21(4), 311-321.
- Divert, C., Mornieux, G., Baur, H., Mayer, F., & Belli, A. (2005b). Mechanical comparison of barefoot and shod running. *International Journal of Sports Medicine*, 26(7), 593-598.
- Egbuonu, M. E., Cavanagh, P. R., & Miller, T. A. (1990). Degradation of running economy through changes in running mechanics. *Medicine & Science in Sports & Exercise*, 22, S17.

- Eriksson, M., Halvorsen, K. A., & Gullstrand, L. (2011). Immediate effect of visual and auditory feedback to control the running mechanics of well-trained athletes. *Journal of Sports Sciences*, 29(3), 253-262.
- Farley, C. T., & Gonzalez, O. (1996). Leg stiffness and stride frequency in human running. *Journal of Biomechanics*, 29(2), 181.
- Farrell, P. A., Wilmore, J. H., Coyle, E. F., Billing, J. E., & Costill, D. L. (1993). Plasma lactate accumulation and distance running performance. *Medicine and Science in Sports and Exercise*, 25(10), 1091-1097.
- Fay, L., Londeree, B. R., LaFontaine, T. P., & Volek, M. R. (1989) Physiological parameters related to distance running performance in female athletes. *Medicine & Science in Sports & Exercise*, 21(3), 319-24.
- Franch, J., Madsen, K., Djurhuus, M. S., & Pedersen, P. K. (1998). Improved running economy following intensified training correlates with reduced ventilatory demands. *Medicine and Science in Sports and Exercise*, 30(8), 1250-1256.
- Franz, C., Wierzbinski, C. M. & Kram, R. (2012). Metabolic cost of running barefoot versus shod: Is lighter better? *Medicine & Science in Sports & Exercise*. Advance online publication. doi:10.1249/MSS.0b013e3182514a88
- Frederick, E. C. (1983). Measuring the effects of shoes and surfaces on the economy of locomotion. In B. M. Nigg & B. A. Kerr (Eds.), *Biomechanical aspects of sport shoes and playing surfaces* (pp. 93-106). Calgary: University of Calgary.

- Frederick, E. C., Clark, T. E., Larsen, J. L., & Cooper, L. B. (1983). The effect of shoe cushioning on oxygen demands of running. In B. M. Nigg & B. A. Kerr (Eds.), *Biomechanical aspects of sport shoes and playing surfaces* (pp. 104-114). Calgary: University of Calgary
- Frederick, E. C., Daniels, J. T., & Hayes, J. W. (1984). The effect of shoe weight on the aerobic demands of running. In N. Bachl & L. Prokop (Eds.) *Current topics in sports medicine* (pp. 616-625). Vienna: Urban & Schwarzenberg.
- Gilbert, W. Lichtenwaltdt, L., Gilbert, J., Zelezny, L., & Cote, J. (2009). Developmental profiles of successful high school coaches. *International Journal of Sports Science and Coaching*, 4(3), 415-431.
- Gillespie, W. J., & Grant, I. (2000). Interventions for preventing and treating stress fractures and stress reactions of bone of the lower limbs in young adults. Retrieved from Cochrane Database Systematic Reviews (CD000450)
- Gleim, G. W., Stachenfield, N. S., & Nicholas, J. A. (1990). The influence of flexibility on the economy of walking and jogging. *Journal of Orthopedic Research*, 8, 814-823.
- Godges, J. J., Macrae, H., Longdon, C., Tinberg, C., & Macrae, P. (1989). The effects of two stretching procedures on hip range of motion and gait economy. *The Journal of Orthopaedic and Sports Physical Therapy*, 10(9), 350-357.
- Hamill, J., Freedson, P. S., Boda, W., & Reichsman, F. (1988). Effects of shoe type on cardiorespiratory responses and rear-foot motion during treadmill running. *Medicine and Science in Sports and Exercise*, 20(5), 515-521.

- Heglund, N. C., & Taylor, C. R. (1988). Speed, stride frequency and energy cost per stride: How do they change with body size and gait? *Journal of Experimental Biology*, 138, 301-318.
- Heglund, N. C., Fedak, M. A., Taylor, C. R., & Cavagna, G. A. (1982). Energetics and mechanics of terrestrial locomotion. IV. Total mechanical energy changes as a function of speed and body size in birds and mammals. *Journal of Experimental Biology*, 97, 57-66.
- Helgerud, J. (1994). Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performance levels in marathons. *European Journal of Applied Physiology*, 68, 155-161.
- Helgerud, J. Storen, O., & Hoff, J. (2009). Are there differences in running economy at different velocities for well-trained runners? *European Journal of Applied Physiology*, 108, 1099-1105. doi:10.1007/s00421-009-1218-z
- Heise, G. D., & Martin, P. E. (2001). Are variations in running economy in humans associated with ground reaction force characteristics? *European Journal of Applied Physiology*, 84, 438-442.
- Hennig, E., Valiant, G., & Liu, Q. (1996). Biomechanical variables and the perception of cushioning for running in various types of footwear. *Journal of Applied Biomechanics*, 12, 141-150.

- Hinrichs, R. N. (1985). A three-dimensional analysis of the net moments at the shoulder and elbow joints in running and their relationship to upper extremity EMG activity. In D. A. Winter, D. A., R. W. Norman, R. P. Wells, A. E. Hayes, & A. E. Patla (Eds.), *Biomechanics IX-B* (pp. 337-342). Human Kinetics: Champaign, IL.
- Hinrichs, R. N. (1987). Upper extremity function in running II: Angular momentum considerations. *International Journal of Sport Biomechanics*, 3, 242-263.
- Hinrichs, R. N. (1990). Whole body movement: Coordination of arms and legs in walking and running. In J. M. Winters & S. L-Y. Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization* (pp. 694-705). New York, NY: Springer
- Hinrichs, R. N., Cavanagh, P. R., & Williams, K. R. (1983). Upper extremity contributions to angular momentum in running. In H. Matsui & K. Kobayashi, (Eds.), *Biomechanics VIII-B* (pp. 641-647). Human Kinetics: Champaign, IL.
- Hof, A. L., Van Zandwijk, J. P., & Bobbert, M. F. (2002). Mechanics of human triceps surae muscle in walking, running, and jumping. *Acta Physiologica Scandinavica*, 174, 17-30.
- Hoff, J., Helgerud, J., & Wisloff, U. (1999). Maximal strength training improves work economy in trained female cross-country skiers. *Medicine & Science in Sports & Exercise*, 31, 830-877.

- Hunter, G. R., Katsoulis, K., McCarthy, J. P., Ogard, W. K., Bamman, M. M., Wood, D. S., . . . Newcomer, B. R. (2011). Tendon length and joint flexibility are related to running economy. *Medicine & Science in Sports & Exercise*, 43(8), 1492-1499. doi:10.1249/MSS.Ob013e318210464a
- Johnston, R. E., Quinn, T. J., Kertzer, R., & Vroman, N. B. (1997). Strength training in female distance runners – Impact on running economy. *Journal of Strength and Conditioning Research*, 11, 224-229.
- Jones, A. M. (2002). Running economy is negatively related to sit-and-reach test performance in international-standard distance runners. *International Journal of Sports Medicine*, 23, 40-43.
- Jones, B. H., Knapik, J. J., Daniels, W. L., & Toner, M. M. (1986). The energy cost of women walking and running in shoes and boots. *Ergonomics*, 29(3), 439-443.
- Ker, R. F., Bennett, M. B., Bibby, S. R., Kester, R. C., & Alexander, R. M. (1987). The spring in the arch of the human foot. *Nature*, 325 (7000), 147-149.
- Kong, P. W., Candelaria, N. G., & Smith, D. R. (2009). Running in new and worn shoes: A comparison of three types of cushioning footwear. *British Journal of Sports Medicine*, 43, 745-749. doi:10.1136/bjism.2008.047761
- Kram, R., & Taylor, C. R. (1990). Energetics of running: A new perspective. *Nature*, 346, 265-267.
- Kumagai, K., Abe, T., Brechue, W. F., Ryushi, T., Takano, S., & Mizuno, M. (2000). Sprint performance is related to muscle fascicle length in male 100-m sprinters. *Journal of Applied Physiology*, 88, 811-816.

- Kyrolainen, H., Belli, A., & Komi, P. V. (2001). Biomechanical factors affecting running economy. *Medicine & Science in Sports & Exercise*, 33, 1330-1337.
- Lake, M. J., & Cavanagh, P. R. (1996). Six weeks of training does not change running mechanics or improve running economy. *Medicine & Science in Sports & Exercise*, 28(7), 860-869.
- Lucia, A., Esteve-Lanao, J., Olivan, J., Gomez-Gallago, F., San Juan, A. F., Santiago, C.... Foster, C. (2006). Physiological characteristics of the best Eritrean runners' exceptional running economy. *Applied Journal of Nutrition & Metabolism*, 31, 530-540. doi:10.1139/H06-029
- Maldonado, S., Mujika, I., & Padilla, S. (2002). Influence of body mass and height on the energy cost of running in highly trained middle- and long-distance runners. *International Journal of Sports Medicine*, 23, 268-272.
- Mann, R. V. (1981). A kinetic analysis of sprinting. *Medicine & Science in Sports & Exercise*, 13, 325-328.
- Mann, R. V., & Herman, J. (1985). Kinematic analysis of Olympic sprint performance: Men's 200 meters. *International Journal of Sports Biomechanics*, 1, 151-162.
- Marino, F. E., Mbambo, Z., Kortekaas, E., Wilson, G., Lambert, M. I., Noakes, T. D., . . . Dennis, S. C. (2000). Advantages of smaller body mass during distance running in warm, humid environments. *European Journal of Physiology*, 441, 359-367. doi:10.1007/s004240000432
- Martin, P. E. (1985). Mechanical and physiological responses to lower extremity loading during running. *Medicine & Science in Sports & Exercise*, 17(4), 427-433.

- Martin, P. E., & Morgan, D. W. (1992). Biomechanical considerations for economical walking and running. *Medicine & Science in Sports & Exercise*, 24(4), 467-474.
- Mayhew, J. L. (1977). Oxygen cost and energy expenditure of running in trained runners. *British Journal of Sports Medicine*, 11, 116-121.
- McArdle, W. D., Katch, F. I., & Katch, V. L. (2007). *Exercise physiology: Energy, nutrition, and human performance* (6th ed.). Philadelphia, PA: Lippincott, Williams, & Wilkins.
- McCarthy, J. P., Hunter, G. R., Larson-Meyer, D. E., Bamman, M. M., Landers, K. A., & Newcomer, B. R. (2006). Ethnic differences in triceps surae muscle-tendon complex and walking economy. *Journal of Strength and Conditioning Research*, 20, 511-518.
- Messier, S. P., & Cirillo, K. J. (2007). Effects of a verbal and visual feedback system on running technique, perceived exertion and running economy in female novice runners. *Journal of Sports Sciences*, 7(2), 113-126.
doi:10.1080/02640418908729830
- Midgley, A. W., McNaughton, L. R., & Jones, A. M. (2007). Training to enhance the physiological determinants of long-distance running performance. *Sports Medicine*, 27(10), 857-880.
- Millet, G. P., Jaouen, B., Borrani, F., & Candau, R. (2002). Effects of concurrent endurance and strength training on running economy and VO₂ kinetics. *Medicine & Science in Sports & Exercise*, 34, 1351-1359.

- Morgan, D. W., & Craib, M. (1992). Physiological aspects of running economy. *Medicine & Science in Sports & Exercise*, 24(4), 456-461.
- Morgan, D. W., Martin, P. E., & Krahenbuhl, G. S. (1989). Factors affecting running economy. *Sports Medicine*, 7, 310-330.
- Morgan, D., Martin, P., Craib, M., Caruso, C., Clifton, R., & Hopewell, R. (1994). Effect of step length optimization on the aerobic demand of running. *Journal of Applied Physiology*, 77(1), 245-251.
- Morgan, D. W., Craib, M. W., Krahenbuhl, G. S., Woodall, K., Jordan, S., Filarski, K.,... Williams, T. (1994). Daily variability in running economy among well-trained male and female distance runners. *Research Quarterly for Exercise and Sport*, 65(1), 72-76.
- Morgan, D. W., Bransford, D. R., Costill, D. L., Daniels, J. T., Howley, E. T., & Krahenbuhl, G. (1995). Variation in the aerobic demand of running among trained and untrained subjects. *Medicine & Science in Sports & Exercise*, 27(3), 404-409.
- Myers, M. J., & Steudel, K. (1985). Effect of limb mass and its distribution on the energetic cost of running. *Journal of Experimental Biology*, 116, 363-373.
- Nash, C., & Collins, D. (2006). Tacit knowledge in expert coaching: Science or art? *Quest*, 58, 465-477.
- Nelson, A. G., Kokkonen, J., Eldridge, C., Cornwell, A., & Glickman-Weiss, E. (2001). Chronic stretching and running economy. *Scandinavian Journal of Medicine and Science in Sports*, 11, 260-265.

- Nielsen B., Hales J. R. S., Strange S., Christensen, N. J., Warberg J., & Saltin, B. (1993). Human circulatory and thermoregulatory adaptation with heat acclimation and exercise in a hot, dry environment. *Journal of Physiology*, 460, 467–485.
- Nigg, B. M., (1983). External force measurements with sport shoes and playing surfaces. In B. M. Nigg & B. A. Kerr (Eds.), *Biomechanical aspects of sport shoes and playing surfaces* (pp. 169-176). Calgary: University Printing.
- Nigg, B. M. (Ed.). (1986). *The biomechanics of running shoes*. Champaign, IL: Human Kinetics Books.
- Noakes, T. D. (1991). *The lore of running*. Champaign, IL: Human Kinetics.
- Nummela, A., Keranen, T., & Mikkelsen, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, 28, 655-661.
- Oyvind, S., Helgerud, J., & Hoff, J. (2011). Running stride peak forces inversely determine running economy in elite runners. *Journal of Strength and Conditioning Research*, 25(1), 117-123.
- Paavolainen, L., Hakkinen, K., Hamalainen, I, Nummela, A., & Rusko, H. (1999). Explosive strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*, 86, 1527-1533.
- Pate, R., Macera, C., Bartoli, W., & Maney, C. (1989). Physiological and anatomical correlates of running economy in habitual runners. *Medicine & Science in Sports & Exercise*, 21(Suppl. 2), S26.

- Pate, R. R., Macera, C. A., Bailey, S. P., Bartoli, W. P., & Powell, K. E. (1992). Physiological, anthropometric, and training correlates of running economy. *Medicine and science in sports and exercise*, 24(10), 1128-1133.
- Pereira, M. A., & Freedson, P. S. (1997). Intraindividual variation of running economy in highly trained and moderately trained males. *International Journal of sports Medicine*, 18(2), 118-124.
- Perl, D. P., Daoud, A. I., & Lieberman, D. E. (2012). Effects of footwear and strike type on running economy. *Medicine and Science in Sports and Exercise*, 44(7), 1335-1343.
- Pollack, M. L., Jackson, A. S., & Pate, R. S. (1980). Discriminant analysis of physiological differences between good and elite distance runners. *Research Quarterly for Exercise and Sport*, 51(3), 521-532.
- Reade, I., Rodgers, W., & Hall, N. (2008). Knowledge transfer: How do high performance coaches access the knowledge of sport scientists? *International Journal of Sports Science and Coaching*, 3(3), 319-334.
- Robbins, S. E., & Hanna, A. M. (1987). Running-related injury prevention through barefoot adaptations. *Medicine & Science in Sports & Exercise*, 19(2), 148-156.
- Robbins, S., & Waked, E. (1997). Balance and vertical impact in sports: Role of shoe sole materials. *Archives of Physical Medicine & Rehabilitation*, 78(5), 463-467.
- Saltin, B., & Astrand, P. O. (1967). Maximal oxygen uptake in athletes. *Journal of Applied Physiology*, 23(3), 353-358.

- Sasaki, K., & Neptune, R. R. (2006). Muscle mechanical work and elastic energy utilization during walking and running near the preferred gait transition speed. *Gait and Posture*, 23, 383-390.
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004a). Factors affecting running economy in trained distance runners. *Sports Medicine*, 34(7), 465-485.
- Saunders, P. U., Pyne, D. B., Telford, R. D., & Hawley, J. A. (2004b). Reliability and variability of running economy in elite distance runners. *Medicine & Science in Sports & Exercise*, 36(11), 1972-1976.
- Saunders, P. U., Telford, R. D., Pyne, D. B., Peltola, E. M., Cunningham, R. B. Gore, C. J., . . . Hawley, J. A. (2006). Short-term plyometric training improves running economy in highly trained middle and long distance runners. *Journal of Strength and Conditioning Research*, 20(4), 947-954.
- Scholz, M. N., Bobbert, M. F., Van Soest, A. J., Clark, J. R., & van Heerden, J. (2008). Running biomechanics: Shorter heels, better economy. *The Journal of experimental biology*, 211(20), 3266-3271.
- Shorten, M. R. (1989, August). *Elastic energy in athletic shoe cushioning system*. Paper presented at the XII International Congress of Biomechanics, Los Angeles, CA.
- Sjodin, B., Jacobs, I., & Svedenhag, J. (1982). Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA. *European Journal of Applied Physiology*, 49, 45-47.

- Slawinski, J. S., & Billat, V. L. (2004). Difference in mechanical and energy cost between highly, well, and non-trained runners. *Medicine & Science in Sports & Exercise*, 36(8), 1440-1446.
- Spurrs, R. W., Murphy, A. J., & Watsford, M. L. (2003). The effect of plyometric training on distance running performance. *European Journal of Applied Physiology*, 89, 1-7.
- Stefanyshyn, D. J., & Nigg, B. M. (2000a). Energy aspects associated with sport shoes. *Sportsverlets Sportschaden*, 14(3), 82-89.
- Steudel-Numbers, K. L., Weaver, T. D., & Wall-Scheffler, C. M. (2007). The evolution of human running: Effects of changes in lower-limb length on locomotor economy. *Journal of Human Evolution*, 53, 191-196.
- Squadrone, R., & Gallozzi, C. (2009). Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *Journal of Sports Medicine & Physical Fitness*, 49, 6-13.
- Taylor, C. R. (1994). Relating mechanics and energetics during exercise. *Advances in Veterinary Science and Comparative Medicine*, 38A, 181-215.
- TenBroek, T., Umberger, B., & Hinrichs, R. (2006, August). *The effect of the shoe midsole thickness on ankle kinematics and kinetics during cutting maneuvers*. Paper presented at the Biennial Conference of the Canadian Society for Biomechanics, Waterloo, ON.

- Tenbroek, T. M. (2011). *Adaptations to running while footwear cushioning and surface are manipulated* (Unpublished doctoral dissertation). University of Massachusetts – Amherst. Amherst, MA.
- Teunissen, L. P. J., Grabowski, A., & Kram, R. (2007). Effects of independently altering body weight and body mass on the metabolic cost of running. *The Journal of Experimental Biology*, 210, 4418-4427.
- Tseh, W., Caputo, J. L., & Morgan, D. W. (2008). Influence of gait manipulation on running economy in female distance runners. *Journal of Sports Science & Medicine*, 7, 91-95.
- Turner, A. M., Owings, M., & Schwane, J. A. (2003). Improvement in running economy after 6 weeks of plyometric training. *Journal of Strength and Conditioning Research*, 17(1), 60-67.
- Utz-Meagher, C., Nulty, J., & Holt, L. (2011). Comparative analysis of barefoot and shod running. *Sport Science Review*, 20(3-4), 113-130. doi:10.2478/v10237-011-0057-0
- Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, 63(3), 1236-1245.
- Williams, K. R., Cavanagh, P. R., & Ziff, J. L. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine*, 8, 107-118.

- Williams, J. S., & Kendall, L. (2007). Perceptions of elite coaches and sports scientists of the research needs for elite coaching practice. *Journal of Sports Sciences*, 25(14), 1577-1586. doi:10.1080/02640410701245550
- Williams, T. J., Krahenbuhl, G. S., & Morgan, D. W. (1991). Daily variation in running economy of moderately trained male runners. *Medicine & Science in Sports & Exercise*, 23(8), 944-948.
- Williams, D. S., McClay, I. S., & Manal, K. T. (2000). Lower extremity mechanics in runners with a converted forefoot strike pattern. *Journal of Applied Biomechanics*, 16, 210-218.