THE EFFECTS OF THREE DIFFERENT STRETCHING INTERVENTIONS ON RUNNING ECONOMY IN TRAINED FEMALE ATHLETES

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To the Dean of the Graduate School:

I am submitting herewith a dissertation written by Kelley Henry entitled "The Effects of Three Different Stretching Interventions on Running Economy in Trained Female Athletes." I have examined this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Kinesiology.

David Nichols, Major Professor

We have read this dissertation and recommend its acceptance:

Department Chair

Accepted:

Dean of the Graduate School

ABSTRACT

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THE EFFECTS OF THREE DIFFERENT STRETCHING INTERVENTIONS ON RUNNING ECONOMY IN TRAINED FEMALE ATHLETES

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The purpose of the current investigation was to determine the effects of three different stretching interventions on running economy (VO_2), lactate, and stride length in female distance runners. Twelve trained females (VO_{2peak} = 52.07 ± 3.8 ml·kg^{-1}·min^{-1}) completed five testing sessions. A VO_{2peak} test was administered in the first session. Sessions 2 – 5 included a 10 min warm up at a self-selected speed, flexibility measures (sit and reach, ankle dorsiflexion), stretching intervention, reassessment of flexibility measures, and a 10 min run at 80% VO_{2peak}. Stride mechanics were assessed during the final 10 min run and blood lactate concentration was sampled at completion of the final 10 min run. The stretching interventions included a control (CON) consisting of a 10 min sit; active isolated stretching (AIS) involving 2 sets of 30 s of 5 stretches that were held for 1-2 s and repeated for the 30 s period; static stretching (SS) involving 2 sets of 30 s of 5 stretches that were held for the 30 s time period; and, dynamic flexibility (DF) involving a series of 10 running specific drills repeated for 2 sets of 30 s. Differences in VO_2 (ml·kg^{-1}·min^{-1}), lactate, and stride length for each condition (control, DF, SS, AIS) were analyzed via a repeated measures multivariate analysis of variance (RM MANOVA) with an alpha levels of .05. The stretching interventions did not have a significant effect on VO_2 ($p = .110$), lactate ($p = .105$) and stride length ($p = .95$).The mean values and standard deviations (SD) for VO_2 (ml·kg^{-1}·min^{-1}) were 42.13 ± 4.7 (CON), 42.4 ± 4.04 (AIS), 42.13 ± 4.06 (SS), and 42.75

± 4.6 (DF). Lactate mean values ($mmol \cdot L^{-1}$) and SD were 4.1 ± 1.6 (CON), 3.4 ± 1.2 (AIS), 3.7 ± 1.4 (SS), and 4.6 ± 1.6 (DF). The mean values for stride length were 2.2 ± .13 for all sessions. In conclusion, AIS, SS, and DF did not alter running performance variables as the submaximal nature of running and the length of the run may have negated the effects of the stretching.

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CHAPTER I

INTRODUCTION

Running economy is an important predictor of running performance in endurance runners with similar VO_{2max} values (Conley & Krahenbuhl, 1980; Costill, Thomason, & Roberts, 1973; Daniels & Daniels, 1992; Morgan & Craib, 1992; Morgan, Martin, Baldini, & Krahenbuhl, 1990).Running performance can be defined as winning a race or an improvement in race time over a set distance. Running economy is defined as the steady state oxygen consumption at a given speed (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992). Steady state oxygen consumption is defined as the plateau in the oxygen consumption curve when the energy demand of the muscles is in balance with the ATP production in oxidative metabolism (McArdle, Katch, & Katch, 2001). Running economy can vary approximately 30% among runners due to a variety of factors including age, gender, training status, environmental conditions, fatigue, stride mechanics, flexibility, and strength training (Morgan, Martin, & Krahenbuhl, 1989).

Running economy can be affected by stride mechanics which may explain up to 54% of the variance in running economy (Williams & Cavanagh, 1987). Stride mechanics include stride length and stride frequency (Williams & Cavanagh, 1987). Through training, runners adopted the most efficient stride rate and length combination to reduce the oxygen cost of running and a different combination exists at different speeds (Brisswalter, Legros, & Durand, 1996; Cavanagh & Williams, 1982). Any alteration from the most efficient stride length results in a decrease in running economy as more muscle mass/fibers may be recruited to support the change (Cavanagh & Williams, 1982; Cavanagh et al., 1985; Heinert et al., 1988; Knuttgen, 1961).

Additionally, fatigue can also cause changes in stride length which further decreases running economy (Hausswirth & Guezennec, 1997; Siler & Martin, 1991).

Flexibility of the hip, ankle, and trunk has also been implicated to alter running economy (Godges, MacRae, Longdon, Tinberg, & MacRae, 1989). Decreased flexibility of the hip, ankle, and trunk has been significantly correlated with running economy in male and female distance runners (Craib et al., 1996; Gleim, Stachenfeld, & Nicholas, 1990; Jones, 2002). Lack of flexibility may improve running economy by enhancing the action of the stretch shortening cycle (SSC) or reducing the recruitment of stabilizer muscles during the running stride (Craib et al., 1996; Jones, 2002).

Most warm-up routines prior to exercise include a stretching component in an attempt to increase flexibility which is thought to improve performance and reduce injury risk (Hedrick, 2000). Numerous researchers (Avela, Kyröläinen, Komi, 1999; Evetovich, Nauman, Conley, & Todd, 2003; Fowles, Sale, & MacDougall, 2000; Nelson, Allen, Cornwell, & Kokkonen, 2001) have examined the role of stretching prior to concentric activities such as weight lifting as well as SSC activities such as vertical jump and sprinting. Despite commonly held beliefs, stretching prior to concentric and SSC activities have been reported to reduce performance possibly due to changes in the stiffness of the muscle tendon unit (MTU; Avela et al., 1999; Evetovich et al., 2003; Fowles et al., 2000; Nelson et al., 2001).

Stretching has been reported to increase range of motion (Bandy & Irion, 1994; Gajdoski, 1991; Henricson et al. 1984; Roberts & Wilson, 1999) thus increasing flexibility. Increased flexibility may have a negative impact on running economy (Craib et al., 1996; Gleim, et al., 1990; Jones, 2002) and static stretching prior to activity has been reported to have a negative impact on performance (Avela et al., 1999; Evetovich et al., 2003; Fowles et al., 2000;

Nelson et al., 2001); therefore, it is hypothesized that static stretching prior to running may have a negative impact on running economy as well. Additionally, studies on the effects of stretching prior to submaximal running are limited as few studies have examined the effects of stretching prior to running on running economy and no effects were reported on running economy for different stretching routines (Allison, Bailey, & Folland, 2008; Hayes & Walker, 2007; Zimmer, Burandt, & Kent, 2007). Compared to static stretching, dynamic flexibility has been reported to improve performance (Herda et al., 2008; Herman & Smith, 2008; Yamaguchi & Ishii, 2005) and is a common warm-up routine used by runners as is active isolated stretching; therefore, the aim of the current study is to investigate the effects of different stretching protocols on running economy. Gender also affects running economy in that males are more economical than females mainly due to differences in stride mechanics (Daniels & Daniels, 1992; Morgan & Craib, 1992). Additionally, Allison et al. (2008),Hayes and Walker (2007), and Zimmer et al. (2007) only examined the effects of stretching on running economy in male distance runners; therefore, there is a need to examine the effects of stretching on running economy in female runners as studies are limited in this area.

Problem Statement

The current study was designed to determine the effects of three stretching interventions on running economy. The effects of three stretching interventions on running economy were determined using trained female athletes during the follicular phase of the menstrual cycle. Oxygen consumption was compared to determine the effects of the stretching interventions on running economy.

Null Hypothesis

1. No differences will exist in VO_2, lactate, and stride length for each stretching intervention (control, active isolated stretching, dynamic flexibility, and static stretching).

Definition of Terms

The following definitions were used in the study:

Active Isolated Stretching: Active isolated stretching was defined according to Mattes (1995) as a type of stretching that is held for 2 s but repeated for 30 s.

Dynamic Flexibility: Dynamic flexibility was defined according to Hedrick (2000) as the use of functional-based exercises utilizing sports specific movements to ready the body for activity.

Follicular Phase of the Menstrual Cycle: The follicular phase of the menstrual cycle was defined according to Guyton and Hall (2006), as beginning on the first day of menses and continuing for the next 7 - 10 days.

Heart Rate: Heart rate was defined according to Anderson and Anderson (1998), as the pulse, calculated by counting the number of ventricular beats per minute. A Polar Vantage Heart Rate Monitor (Polar Vantage, Polar Electro OY, Kempele, Finland) measured heart rate.

Muscle Tendon Unit: The muscle tendon unit was defined elastic components arranged in series and parallel that work with the contractile elements of the muscle (Brooks et al., 2003).

Trained Athlete: Trained athlete was defined operationally as an athlete with a VO_2 peak of 45 $ml \cdot kg^{-1} \cdot min^{-1}$ or greater.

Oxygen uptake: Oxygen uptake was defined according to McArdle, Katch and Katch (2003) as the ability of the body to transport and utilize oxygen during exercise. Oxygen uptake was determined by the ParvoMedics Truemax 2400 metabolic cart (Consentius Technologics, Sandy, UT) and a two-way breathing mask (Hans Rudolph, Survivair, Comasec, Inc.) and represented as $ml \cdot kg^{-1} \cdot min^{-1}$.

Respiratory Exchange Ratio: Respiratory exchange ratio was defined according to McArdle, Katch, and Katch (2001), as the ratio of carbon dioxide expired to the oxygen consumed at the level of the lungs. Respiratory exchange ratio measurements were obtained by the ParvoMedics Truemax 2400 metabolic cart (Consentius Technologics, Sandy, UT) and a two-way breathing mask (Hans Rudolph, Survivair, Comasec, Inc.) and expressed as VCO_2/VO_2.

Running Economy: Running economy was defined according to Martin and Craib (1992), as the submaximal oxygen consumption at a given speed as measured by the ParvoMedics Truemax 2400 metabolic cart (Consentius Technologics, Sandy, UT) and a two-way breathing mask (Hans Rudolph, Survivair, Comasec, Inc.) and expressed as milliliters of oxygen·kilogram body $weight^{-1} \cdot minute^{-1}$.

Static Stretching: Static stretching was defined according to Hedrick (2000) as a type of passive stretching held at the point of discomfort for an extended period of time (30 s).

Stretch Shortening Cycle: The stretch shortening cycle is defined as using an eccentric muscle contraction to augment the following concentric contraction (Gleim & McHugh, 1997).

Stride Rate: Stride length and stride rate were defined operationally according to Gleim et al. (1990), as the time for 15 right foot contacts. Steps per minute were determined by the following equation: 30/time(s) x 60. Step length was determined as the treadmill speed in $meters \cdot minute^{-1}$ divided by the step frequency. Stride length was determined as the step length multiplied by 2.

VO_{2Peak} : VO_2 peak was defined according to Baxter-Jones and Maffulli (2003), as the highest VO_2 during an exercise test to exhaustion in the absence of a plateau in VO_2 which would indicate the achievement of VO_{2max}.

Assumptions

1. The researcher assumed that participants did not participate in strenuous activity the 24 hr prior to testing.
2. The researcher assumed that each participant accurately reported the beginning of the menstrual cycle.

Limitations

1. The ParvoMedics Truemax 2400 metabolic cart (Consentius Technologics, Sandy, UT) accurately recorded oxygen consumption.
2. The value of this study is limited to trained female athletes aged 18 – 49 years.
3. The researcher was unable to control for the motivational level of the participants.
4. The accuracy of the results is only as valid as the compliance of the participants with the protocol and the ability of the researcher to measure and record all variables of the study.
5. The researcher was unable to control for human error when using a stop watch to record the time for 15 right foot contacts to determine stride length.

Significance of the Study

Although numerous research has evaluated the effects of preexercise stretching on performance in power and anaerobic activities (Avela et al., 1999; Evetovich et al., 2003; Fowles et al., 2000; Nelson et al., 2001), little research has been performed on the effects of preexercise stretching on running economy (Hayes & Walker, 2007; Allison et al., 2008; Zimmer et al., 2007).

Given that the previous research relating to preexercise stretching and performance overwhelming demonstrates a reduction in performance following certain types of stretching (Avela et al., 1999; Evetovich et al., 2003; Fowles et al., 2000; Nelson et al., 2001), the purpose of this study will be to determine if three different stretching interventions impact running economy. At high levels of fitness, running economy becomes a main determinant of successful performance as evidenced by improvements in time over a set distance (Conley & Krahenbuhl, 1980; Costill, Thomason, & Roberts, 1973; Daniels & Daniels, 1992; Morgan & Craib, 1992; Morgan, Martin, Baldini, & Krahenbuhl, 1990) thus factors that affect running economy, positively or negatively, should be identified to improve performance.

CHAPTER II

REVIEW OF LITERATURE

The purpose of this study was to determine the effects of three different stretching interventions on running economy. The literature regarding this topic was reviewed in the following section headings (a) running economy, (b) flexibility, (c) running economy and flexibility, (d) stretching, (e) preexercise stretching and performance, and (f) menstrual cycle and running economy.

Running Economy

The ability of an athlete to maximally consume oxygen (VO_{2max}) has been linked to success in distance running (Ariyoshi, Yamaji, & Shepard, 1979; Conley & Krahenbuhl, 1980; Costill et al., 1973; Daniels & Daniels, 1992; Heck et al., 1985; Morgan & Craib, 1992). Maximal oxygen consumption significantly correlates (r = -.66 to -.91) with distance running performance in a group of heterogeneous runners (Conley, Krahenbuhl, Burkett & Millar, 1981; Costill et al., 1973; Daniels & Daniels, 1992). Distance running performance is defined as the improvement in race time over a set distance (Conley et al., 1981). The strength of the correlation between VO_{2max} and performance decreases (r = -.12) in a group of homogeneous runners in terms of VO_{2max}; whereas, running economy and performance become highly correlated (r = .79 to .83; Conley & Krahenbuhl, 1980; Costill et al., 1973; Daniels & Daniels, 1992; Morgan & Craib, 1992; Morgan et al., 1990). Running economy is defined as the steady-state oxygen consumption ($VO_{2submax}$) at a given speed (Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Heise & Martin, 1998; Heise, Morgan, Hough, & Craib, 1996; Morgan et al., 1990; Morgan, Martin, & Krahenbuhl, 1989).

Running economy can be determined by measuring the steady-state VO_2 for a given speed and is measured in units of milliliters of oxygen per kilogram body weight per minute ($ml \cdot kg^{-1} \cdot min^{-1}$; Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992; Heise et al., 1996; Morgan et al., 1989). Metabolic rate is accurately measured during exercise via indirect calorimetry (Brooks, Fahey, & Baldwin, 2005). The accuracy of measurement is based on two assumptions. The first assumption is that the adenosine triphosphate (ATP) utilized during exercise at a steady-state comes only from cell respiration and not from phosphagen breakdown or the anaerobic breakdown of carbohydrates. The second assumption is that protein and amino acid energy contribution is minimal. Protein metabolism contributes to the energy requirement of severe exercise; prolonged, exhaustive exercise; and during glycogen depletion (Brooks et al., 2005). Running economy assessments usually last approximately 6 to 10 min and are run at a speeds below lactate threshold, indicating that anaerobic and protein catabolism contributions to the exercise bout should be minimal (Morgan et al., 1989).

Morgan, Martin, Krahenbuhl, & Baldini (1991) assessed daily variability in running economy in 17 male distance runners ($VO_{2max} = 58.8 \pm 4.4$ $ml \cdot kg^{-1} \cdot min^{-1}$). Participants performed two running economy sessions two days apart after a 30-60 min treadmill familiarization session. Each session involved a 10 min run at 3.33 $m \cdot s^{-1}$. The correlation between daily running economy measures was .95 and the average coefficient of variance (CV) was 1.32% indicating that a single session can be used to obtain stable running economy measures (Morgan et al., 1991).

In a similar study to Morgan et al. (1991), Williams, Krahenbuhl, and Morgan (1991) tested 10 male runners ($VO_{2max} = 61.41 \pm 3.56$ $ml \cdot kg^{-1} \cdot min^{-1}$) 5 days per week for 4 weeks to assess daily variability in running economy. Participants ran for 6 min each at speeds of 2.68, 3.13, and 3.58 m·s^{-1} which represented 50, 60 and 70% VO_{2max} with no rest between each run. Participants had 60 min of treadmill familiarization time prior to the running economy sessions. Mean CV for each speed were 3.08, 2.60 and 2.48%, respectively, and these values were not significantly different from each other. The researchers also examined the number of testing days needed to obtain an accurate running economy measure. The stability of running economy measures on consecutive and nonconsecutive days was compared. Despite an improvement in running economy variability with more days tested, the researchers suggested that two days of testing is as accurate as five days of testing as 90% of the variance in running economy was accounted for after two days of testing. This number increases to 98% after 5 days of testing; a small increase that the researchers indicate is minimal compared to the cost and time of three extra days of testing (Williams et al., 1991).

In a follow-up study to Morgan et al. (1991) and Williams et al. (1991), Morgan et al. (1994) tested four male and four female actively training and competing distance runners to determine the daily variability in running economy. The participants in the Morgan et al. (1991) and Williams et al. (1991) studies were asked to refrain from racing and reduce the intensity and length of their training runs. Running economy was assessed 5 days a week for 5 weeks via a 6 min run at varying speeds (males = 3.57, 4.02 and 4.47 m·s^{-1}; females = 3.13, 3.57, and 4.02 m·s^{-1}) after 60 min of treadmill familiarization. No significant differences (p = .59, .53) were reported for male or female runners in regards to day to day VO_2 measurements. The average daily coefficient of variance (CV) was reported to range from 1-2%. The researchers concluded that stable measurements of running economy can be assessed by averaging two consecutive or nonconsecutive measures and participants can maintain regular training and racing schedules (Morgan et al., 1994).

Conley and Krahenbuhl (1980) reported significant correlations (r = .79, .83 and .83) between 10-km race time and the oxygen cost of three standard running speeds (241, 268, and 296 $m \cdot min^{-1}$) for 6 min each. Conley and Krahenbuhl reported that 65.4% of the variance in performance for a 10-km race could be explained by variations in running economy. Housh, Thorland, Pohnson, Hughes, and Cisar (1988) also reported that running economy was a significant predictor of middle distance performance and was positively correlated (r = .54) with 3.22-km time. The more economical runner performs at a lower percentage of VO_{2max} leading to enhanced performance and better 10-km times compared to less economical runners (Conley & Krahenbuhl, 1980).

More economical runners perform at a lower percentage of VO_{2max} and lactate threshold (Conley & Krahenbuhl, 1980). Plasma lactate accumulation is a function of percent VO_{2max} (Conley & Krahenbuhl, 1980; Costill et al., 1973). Plasma lactate accumulation has been suggested to be closely related to the pace a runner can maintain for long races (Conley & Krahenbuhl, 1980; Nicholson & Sleivert, 2001). Costill et al. (1973) reported blood lactate concentrations for a group of fit (VO_{2max} = 78.6 $ml \cdot kg^{-1} \cdot min^{-1}$) and less fit runners ($VO_{2max}$ = 57.3 $ml \cdot kg^{-1} \cdot min^{-1}$). Both groups ran at a speed of 268 $m \cdot min^{-1}$. The fit group was running at 66% VO_{2max} with blood lactate levels of 1.2 $mM \cdot L^{-1}$; whereas, the less fit group was running at 91% VO_{2max} with blood lactate values of 8.8 $mM \cdot L^{-1}$ (Costill et al., 1973). Additionally, Farrell, Wilmore, Coyle, Billing, and Costill (1979) reported a significant ($r \geq .91$; $p < .05$) relationship between the onset of blood lactate accumulation and racing performance.

Accumulation of blood lactate indicates a higher glycolytic rate compared with the rate of pyruvate oxidation (Beneke, Hutler, & Leithauser, 2000). A greater glycolytic rate indicates a shift from oxidative to nonoxidative metabolism. Insufficient amounts of ATP are produced nonoxidatively which limits prolonged exercise as sufficient energy is not present to support the continuation of the activity (Beneke et al., 2000).

Significant variation exists in running economy for a group of runners with similar VO_{2max} values (Williams & Cavanagh, 1987). Heise and Martin (1998) reported that running economy can vary 20 to 30% among runners matched for age, gender and performance. Morgan et al. (1989) reported that intraindividual variation in running economy is 2 to 11%. Factors affecting running economy include core temperature, age, gender, training, air and wind resistance, stride length, external mass loading, and fatigue (Morgan et al., 1990). Fatigue and stride mechanics are included in the review as two important determinants of running economy.

Fatigue

Fatigue is defined as the reduction of force-generating capacity of the neuromuscular system (Nummela et al., 1996). VO_2 may increase during exercise as a result of an increase in muscle temperature, plasma catecholamine concentration, type II fiber recruitment, glycogen depletion, increased fatty acid metabolism, and muscle damage (Calbet, Chavarren, & Dorado, 2001). Morgan et al. (1990) reported no change in aerobic demand following a 30 min run at 89% VO_{2max} in 16 male distance runners ($VO_{2max} = 59.0 \pm 4.5$ ml·kg^{-1}·min^{-1}) . Heart rate and economy remained unchanged following a prolonged maximal run while the respiratory exchange ratio (RER) decreased, suggesting a greater reliance on fatty acids for fuel. The use of fat as a fuel was not sufficient enough to increase the aerobic demand of running. The researchers suggested that the fall in RER was due to incomplete muscle glycogen restitution or dietary intake as a diet log was not recorded for each participant. Muscle glycogen levels should not have been severely depleted given the short duration of the maximal run (30 min; Morgan et al., 1990).

Morgan et al. (1996) tested 10 runners to determine the effects of a 30 min high intensity run on 10-km race pace economy and gait mechanics. The researchers reported no significant difference in gait mechanics and running economy following a 30 min run at 90% VO_{2max}, which was in agreement with the findings of Morgan et al. (1990). Discrepancies in the literature may be due to differences in sample size, training and performance demands, treadmill accommodation time, and mode of exercise performed. The downhill run in the study performed by Wilcox et al. (1989) may have caused muscle damage leading to the recruitment of additional motor units; thus, resulting in changes in economy and gait mechanics. A high intensity run increases the recruitment of type II motor units as the runner fatigues. As a result, VO_2 will increase during subsequent high intensity runs. The 30 min run in the study by Morgan et al. (1996) may have not been intense enough to elicit the above response.

Cavanagh et al. (1985) reported greater oxygen demand for two elite male runners within the days following a competitive 10-km race. The runners exhibited better economy in the second economy test compared to the first economy test (55.6 $ml \cdot kg^{-1} \cdot min^{-1}$ vs 58.1 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively). The researchers suggested that the differences were due to the immediate postrace conditions of the athletes (Cavanagh et al., 1985).

Sproule (1998) studied 15 active male students to determine the effects of exercise duration and intensity on running economy. Participants were required to perform three treadmill runs of differing duration and intensity: 80% VO_{2max} for 40 min, 70% VO_{2max} for 60 min, and 80% VO_{2max} for 60 min. Running economy tests were performed before and after the treadmill runs for 10 min at a speed of 10 $km \cdot h^{-1}$. No significant difference was reported in VO_2 after the 80% run at 40 min, which supports Morgan et al. (1990) and contradicts Cavanagh et al. (1985), as a 10-km race is typically run at 80% VO_{2max} for approximately 40 min. Sproule

(1998) reported that significant differences existed in VO_2 following runs at 70% VO_{2max} and 80% VO_{2max} for 60 min suggesting that running economy declines with an increase in duration and intensity.

Collins et al. (2000) studied 12 highly trained distance runners to determine the effects of intense interval training on running pattern, recovery duration on running kinematics, and the relationship between changes in running economy and running kinematics. Participants were required to run 10 x 400-m repeats with either 60, 120, or 180 s recovery. Running economy tests were performed 10 min before and after the interval session. The researchers reported an increase in VO_2 of 4.6% and 1.8% at speeds of 3.33 $m \cdot s^{-1}$ and 4.47 $m \cdot s^{-1}$ following intense interval running at 100% VO_{2max} independent of recovery time. The researchers suggested that an increase in the utilization of fat accounted for 83% of the decline in running economy as evidenced by a decrease in RER. Fat oxidation increased from 33 to 70% at a speed of 3.33 $m \cdot s^{-1}$ and increased from 26 to 39% at a speed of 4.47 $m \cdot s^{-1}$. Stride length did not change as a result of the interval session but stride length did increase with an increase in speed (Collins et al., 2000).

In a similar study to Collins et al. (2000), Zavorsky et al. (1998) tested 12 highly trained runners to determine the effects of interval workouts on running economy. Participants were required to perform 10 x 400-m run repeats at 100% VO_{2max} with either 60, 120, and 180 s recovery. Running economy tests of 6 min in length were performed before and after the interval workout at speeds of 268 and 200 $m \cdot min^{-1}$. The researchers reported that the oxygen cost of running at 268 and 200 $m \cdot min^{-1}$ increased 2.6% and 5.0%, respectively, following an intense interval workout independent of recovery time which was in agreement with the results reported by Collins et al. (2000).

Nicol et al. (1991) tested eight runners to determine the effects of marathon running on running economy and kinematics. The researchers reported a significant decline in running economy during the latter part of the marathon run (Nicol et al., 1991). Additionally, Brueckner et al. (1991) reported an increase in oxygen demand of 5% at the end of a marathon; whereas, Thomas et al. (1999) reported a significant decrease in running economy from the beginning to the end of a 5-km race. Brueckner et al. (1991), Nicol et al. (1991), and Thomas et al. (1999) were in agreement with Sproule (1998), who stated that running economy declined with increasing duration and intensity.

Glace, McHugh, and Gleim (1998) studied eight male and eight female runners to determine the effects of a 2 hr run at 65 to 70% VO_{2max} on running economy and lower extremity strength. Glace et al. reported that the female runners were able to maintain running economy whereas the running economy of the male runners declined, which is in agreement with the findings of Brueckner et al. (1991), Nicol et al. (1991), and Sproule et al. (1998). Heart rate increased for both male and females during the run but VO_2 in the male runners increased 4.8%; whereas, the women runners experienced an insignificant increase in VO_2 of 2.2%. Glace et al. suggested that the reduction in running economy of male runners was due to the additional oxygen cost to support sweating, respiration, and an increase in core temperature. Despite similar fluid intake, the male runners experienced a 2% reduction in postexercise mass which was a significantly greater weight loss than the female runners suggesting that the male runners sweat more than the female runners. Women were reported to have a greater evaporative sweat rate compared to males; therefore, males have to increase in sweat production to regulate core temperature. The greater sweat rate of the male runners may explain the significant loss of body weight postexercise (Glace et al., 1998).

Differences were also reported in relation to leg strength (Glace et al., 1998). Knee extension and flexion strength decreased by 17.9 and 15.9%, respectively, for the male runners; whereas, the female runners experienced a statistically insignificant decrease in strength of 1.8 and 0.4%. Muscle fiber recruitment or biomechanics of running may have been altered in the male runners as a result of a decrease in quadriceps strength (Glace et al., 1998). Dick and Cavanagh (1987) suggested that altered biomechanics may result in the recruitment of less efficient fast twitch fibers thus reducing running economy.

Hausswirth, Bigard, and Guezennec (1997) reported a greater decrease in running economy following the last 45 min of a marathon run compared to the last 45 min of a triathlon marathon run of equal time, which agrees with Brueckner et al. (1991), Glace et al. (1998), and Nicol et al. (1991). Hausswirth et al. (1997) reported decreased stride length and greater knee extension at foot-strike during the marathon run possibly caused by the greater eccentric portion of the marathon run compared to swimming and cycling in the triathlon.

Wilcox et al. (1989) reported an increase in oxygen consumption of participants while running at speeds of 6 and 7 mph following a 3 mile downhill run (-10% grade) at 48% VO_{2max}. The purpose of the downhill run was to elicit delayed onset muscle soreness (DOMS). Running economy tests were administered before, 24, 48, and 72 hr postdownhill runs. All postdownhill run VO_2 values were elevated from the predownhill run values but were not significantly different from each other. The researchers concluded that DOMS significantly increased the oxygen cost of running at a given speed for up to 3 days after a downhill run (Wilcox et al., 1989).

Similarly, Chen, Nosaka, and Wu (2008) required 50 male participants to run downhill (-15%) for 30 min. Over the following six days, participants ran at a given percentage of VO_{2max} (40

– 70%) for 30 min. Running economy was assessed 2 and 4 days prior to the downhill run as well as 2, 5 and 7 days post downhill run. Running economy was determined by averaging the VO_2 for the final 60 s of a 5 min run at 85% VO_{2max}. The researchers reported a significant (p=.001) increase in VO_2 of 5% at Day 2 and 2% at Day 7 post downhill run.

Calbet et al. (2001) tested nine active male and six active female students to determine the effects of DOMS on running economy. Participants were required to participate in a duathlon competition consisting of 5-km run, 16-km bike and a 2-km run. A 6 week training protocol followed the initial duathlon to improve subsequent duathlon performance. Running economy was assessed 2 and 7 days following the second duathlon competition (Calbet et al., 2001).

Running economy was significantly impaired by 8%, 48 hr following a 1 hr duathlon but was almost normal after 7 days (Calbet et al., 2001). Running economy was most affected by the highest speeds run during the duathlon but only 1/5 of the impairment in running economy can be accounted for by an increase in fat oxidation. Calbet et al. reported a significant difference in RER values for 48 hr and 7 days following the duathlon. Respiratory exchange ratio (RER) was lower 48 hr after the duathlon compared to before the duathlon and RER was 0.04 units higher 7 days after the duathlon compared to 48 hr after the duathlon suggesting an increase in fat oxidation. Fat oxidation can only account for 18 to 19% of the additional oxygen consumption observed 48 hr after the duathlon. Muscle damage may have accounted for a greater percentage of the decline in running economy as all the participants experienced soreness after the duathlon, which is in accordance with the data presented by Wilcox et al. (1989) that DOMS results in a significant reduction in running economy (Calbet et al., 2001). Dick and Cavanagh (1987) and Westerlind, Byrnes, and Mazzeos (1992) also reported that downhill running of 30 to

40 min resulted in an increase oxygen demand of 6 to 15% compared to level running at the same intensity as a result of unhabituated eccentric contractions.

Impairment of running economy may be caused by an increase in ATP usage or a decreased efficiency in ATP production (Morgan et al., 1989). An increase in fat oxidation and muscle damage may decrease the efficiency of ATP production. Muscle glycogen is the main fuel used during intense exercise lasting 30 to 90 min but during moderate intensity exercise, metabolism shifts to fat oxidation. The VO_2/ATP molar ratio of fat oxidation is 14 to 15% higher than that of carbohydrate oxidation suggesting an increase in oxygen consumption for ATP resynthesis when glycogen stores are low (Morgan et al., 1989).

Warren et al. (1996) suggested that muscle efficiency declined in damaged muscles as a result of minor disruptions in contractile elements responsible for force transmission. Oxidative phosphorylation uncoupling may also impair muscular efficiency. Uncoupling could be the result of a disruption of the inner mitochondrial membrane or an increase in the intramitochondrial calcium concentration. A proton gradient across the inner mitochondrial membrane provides energy for ATP synthesis. A disruption in the membrane permeability to protons may cause protons to leak back into the mitochondrial matrix resulting in any energy to be released as heat. As a result, a reduction in the ATP/Oxygen ratio occurs creating a greater need for oxygen to maintain ATP synthesis (Warren et al., 1996).

Stride Mechanics

Stride mechanics are the most important mechanical factors affecting running economy (Heinert, Serfass, & Stull, 1988) and have been reported to explain 54% of the variance in running economy (Williams & Cavanagh, 1987). An infinite number of combinations of stride length and stride frequency exist in steady-state running (Cavanagh & Williams, 1982). Stride length and stride frequency determination is a subconscious self-selection by the athlete as coaches typically do not recommend experimenting with the natural stride of an athlete (Cavanagh & Williams, 1982).

The relationship between running economy and stride length represents a U-shaped curve (Martin & Morgan, 1992). Muscular force and power generating capabilities may affect running economy when stride length is altered. Muscle efficiency varies with shortening velocity suggesting that an optimal velocity for muscle shortening exists. Alterations in stride length affect the rate of muscle lengthening and shortening as well as the rate of force development, all of which should have an impact on aerobic demand. Low stride rates have been associated with high external mechanical power; whereas, high stride rates have the highest level of external mechanical power. An optimal stride rate has been associated with optimal external mechanical power. External mechanical power was determined from changes in the center of mass as computed from kinetic and potential energy changes. Lower or higher stride rates are associated with greater dependence on the less economical fast twitch muscle fibers (Martin & Morgan, 1992).

Cavanagh and Williams (1982) reported that well-trained runners most likely run with a combination of stride length and stride frequency that is close to optimal for the runner. The researchers suggested that runners may adjust stride length and stride frequency to almost optimal conditions via perceived exertion. Over the course of training runs, the runner is able to identify physiological differences, whether conscious or subconscious, at varying stride lengths and stride frequencies and is able to adjust to an almost optimal stride combination to reduce perceived exertion. The researchers also suggested that through training, runners may have adapted to a particular stride combination that suits the running style of the runner. An optimal stride combination may be influenced by a prolonged training period at a suboptimal stride combination. Cavanagh and Williams (1982) concluded that stride length is not a critical determinant of running economy in well-trained runners, and that an optimal stride length exists at every running speed to minimize oxygen consumption.

Nelson and Gregor (1976) reported that during 4 years of college running, the stride length and stride frequency combination of a group of distance runners shortened by 7 cm, suggesting that the stride length and stride frequency combination at a given speed changes over time. The shorter stride length may alter muscular response as a result of changes to the force produced by the muscles and the rate at which the force is produced which can change the efficiency of muscular activity (Nelson & Gregor, 1976).

Brisswalter et al. (1996) studied 28 elite male middle-distance runners to determine the relationship between step length, running economy and anthropometric measures at speeds of 15 $km \cdot h^{-1}$ and 9 $km \cdot h^{-1}$. The researchers reported that running at speeds ranging from 40 to 60% VO_{2max} were less economical and running at speeds ranging from 60% to 80% VO_{2max} represented a zone of optimal efficiency. The speed of 15 $km \cdot h^{-1}$ represented a normal training pace for the runners; therefore, daily adaptation to 15 $km \cdot h^{-1}$ allowed the runners to be more efficient at 15 $km \cdot h^{-1}$ opposed to 9 $km \cdot h^{-1}$, which represented a much slower speed. A significant relationship was reported between step length and running economy at 9 $km \cdot h^{-1}$, but not at 15 $km \cdot h^{-1}$ suggesting that when running near normal training speeds, stride length variation had no effect on running economy (Brisswalter et al., 1996). Williams, Cavanagh, and Ziff (1987) also reported that no significant relationship existed between step length and running economy when running at speeds close to normal training speeds.

Knuttgen (1961) reported that no significant change in oxygen consumption with a slightly shorter than optimal stride length; whereas, larger deviations of stride length at higher running speeds resulted in significant changes in oxygen consumption. Stride length, not stride frequency, was increased as running speed increased, resulting in a less than optimal stride length and an increase in oxygen consumption (Knuttgen, 1961).

Heinert et al. (1988) tested 16 male runners to determine the effects of a level and 4% grade treadmill run on the oxygen cost of running at 8% above and 8% below an optimal stride length. The researchers reported that the aerobic demand of running increased with a shorter or longer than normal stride length, which was consistent with the findings of Knuttgen (1961). Certain participants did not follow the above pattern. For example, during level running, 10 participants were most efficient at the chosen stride length, two participants were most efficient with a longer stride length and four participants were most efficient with a shorter stride length. A similar pattern occurred for graded running where 12 participants were most economical at the chosen stride length, three participants were most economical at a shorter stride length and one participant was most economical at a longer stride length. Heinert et al. (1988) concluded that well-trained runners chose the most economical stride, and oxygen consumption increased with a shorter or longer than normal stride length, although not all runners exhibited the above characteristic.

Cavanagh et al. (1985) collected data on two elite male distance runners competing in the 23rd Olympiad in Los Angeles to develop a biomechanical profile of elite distance runners. Results for optimal stride length were only reported for one athlete as the other athlete demonstrated inconsistent stride patterns on a previous testing day. The selected deviation from optimal stride length was 18 cm shorter and 18 cm longer than normal to assess effects on running economy. The researchers reported a significant increase in the oxygen cost of running for the athlete with a shorter than normal stride length, which is in agreement with Heinert et al. (1988), and Knuttgen (1961). No significant difference in oxygen consumption was reported when running with a longer than normal stride length, which is in contrast to the results reported by Heinert et al. (1988), and Knuttgen (1961). Cavanagh et al. (1985) concluded that the athlete should not attempt to have a shorter stride than the freely chosen stride length whereas a longer than normal stride length may not have detrimental effects on running economy.

Cavanagh and Williams (1982) stated that the effect of a shorter or longer than optimal stride length on oxygen consumption varied considerably between participants. Cavanagh and Williams tested 10 trained, male runners to determine the effect of stride length on oxygen consumption during distance running. The researchers reported a small deviation ($0.2\ ml{\cdot}kg^{-1}{\cdot}min^{-1}$) in oxygen consumption when comparing the chosen stride length of the participant and a predicted optimal value suggesting that the freely chosen stride length is close to a predicted optimal stride length. The predicted optimal stride length was expressed as a multiple of leg length (SL[%LL]). Stride length was determined by multiplying the velocity of the treadmill by the average time between each foot contact. Leg length was determined by measuring the length from the greater trochanter of the femur to the floor while the participants stood at ease barefoot. Cavanagh and Williams (1982) reported a significant (r = -.69; r = .42) relationship between SL(%LL) and the increment in VO_2 above optimal stride length for the shorter stride and longer stride lengths, respectively, suggesting that suboptimal stride lengths have a negative effect on running economy as was also concluded by Cavanagh et al. (1985), Heinert et al. (1988), and Knuttgen (1961).

Power, Hopkins, and Ragsdale (1982), in a follow up study to Cavanagh and Williams (1982), tested 12 trained female runners to determine the oxygen cost of running at differing stride lengths. Power et al. (1982) hypothesized that due to a wider pelvis, females may be at a mechanical disadvantage as a greater pelvic shift over the weight bearing load is required in females. As a result, females made additional adjustments of the postural muscles, which could result in changes in stride length relative to leg length (Power et al., 1982).

Power et al. (1982) reported no significant difference in running economy when comparing suboptimal stride lengths (15% above and 15% below optimal). Significant differences were reported when comparing subnormal stride lengths to normal stride lengths. Nelson and Gregor (1976) determined that running efficiently involved placing the foot as closely as possible under the center of gravity. A longer stride length would cause the foot to be placed outside the center of gravity resulting in a breaking action (Nelson & Gregor, 1976). The rate of muscular contraction would increase with use of a short stride thus increasing oxygen consumption at any speed (Henry, 1951). Any deviation from a normal stride length might change neuromuscular recruitment patterns resulting in a possible change in the mechanical economy of running (Henry, 1951). Power et al. (1982) concluded that for female runners a self-chosen stride consumed less oxygen than stride lengths 15% above and 15% below a normal stride length, which corresponded with the results reported by Cavanagh and Williams (1982), Cavanagh et al. (1985), Heinert et al. (1998), and Knuttgen (1961).

General fatigue may alter running economy by altering the biomechanics of the runner (Hausswirth & Guezennec, 1997). Fatigue during running has been associated with a decrease in speed, shorter stride length, and a reduction in range of motion (ROM) at the joints of the lower extremities (Elliott & Ackland, 1981; Elliott & Roberts, 1980; Nummela et al., 1996). Joint movement patterns may be altered during fatiguing exercise due to an increase in muscle acidity and altered force generation due to a decrease in phosphagen stores (Collins et al., 2000).

Siler and Martin (1991) studied 19 male runners to compare changes in running pattern of faster and slower runners during a run to fatigue. Siler and Martin indicated that the consequences of fatigue (i.e., shorter stride and reduced ROM of the lower extremities) also occurred with a decrease in running speed suggesting that different changes may occur if speed were held constant. Faster runners may be more resistant to changes in running pattern as faster runners adopt a running pattern that minimizes fatigue which may not occur in slower runners. The researchers reported a significant increase in stride length as a result of the fatiguing run, which is in agreement with the findings of Cavanagh et al. (1985). Additionally, Nummela et al. (1996) reported a significant difference in stride length and rate during a fatigued 400 m run compared to baseline values (Nummela et al., 1996). No significant difference was reported for running pattern changes between faster and slower runners indicating that faster and slower runners may adapt to fatiguing runs in a similar manner (Siler & Martin, 1991).

Flexibility

Alter (1996) defined flexibility as the "extensibility of periarticular tissues to allow normal or physiological motion of a joint or limb" (p. 2). Flexibility measures are performed to determine the ability of skeletal muscle and tendon to lengthen (Gleim & McHugh, 1997; Magnusson, 1998; Magnusson et al., 1997; Wang, Whitney, Burdett, & Janosky, 1993). Various types of flexibility exercises exist including static, ballistic, and dynamic flexibility. Static flexibility refers to the ROM about a joint. Ballistic flexibility involves rhythmic motion, but is generally not performed due to increased injury risk associated with rapid, stretching motions. Dynamic or functional flexibility refers to the ease of movement within a given ROM. Dynamic flexibility measures stiffness or resistance to deformation of a joint (Gleim & McHugh; Magnusson; Magnusson et al; Wang et al., 1993).

Flexibility is determined by joint structure and by muscle, tendon, ligament, and joint capsule laxity (Krivickas & Feinberg, 1996; Murphy, Connolly, & Beynnon, 2003). Specific contractile components such as tropomyosin and titin, collagen fibers and elastic elements of the musculo-tendon unit are limiting factors to flexibility (Alter, 1996). Tropomyosin progressively crystallizes as the sacromere lengthens, to a point where further elongation will result in a rupture thus keeping the sarcomere within working length. Titin is recruited during elongation to support elongation of the sarcomere. Continued elongation will also cause a rupture of titin. Tropomyosin and titin function to prevent overextension of the sacromere and keep the sacromere within optimal working lengths (Alter).

Collagen is a strong, inextensible piece of connective tissue which composes tendons and ligaments (Alter, 1996). Collagen does exhibit some ability to elongate. Muscle fibers begin to straighten in response to elongation, which is followed by a gradual slip of one fiber relative to another. Further elongation is prevented as the intermolecular bonds strengthen and increase the resistance to continued lengthening (Alter).

Elastic tissue is located in large amounts around the sarcolemma (Alter, 1996). Elastin is a biochemical characteristic of elastic fibers composed of nonpolar hydrophobic amino acids. Elastic tissue can stretch up to 150% of resting length before rupture, and will return to original length after elongation. Elastin is arranged in cross links with wide spaces in between which allows elastin to lengthen until the cross links begin to restrict movement. Collagen and elastic fibers function together to provide strength and varying degrees of extensibility (Alter).

Various tests exist to assess flexibility (Gleim & McHugh, 1997). The most commonly performed flexibility assessment is the sit-and-reach test. The sit-and-reach test gives a general measure of flexibility for the lower back and hamstrings but may be limited by anthropometric measures (Gleim & McHugh).

The flexibility and structure of a muscle has an impact on the stretch-shortening cycle (Alter, 1996). The stretch-shortening cycle (SSC) is defined as using an eccentric muscle contraction to augment the following concentric contraction (Gleim & McHugh, 1997). Stretching-shortening cycle movements are affected by the elasticity of tendons and muscles (Wilson, Murphy, & Pryor, 1994). The amount of elastic energy stored in the muscles and tendons during an eccentric contraction is a function of the stiffness and compliance of the muscles and tendons. Mechanical energy may be stored in the series elastic component (SEC) during the eccentric contraction of active muscles to be reused in the following concentric contraction (Asmussen & Bonde-Peterson, 1974). The SEC consists of elastic components in line with the contractile components (Alter). The SEC is composed of the tendon and Z-line of a muscle. Actin filaments pull on the Z-line when the muscle is under tension accentuating the fold angle in the Z-line. The increase in the fold angle causes the Z-line to thicken thus creating elasticity of the muscle (Alter).

The SEC must be tightened to transfer the energy generated during the eccentric contraction of an activity to the concentric contraction of the activity (Gleim & McHugh, 1997; Wilson, Wood, & Elliot, 1991). The SSC augments the concentric phase of movement resulting in increased efficiency of movement compared to movements performed without prior stretch.

The concentric phase is augmented by the utilization of elastic strain energy stored in the SEC during the eccentric contraction but may also involve reflex induced neural input. Optimal SEC stiffness depends on the activity performed as a bench press requires a compliant SEC whereas a stiffer SEC may be preferred during sprinting activities (Wilson et al., 1991).

The SEC of a compliant muscle has greater slack when relaxed than does the SEC of a tighter muscle (Wilson et al., 1994). The compliant muscle must have greater sarcomere shortening to generate the same tautness of the SEC in the tighter muscle. As a result, force transmission to the joint of the complaint muscle is delayed resulting in a less forceful concentric contraction (Gleim & McHugh, 1997; Wilson et al., 1994). A tighter MTU produces greater force due to improved length and velocity of contractions, and increases in the initial transmission of force to the muscle; thus, increasing the initial rate of force development (Wilson et al., 1994).

Running has been identified as an activity during which elastic energy is stored and then used throughout the running stride (Asmussen & Bonde-Peterson, 1974). At a stride rate of 180 strides/min, each stride lasts 333 ms at 10 $km \cdot h^{-1}$. Ground contact accounts for 80% or 260 ms of each stride, half of which is involved in eccentric contractions. A single twitch contraction of the calf muscle reaches peak in approximately 74 ms with the active state lasting twice as long. The time difference for peak twitch contraction and active state of the calf muscle indicated that the period of eccentric contraction, which stores elastic energy is short enough for the active motor units to carry the elastic energy into the concentric contraction phase without increasing the use of metabolic energy (Asmussen & Bonde-Peterson, 1974).

Running Economy and Flexibility

Flexibilty has been identified as an important factor affecting running economy (Godges, et al., 1989). Gleim et al., (1990) examined the relationship between flexibility, walking, and running economy. The participants included 38 females and 63 males aged 20-62 years. Flexibility was measured using 11 gross clinical measures. Steady-state VO_2 was measured during an incremental treadmill test to determine running economy (Gleim et al., 1990).

Gleim et al. (1990) reported that less flexible runners were more economical during walking and running. Flexibility was the only measure that had a relationship with oxygen consumption when age and strength were taken into account. The researchers reported an inverse relationship (r = -.433) between flexibility and running economy. Elastic recoil of the SEC, as described previously, generated 25-40% of the energy needed for further movement indicating that the more flexible participants used 10% more energy than the tighter participants to perform the same activity (Gleim et al., 1990).

Participants with greater trunk and lower limb tightness had lower VO_2 values by 8-12% compared to participants with the greatest amount of trunk and lower limb flexibility at every speed (107.3, 134.3, 160.9 and 187.7 $m \cdot min^{-1}$) assessed during the treadmill test (Gleim et al., 1990). Tightness of the trunk and lower limb resulted in a decrease in rotary movement with an increase in speed. Movement in the transverse plane decreased the efficiency of running as rotary movement did not assist in the forward motion of running. Trunk and lower limb tightness reduced the need for additional muscular activity to control the rotary movement which decreased the energy requirement of running thereby augmenting running economy (Gleim et al., 1990).

Craib et al. (1996) indicated limitations in the study of Gleim et al. (1990). Appropriate treadmill accommodation was not provided in either study which may have resulted in the improvement of running economy reported. Gait patterns change as participants become familiar with the use of a treadmill. $VO_{2submax}$ measures may have decreased at a given speed with accommodation as fewer muscles are recruited to support the activity. Gleim et al. (1990) did not specify the experience of the participants (i.e. novice vs. experienced runners) as novice runners may be unfamiliar with the gait patterns of running. As stated above, increasing gait familiarity has the potential to improve economy at a given speed. The use of both male and female participants by Gleim et al. (1990) created additional problems in the interpretation of the results as females are generally more flexible and less economical than males (Craib et al., 1996).

Craib et al. (1996) studied 19 competitive male distance runners to determine the relationship between trunk and lower limb flexibility, and running economy. The flexibility assessment included nine different measures of trunk and lower limb flexibility. Running economy was determined by measuring $VO_{2submax}$ during a 10 min run (Craib et al., 1996).

Craib et al. (1996) reported significant relationships (r = .65 and .53) between ankle dorsiflexion and standing external hip rotation, and $VO_{2submax}$ suggesting that greater tightness in ankle dorsiflexion and standing external hip rotation resulted in better running economy. In contrast, Beaudoin and Whately-Blum (2005) did not report any significant correlations between running economy and ankle dorsiflexion or standing external hip rotation in female distance runners. An improvement in running economy as a result of dorsiflexion tightness may be caused by an increase in elastic energy storage. Elastic energy was returned to the calf muscles via the Achilles tendon thus reducing the need for additional muscle activation during the push-off phase of running. Standing external hip rotation tightness enhanced pelvic stability upon footstrike, reducing the need for additional muscular activation. Enhanced pelvic stabilization reduced oxygen consumption at a given speed thereby improving running economy (Craib et al., 1996).

Kyrolainen, Belli, & Komi (2001) stated that greater stiffness around the knee and ankle joints in the braking phase of running causes further force potentiation in the push-off phase of running with less energy expenditure and greater running economy. Preactivation of limb musculature in anticipation of landing may increase landing stiffness which further augments SSC. Preactivation may increase the sensitivity of the muscle spindle through enhanced alpha-gamma-coactivation potentiating stretch reflexes which musculotendon stiffness and running economy (Kyrolainen et al., 2001).

Jones (2002) studied 34 international male distance runners to determine the relationship between lower limb flexibility and running economy. A sit and reach test was used as an overall measure of hamstring, hip and lower back flexibility. Running economy was measured using a VO_{2max} treadmill test (Jones, 2002).

Jones (2002) supported the conclusions of Craib et al. (1996) and Gleim et al. (1990) but were in contrast to the findings of Beaudion and Whately-Blum (2005). Jones (2002) reported a significant relationship (r = -.68) between $VO_{2submax}$ at 16 km/hr and the sit and reach scores indicating that lower sit and reach scores were inversely correlated with better running economy. No significant relationships existed between running economy, and age, height, weight, or VO_{2max} (Jones, 2002). Likewise, Trehearn and Buresh (2009) reported a significant relationship (r = .826) between sit and reach scores and running economy in eight collegiate male and female distance runners. The significant relationship reported by Jones (2002) and

Trehearn and Buresh (2009) between running economy and flexibility could be explained by enhanced elastic return and pelvic stability as described previously.

Nelson et al. (2001), in a follow up study to Craib et al. (1996) and Gleim et al. (1990) examined the relationship between chronic stretching and running economy. Nelson et al. (2001) studied 16 male and 16 female college aged students to determine the effects of a 10-week stretching program on running economy. $VO_{2submax}$ was measured during a 10 min run to determine running economy. Participants were randomly assigned to a stretching and a nonstretching group. The stretching group was required to perform 3 sets of 15 stretches for lower body, 3 days a week. Each stretch was held for 15 s (Nelson et al., 2001).

Nelson et al. (2001) reported that the stretching group had a 9% increase in sit and reach scores whereas the control group did not report any changes in sit and reach scores. No significant differences were reported for the stretching and nonstretching groups in regards to average $VO_{2submax}$ at a given running speed. Nelson et al. concluded that stretching may not inhibit running performance which is in contrast to the conclusions of Craib et al. (1996), Gleim et al. (1990), and Jones (2002).

Magnusson (1998) reported that an increase in ROM resulting from chronic stretching may be due to an increase in stretch tolerance rather than an alteration in the visoelastic properties of the muscle. Craib et al. (1996) and Gleim et al. (1990) reported a decrease in flexibility due to a change in the stiffness of the musculoskeletal unit resulted in an increase in running economy. Magnuson (1998) challenged Craib et al. (1996) and Gleim et al. (1990) and supported Nelson et al. (2001) by stating that the visoelastic properties of the muscle did not change with stretching; therefore, running economy should not change as a result of stretching as reported by Nelson et al. (2001).

Stretching

Stretching prior to exercise is a common component of a traditional warm-up routine (Rubini, Costa, & Gomes, 2007). Common beliefs are that stretching prior to activity will increase performance and reduce the risk of injury by improving flexibility (Herda, Cramer, Ryan, McHugh, & Stout, 2008). Stretching has been reported to positively increase ROM by possible lengthening of the connective tissue within the muscle (Bandy & Irion, 1994; Bandy, Irion, & Briggler, 1997; De Pino, Webright, & Arnold, 2000; Gajdoski, 1991; Henricson et al. 1984; Hubley, Kozey, & Stanish, 1984; Madding, Wong, Hallum, & Medeiros, 1987; Roberts & Wilson, 1999). ACSM (2010) recommends performing stretching and/or flexibility exercises to increase ROM at least 2 – 3 days per week. Each stretch should be brought to the point of mild discomfort but not pain and held for 15 – 30 s for two to four repetitions (ACSM, 2010). However, Bandy and Irion (1994) reported greater gains in ROM when stretching for 30 (+ 12.50°) and 60 s (+ 10.86°) compared to 15 s (+3.78°) and suggested that the optimal stretching duration is 30 s. Roberts and Wilson (1999) reported that ROM gains were greater when holding a stretch for 15 s opposed to 5 s. Additionally, Bandy et al. (1997) reported that one 30 s stretch per day was just as effective in increasing flexibility compared to longer duration stretches and more repetitions. In contrast, Ioannis, Christos, Nikolaos, Aikaterini, and Efstratios (2005) reported that one 60 s stretch was just as effective in improving ROM as two 30 s, four 15 s, and twelve 5 s stretches indicating that the total duration of stretching is more important for improving ROM than the number of repetitions. However, De Pino et al. (2000) reported that following four 30 s static stretches, the increases in ROM were only maintained for up to 3 min post-stretch as viscoelastic parts of the muscle were not deformed enough following stretching to produce a permanent change. Indeed, Kubo, Kanehisa, Kawakami, and Fukunaga (2001) reported that static stretching decreases the viscosity of the tendon and increases its elasticity resulting in a decrease in passive resistance and improved ROM following stretching. However, Magnusson, Aagaard, and Nielson (2000) reported that while three stretches of 45 s each increased ROM and resulted in a viscoelastic stress relaxation, resistance to stretch was unchanged by the stretching indicating the stretching had no effect on the viscoelastic properties of the human skeletal muscle. Additionally, Muir, Chesworth, and Vandervoort (1999) reported that stretching of the calf muscle did not reduce the passive resistance of the connective tissue within the muscle and surrounding ankle joint.

Preexercise Stretching and Performance

Recent researchers (Avela et al., 1999; Behm et al., 2001; Cornwell et al., 2002; Evetovich et al., 2003; Fowles et al., 2000; Godges et al., 1989; Hayes & Walker, 2007; Kokkonen et al., 1998; Nelson et al., 2001; Nelson et al., 2005; Nelson et al., 2001; Nelson & Kokkonen, 2001; Nelson et al., 2005; Nelson et al., 2001; Siatras et al., 2003) have examined the role of stretching prior to concentric activities as well as stretch-shortening cycle (SSC) activities. Despite commonly held beliefs, stretching prior to concentric and SSC activity has been consistently reported to reduce performance.

PreRun Stretching

Godges et al. (1989) performed one of the initial studies positively relating walking and running economy to pre-exercise stretching. Godges et al. examined the effect of static stretching and soft tissue mobilization with proprioceptive neuromuscular facilitation (STM/PNF) in improving hip range of motion (ROM) and the effect of the stretching techniques on gait economy as measured by submaximal oxygen consumption on a given speed on seven college age males. The researchers reported that 10 min of end range static stretching reduced

VO_2 by 4-7% at 40, 60 and 80% VO_{2max}. The greatest gains in economy were at 80% VO_{2max} which also represented the greatest gains in hip ROM. Godges et al. hypothesized that the improvements in running economy were due to an improvement in hip range of motion. The participants may have had a more economical gait after static stretching because the stretching was performed in the same plane as the muscles used in walking and running. Godges et al. proposed that stretching the shortened connective tissue of the hip may have allowed for an improved contraction of the antagonists, creating a balance of the agonist/antagonist hip muscles and pelvic symmetry resulting in a more economical movement pattern. Additionally, Godges et al., in an unpublished study, reported an improvement in 10 km race time following 10 sessions of STM, joint mobilization, static stretching, PNF diagonal patterns and gait training cues suggesting that intense therapy sessions may aid in improving running economy (Godges et al.).

In contrast to Godges et al. (1989), Hayes and Walker (2007) reported that there were no differences in running economy across three different stretching interventions which included static stretching (SS), progressive static stretching (PSS), and controlled velocity dynamic stretching (CVDS). However, the SS group reported the highest steady state VO_2 values (50.3 ± 5.7 $ml \cdot kg^{-1} \cdot min^{-1}$) and the PSS group reported the lowest values (49.1 ± 6.3 $ml \cdot kg^{-1} \cdot min^{-1}$). ROM was increased from the prestretching condition to the poststretching condition for each intervention but was not significantly different between the conditions. Jones (2002) reported a negative correlation ($r = -.68$) between the sit and reach test and running economy suggesting that less flexible runners have better running economy due to a stiffer MTU. Additionally, Gajdosik and Riggin (2005) reported that distance runners had enhanced passive properties compared to untrained individuals which may be the result of adaptations in MTU connective tissue and titin due to eccentric loading and stretching.

As suggested by Jones (2002), the flexibility and structure of a muscle has an impact on the stretch-shortening cycle (Alter, 1996). The stretch-shortening cycle (SSC) is defined as using an eccentric muscle contraction to augment the following concentric contraction (Gleim & McHugh, 1997). Stretch-shortening cycle movements are affected by the elasticity of tendons and muscles (Wilson, Murphy, & Pryor, 1994). The amount of elastic energy stored in the muscles and tendons during an eccentric contraction is a function of the stiffness and compliance of the muscles and tendons. Mechanical energy may be stored in the series elastic component (SEC) during the eccentric contraction of active muscles to be reused in the following concentric contraction (Asmussen & Bonde-Peterson, 1974). The SEC consists of elastic components in line with the contractile components (Alter, 1996) and is composed of the tendon and Z-line of a muscle. Actin filaments pull on the Z-line when the muscle is under tension, accentuating the fold angle in the Z-line. The increase in the fold angle causes the Z-line to thicken thus creating elasticity of the muscle (Alter, 1996).

The SEC must be tightened to transfer the energy generated during the eccentric contraction of an activity to the concentric contraction of the activity (Gleim & McHugh, 1997; Wilson, Wood, & Elliot, 1991). The SSC augments the concentric phase of movement resulting in increased efficiency of movement compared to activities performed without prior stretch. The concentric phase is improved by the utilization of elastic strain energy stored in the SEC during the eccentric contraction but may also involve reflex induced neural input. Optimal SEC stiffness depends on the activity performed as a bench press requires a compliant SEC; whereas, a stiffer SEC may be preferred during sprinting activities. The SEC of a compliant muscle has greater slack when relaxed than does the SEC of a tighter muscle (Wilson et al., 1994). The compliant muscle must have greater sarcomere shortening to generate the same tautness of the SEC in the tighter muscle. As a result, force transmission to the joint of the complaint muscle is delayed resulting in a less forceful concentric contraction (Gleim & McHugh, 1997; Wilson et al., 1994). A stiffer MTU produces greater force due to improved length and velocity of contractions, and increases in the initial transmission of force to the muscle; thus, increasing the initial rate of force development (Wilson et al., 1994).

Hayes and Walker (2007) reported that the stretching interventions did result in an increase in ROM but did not affect running economy. The researchers suggested that running economy was not affected by pre-stretching despite a change in ROM as running economy was not measured until the last 2 min of the 10 min run which may have reversed the stretching affects. Indeed, Rosenbaum and Hennig (1995) reported that following static stretching, a 10 min run reversed the reduction in active peak force and rate of force development but retained the improved stretch-absorbing capacity. De Pino et al. (2000) and Spernoga, Uhl, Arnold, and Gansneder (2001) reported that any increases in ROM following static stretching and PNF stretching , respectively, were diminished within 6 min suggesting that any affects of stretching on running economy in the study by Hayes and Walker (2007) may have worn off by the time running economy measures were recorded. Magnusson, Aagaard, Larsson, and Kjaer (2000) reported a decrease in energy absorption of the MTU immediately following three different lower limb stretches held for 90 s each. However, after 10 min of running at 70% VO_{2max} and 30 min of running at 75% VO_{2max}, energy absorption was not different from prestretch levels suggesting that running after stretching may counteract the negative affects of preexercise stretching (Magnusson et al., 2000). Hayes and Walker (2007) concluded that preexercise stretching does not affect running economy possibly because running economy was assessed following submaximal running.

Allison, Bailey, and Folland (2008) examined the effects of prolonged static stretching on running economy in 10 male runners (VO_{2max} = 60.1 ± 7.3 ml·kg^{-1}·min^{-1}). Running economy was assessed during a 10 min run at 70% VO_{2max}. Another 10 min at 70% VO_{2max} served as a warm-up prior to the stretching intervention. VO_2 values were averaged over minutes 3-10. The stretching intervention included eight stretches for the lower limbs that were held for 40s and repeated three times on each side. The control session involved sitting quietly for 38 min to match the length of the static stretching protocol. ROM, strength, and power were assessed on a separate day from the running economy session but following the same stretching interventions. Stride mechanics were also assessed for each protocol. No significant differences were reported between the control and static stretching protocols for VO_2 or stride parameters which is in agreement with Hayes and Walker (2007) but in contrast to Godges et al. (1989). However, ROM as measured via sit and reach was significantly increased post static stretching (+ 2.7 ± 1.6 cm). The running economy CV was reported to be 1.7% which is within the range of variances reported by Morgan et al. (1991), Williams et al. (1991) and Morgan et al. (1994). Additionally, isometric strength (-5.6 ± 3.4%) and countermovement jump height (-5.5 ± 3.4%) were significantly decreased following static stretching. Increased ROM decreases MTU stiffness (Kubo et al., 2001; McNair & Stanley, 1996) which may also affect neuromuscular function as assessed by the strength and power tests (Behm et al., 2001; Cramer et al., 2005; Fowles et al., 2000; Marek et al., 2005). Reductions in isometric strength may be due to reductions in muscle activation and the reductions in jumping power may have occurred as a result of reduced MTU stiffness which is evident by the increases in ROM (Allison et al., 2008). Despite these changes, running economy was not affected possibly due to the submaximal nature of the activity (Allison et al., 2008), results of which are supported by Hayes and Walker (2007).

Zimmer, Burandt, and Kent (2007) examined the affects of static and dynamic stretching on running economy in 12 male runners. Running economy was assessed over a 7 min run at 6.2, 7.5 and 8.7 mph. The dynamic stretching protocol included 6 movements for the lower limbs that were performed over 50 yd and repeated twice. The static stretching protocol utilized 6 stretches for the lower limbs that were held for 30 s each and repeated two times. No difference for running economy was reported between the protocols possibly due to the submaximal nature of the running economy tests and greater reliance on Type I slow twitch fibers. The researchers speculated that if more Type I fibers were recruited during the running economy sessions, the muscles would have more time to react to the changes in the MTU caused by stretching (Zimmer et al., 2007).

Typically, stretching is an on-going activity and not just performed prior to a specific event; therefore, Nelson et al. (2001) examined the effects of a 10 week stretching program on running economy in 32 college-age males and females. The stretching group actively performed 3 sets of 15 stretches which were held for 15 s each for the lower body, 3 days a week for 10 weeks. Additionally, 12 of the 15 stretches were also performed passively. The control group refrained from any stretching activities during the study. Running economy was assessed during a 10 min run at 70% VO_{2max}. The participants in the stretching group were reported to have had a 9% increase in sit-and-reach scores; whereas, the control group did not report any changes in sit-and-reach scores. Similar to Hayes and Walker (2007), Nelson et al. reported no changes in running economy after 10 weeks of stretching despite an increase in flexibility. Magnusson (1998) reported that an increase in ROM resulting from chronic stretching may be due to an increase in stretch tolerance rather than a change in the stiffness of the MTU as no changes in stiffness, energy and passive torque were reported after long-term stretching. As a result, Nelson et al. (2001) concluded that running economy should not change as a result of increased ROM due to prolonged stretching, conflicting with the results reported by Godges et al. (1989).

The effects of preexercise stretching have also been reported for sprinting activities (Fletcher & Jones, 2004; Kokkonen, Nelson, Eldredge, & Winchester, 2007; Nelson et al., 2005; Siatras et al., 2003) Siatras et al. (2003) reported that mean speed during vaulting was significantly ($p < .001$) reduced after the static stretching warm-up compared to the general warm-up of jogging, jumping and sprinting, and dynamic stretching. Likewise, Nelson et al. (2005) reported that the times for a 20 m sprint out of starting blocks following the three stretching interventions were significantly slower compared to the no stretch condition (No stretch = 3.17 $\pm$ 0.04 s; Both legs stretched = 3.21 $\pm$ 0.04 s; Forward leg in starting position stretched = 3.21 $\pm$ 0.04; Rear leg in starting position stretched = 3.22 $\pm$ 0.04 s). In agreement with Nelson et al. (2005) and Siatras et al. (2003), Fletcher and Jones (2004) reported that passive and active static stretching increased 20 m sprint time, while 20 m sprint time was reduced following an active dynamic warm-up contradicting the findings of Siatras et al. (2003) possibly due to differences in the dynamic stretching protocols. Winchester, Nelson, Landin, Young, and Schexnayder (2008) also reported a slower (-3%) total 40 m sprint time which seemed to occur during the second 20 m after static stretching that followed a dynamic warm-up suggesting that static stretching reversed the positive benefits of a dynamic warm-up. Similarly, Fletcher and Anness (2007) reported an increase in 50 m sprint time following a static passive + active dynamic stretch protocol and a reduction in sprint time following active dynamic stretching and static dynamic + static dynamic stretching. In contrast, Kokkenon et al.

(2007) reported a 1.3% improvement in 20 m sprint time following chronic static stretching possibly due to gains in muscle strength. Fletcher and Anness (2007), Fletcher and Jones (2004), Nelson et al. (2005) and Siatras et al. (2003) suggested that the changes in sprinting speed were due to alterations in MTU stiffness. Siatras et al. (2003) speculated that dynamic stretching did not affect running speed due to the myotatic reflex which causes a tonic contraction in the muscles due to stretching. The myotatic reflex is related to stretching velocity suggesting that the ballistic type stretching such as dynamic stretching, may enhance the action potential of the myotatic reflex and increase MTU stiffness (Siatras et al., 2003). However, Fletcher and Jones (2004) speculated that dynamic stretching resulted in a faster sprint time as core temperature was elevated above the other forms of stretching. Fletcher and Anness (2007), and Fletcher and Jones (2004) also suggested that the dynamic stretching allowed for a rehearsal of the movement pattern to be used in sprinting resulting in greater and earlier excitement of the muscle thus producing more power and a faster sprint time. Additionally, Nelson et al. (2005) suggested that stretching may disrupt stretch reflex activity which is defined when the eccentric phase of the SSC initiates a stretch reflex that increases the muscle activation during the concentric period. This disruption may decrease performance after stretching due to disruption of the response of the post synaptic nerve to stimulation across the synapse . Autogenic inhibition of the muscle being stretched and its synergists via the Golgi tendon organs may also inhibit muscle activity following stretching (Nelson et al., 2005). The researchers (Fletcher & Jones, 2004; Siatras et al., 2003; Nelson et al., 2005) concluded that preexercise static stretching is detrimental to sprinting performance and should be performed with caution prior to sprinting activities.

PreWeight Lifting Stretching

Stretching prior to submaximal and maximal weight lifting has also been examined (Kokkonen et al., 1998; Nelson & Kokkonen, 2001; Nelson et al., 2005). Nelson et al. (2005) examined the effects of acute stretching of the hip, thigh, and calf muscle on knee flexion muscle strength endurance on 11 women and 11 men of college age. The researchers reported that following the stretching protocol (ST) for the workload corresponding to 60% of the body weight of the participant, the participants had a 24.4% decrease in the number of lifts completed compared to the non-stretching protocol (NS; 10.9 $\pm$ 4.2 vs 14.4 $\pm$ 4.0 lifts). The results were similar for the 40% trial following the ST protocol as the participants exhibited a 9.8% decrease in the number of lifts completed (ST = 29.3 $\pm$ 12.5 lifts; NS = 31.6 $\pm$ 12.1 lifts). Nelson et al. suggested that the reduction in the number of lifts is most likely due to a neurological impairment due to a reduction in excitatory inputs. The additional recruitment of new motor units occurs to overcome the reduction in excitatory input thus placing some of the motor units into a fatigue-like state prior to the lifting task which would decrease the motor unit pool available for activation; thus, accelerating the onset of fatigue and decreasing performance (Nelson et al., 2005).

Similiarly, Kokkonen et al. (1998) and Nelson and Kokkenon (2001) investigated the effects of static stretching and ballistic stretching, respectively, of the hip, thigh and calf on 1RM knee extension and flexion performance. Both researchers reported a decrease in knee flexion (Kokkonen et al. = 7.3%; Nelson & Kokkenon = 7.5%) and knee extension strength (Kokkonen et al. = 8.1%; Nelson & Kokkenon = 5.6%) results of which are similar to Nelson et al. (2005). Both researchers suggested a reduction in MTU stiffness and/or autogenic inhibition as possible mechanisms for the reduction in 1RM performance following static and ballistic stretching. As with Siatras et al. (2003) and Nelson, Driscoll et al. (2005), Nelson, Kokkonen et al. (2005), Kokkonen et al. (1998), and Nelson and Kokkenon (2001) concluded that static or ballistic stretching prior to submaximal or maximal lifting can be detrimental to performance.

Contrary to the acute detrimental effects of static stretching on submaximal and maximal lifting performance, Kokkonen et al. (2007) reported that static stretching for 10 weeks, 40 min, 3 days per week resulted in a 15.3 and 32.4% increase in knee flexion and extension 1 RM, respectively. Additionally, the protocol also resulted in a 30.4 and 28.5% increase in knee flexion and extension endurance, respectively. The researchers speculated that chronic stretching may have resulted in strength gains via an increase in muscle length which lead to increases in contractile velocities and the generation of force at a given shortening velocity. Kokkonen et al. also speculate that contractions of the non-stretching leg for stabilization may have lead to increases in strength over the 10 week training period. The effects of static stretching may be detrimental to short-term performance but may lead to improvements in performance when performed over a period of weeks.

Stretching and Maximal Voluntary Contraction (MVC)

Preexercise stretching has been reported to decrease MVC and torque for the quadriceps, biceps brachii and plantar flexor muscles (Avela et al., 1999; Behm et al., 2001; Evetovich et al,, 2003; Fowles et al., 2000; Nelson et al., 2001; Nelson, Guillory et al., 2001). Decreases in MVC and peak torque ranged from approximately 12 – 25% (Avela et al., 1999; Behm et al., 2001; Evetovich et al., 2003; Fowles et al., 2000; Nelson, Allen et al., 2001; Nelson, Guillory et al., 2001). Nelson, Guillory et al. (2001) reported that maximal voluntary isokinetic knee extension torque was reduced 7.2 and 4.5% at 1.05 and 1.57 rad·s^{-1}, respectively, following the stretching protocol suggesting that prestretching is detrimental at slower velocities for maximal concentric contractions. Additionally, Nelson, Allen et al. (2001) suggested that maximal voluntary isokinetic knee extension torque was also dependent on the angle measured as torque was reduced 7% at 162°; whereas, angles ranging from 90 - 144° were reported to have no significant difference for maximal voluntary isokinetic knee extension torque. The researchers hypothesized that stretching the muscle tendon caused the sacromeres to be in a non-optimal position for the most efficient contraction and the decrease in performance would be most evident at near full extension (Nelson, Allen et al., 2001). The latter two studies suggest that the effect of stretching on MVC is both velocity and angle dependent (Nelson, Allen et al., 2001; Nelson, Guillory et al., 2001). Marek et al. (2005) reported similar results to Nelson, Allen et al. (2001) and Nelson, Guillory et al. (2001) in that static and PNF stretching resulted in a decrease in peak torque and mean power output. In contrast to Marek et al. (2005), Nelson, Allen et al. (2001) and Nelson, Guillory et al. (2001), Egan, Cramer, Massey, and Marek (2006) measured peak torque and mean power output at 60 and $300°\cdot s^{-1}$ following a stretching intervention of 4 sets of 30 s each for static stretching of the leg extensors. Egan et al. (2006) reported no changes in peak torque or mean power output following static stretching possibly due to differences in training status of the participants. Contrary to the results reported by Marek et al. (2005), Nelson, Allen et al. (2001), Nelson, Guillory et al. (2001) and Egan et al. (2006), Handel, Hortsmann, Dickhuth, and Gülch (1997) reported increases in torque (up to 21.6%) following 8 weeks contract-relax stretching training possibly due to the different stretching techniques utilized as contract-relax involves an isometric contraction phase which may serve to increase muscle strength. Additionally, Worrell, Smith, and Winegardner (1994) reported increases (up to 13.5%) in eccentric peak torque following static and PNF stretching of the hamstring muscles. The researchers speculated the increases were the result of increased compliance of the SEC thus resulting in greater energy storage during the eccentric phase of contraction (Worrell et al., 1994).

The suggested mechanisms for the reduction in MVC and peak torque are inconsistent. Behm et al. (2001) suggested that quadriceps MVC was reduced 12.2% due to a reduction in muscle activation as evidence by the decreases of 2.8 and 20.2%, respectively, in interpolated twitch technique (ITT) and EMG activity. Interpolated twitch technique measures the degree of muscle activation. Additionaly, the researchers suggested that the decline in MVC was not due to a more compliant MTU as tetanic force did not change as a result of stretching. The increased compliance of the MTU may have been overcome by the summated contractions of 300 ms high frequency tetanic stimulation resulting in efficient transfer of force from the muscle to the bone. Additionally, increased duration and force of the MVC should also be enough to overcome increased MTU compliance (Behm et al., 2001). In contrast, Evetovich et al. (2003) suggested that the decrease in biceps brachii torque at slower and faster velocities (Non-stretching: $30°·s^{-1}$ = 50.4 $\pm$ 4.1 N·m; $270°·s^{-1}$ = 23.4 $\pm$ 2.5 N·m; Stretching: $30°·s^{-1}$ = 49.5 $\pm$ 4.1 N·m; $270°·s^{-1}$ = 20.9 $\pm$ 2.5 N·m) reported for the stretching group, which is in contrast with Nelson, Guillory et al. (2001), was due to a more compliant MTU as mechanomyography (MMG) amplitude was greater for the STR group ($30°·s^{-1}$ = 93.5 $\pm$ 14.4 mV; $270°·s^{-1}$ = 207.6 $\pm$ 35.6 mV) compared to the NSTR group ($30°·s^{-1}$ = 63.1 $\pm$ 10.6 mV; $270°·s^{-1}$ = 136.4 $\pm$ 31.7 mV) for both velocities as the NSTR group had a 34.3 and 32.5% decline in MMG amplitude for $30°·s^{-1}$ and $270°·s^{-1}$, respectively. Mechanomyography amplitude is suspected to increase in the presence of a more compliant muscle as the muscle would be less stiff, have more muscle fiber oscillations and produce greater MMG amplitude. Additionally, EMG activity was not significantly different between the groups at either velocity suggesting that muscle activation was not decreased following a stretching protocol (Evetovich et al., 2003).

In agreement with Evetovich et al. (2003) and Behm et al. (2001), Fowles et al. (2000) suggested that a 25% loss in maximal voluntary force was possibly due to motor unit activation (MUA) which was decreased 16 and 13% at 0 and 15 min post stretch. The force loss may also be due to reduced muscle force-generating capacity as EMG activity was decreased by 15.1% following the stretching protocol. MUA was restored with 15 min of recovery but MVC was still 8-12% below pre-stretching values suggesting that muscle force generating capacity was still impaired. The researchers calculated that 60% of the 25% reduction in MVC was due to neural impairment and 40% originated in the muscle. Approximately 1% of the 10% reduction in MVC at min 30 was due to neural impairment suggesting that force loss due to muscle impairment following stretching takes time to regain prestretch values (Fowles et al., 2000).

Possible explanations for the force deficit include the Golgi tendon reflex, and mechanoreceptor and nociceptor pain feedback but were discounted as mechanisms as the results did not support the idea (Fowles et al., 2000). The Golgi tendon reflex results in autogenic inhibition when the Golgi tendon organs detect high force with muscle lengthening causing a reduction in agonist activation to decrease force production and prevent injury to the muscle. The mechanoreceptor and nociceptor theory would require the sensation of pain or discomfort during the poststretch MVC which was not present for any of the participants. Additionally, fatigue due to stretching was also not a factor as no EMG activity was evident during the passive stretching. The reduction in force-generating capacity may be due to lengthening of the muscle fascicles creating a less than optimal position on the length-tension curve when returned to the same absolute testing angle (Fowles et al., 2000).

Avela et al., (1999) provided a more complete explanation of the mechanism of decreased MUA and muscle-force generating capacity as a result of prestretching. The researchers measured MVC of the triceps surae muscles, maximal mass compound action potential (M wave) and the Hoffman reflex (H-reflex) which are a measure of α motor neuron activation. Blood was drawn immediately after the stretching protocol to be analyzed for markers of muscle damage including serum creatine kinase (CK). Lactate was also measured 5 min post dynamic stretching. Maximal voluntary plantar flexion torque decreased 23.2 ± 19.7% following the stretching protocol. Neural input to the gastrocnemius and soleus, as measured via EMG activity, was reduced 19.9 ± 29.4 and 16.5 ± 24.4%, respectively. All measures were recovered within 15 min of completing the stretching protocol. Maximal H-reflex decreased 46.1 ± 38.3% following the stretching protocol but was not associated with a decrease in maximal M wave suggesting that there was no failure in muscle fiber excitation or slowing in the impulse conduction in the muscle fibers. The maximal H-reflex/M-wave ratio decreased 43.8 ± 41.4% indicating impaired excitation of the α-motorneuron pool from the group Ia afferent nerve fibers due to increased muscle compliance. Serum CK and lactate exhibited small nonsignificant increases poststretching indicating that the reduction force was not due to metabolic fatigue or muscle damage. Additionally, motor unit firing rates were indirectly estimated from the 50% MVC. Electromyography data was used to measure the number of times that the amplitude crossed the zero value of the signal (ZCR). The zero value of the signal decreased 12.2 ± 11.4% immediately post stretching suggesting a reduction in motor unit firing rate at ZCR. However, EMG activity was unchanged indicating that synchronization of motor unit firing was not the cause for ZCR reduction. The researchers also reported that passive stretch-resisting force was reduced 16% following the stretching protocol suggesting that the muscle became more compliant. As a result of increased compliance, the external force response of the muscle and the stretch response of the muscle spindle are reduced, the latter resulting in a decrease in the intrafusal force. As a result, inflow of autogenic excitatory impulses to the α-motorneurons via the Ia afferents were decreased. Additionally, the compliance of the intrafusal fibers may also increase, causing a decrease in intrafusal force despite γ-motorneuron activation which ultimately decreases MUA (Avela et al., 1999).

Cramer et al. (2005) performed a follow up study to the studies of Avela et al. (1999), Behm et al. (2001), Evetovich et al. (2003), Fowles et al. (2000), Kokkonen et al. (1998), and Nelson, Guillory et al. (2001). Cramer et al. (2005) examined the effects of static stretching on peak torque, mean power output, and EMG and MMG amplitude. Peak torque at 60 and $240°\cdot s^{-1}$ was decreased 3.3% following the protocol set by Nelson, Guillory et al. (2001; 4 sets of stretches for the leg extensors that were held for 30 s each) in both the stretched and non-stretched leg which is in agreement with previous researchers (Avela et al., 1999; Behm et al., 2001; Cramer et al., 2007; Evetovich et al., 2003; Fowles et al., 2000; Kokkonen et al., 1998; McNeal & Sands, 2001; Nelson, Guillory et al., 2001; Young & Elliot, 2001) who also reported a decrease in peak torque following static stretching. However, the current results are not in agreement with Nelson, Guillory et al. (2001) in that peak force was also reduced at faster velocities not only at slower velocities indicating that decreases in peak torque following stretching may not be velocity specific. Similar to Avela et al. (1999), Behm et al. (2001), Cramer et al. (2007) and Fowles et al. (2000), but in contrast to Evetovich et al. (2003), Cramer et al. (2005) reported a reduction in EMG amplitude at each velocity in both legs following a stretching protocol which is similar to results of Marek et al (2005). The differences in EMG activity reported for Cramer et al. (2005; 2007) and Evetovich et al. (2003) may be due to the different muscle groups tested (quadriceps versus biceps). The reduction of peak torque in both legs supports the theory of Avela et al. (1999) that decreases in maximal force production following stretching may be the result of changes in MUA and/or firing rate. Mean power output was not decreased in the current study, contradicting the conclusions of Marek et al. (2005) for MVC. Cramer et al. (2005) suggested that mean power output was not reduced because while static stretching reduced peak torque, the reduction was not enough to change the impulse of the torque versus ROM relationship thus allowing for a greater force production at other joint angles to compensate for the decrease in peak torque. Likewise, Cramer et al. (2005; 2007) reported that MMG activity was also not different following stretching contradicting Evetovich et al. (2003) and Marek et al. (2005) possibly due to the different muscles used in each study. The researchers concluded that pre-activity static stretching results in a decrease in force production and muscle activation (Cramer et al., 2005; 2007).

Criticisms of the research of Fowles et al. (2000) include that the stretch duration (30 min) is not common practice prior to exercise or sporting events; therefore, Ryan et al. (2008) examined the effects of more commonly used stretching durations (2, 4, and 8 min) on muscle strength of the plantarflexors. Each stretch was held for 30 s followed by 20 s rest which was repeated for the specified time period. The researchers reported that muscle strength was not compromised for any stretching duration up to 8 min. Comparing studies (Fowles et al., 2000; Herda et al., 2008; Weir, Tingley, & Elder, 2005) using different durations of stretching, Ryan et al. (2008) hypothesized that a threshold for stretching induced decreases in muscle strength may fall between 8 and 10 min of stretching as the decrease in muscle strength is most apparent at 30 min (28%; Fowles et al., 2000) but the effect is not as greater with shorter stretching periods (20 min – 10%; Herda et al., 2008 and 10 min – 7%; Weir et al., 2005) and completely disappears with durations less than 8 min (Ryan et al., 2008). Likewise, Young et al. (2006) also reported an additive effect of stretch duration on drop jump height as 4 min of stretching resulted in significantly worse drop jump height compared to 1 min of stretching.

Weir et al. (2005) suggested that the reduction in MVC of the plantarflexors was the result of changes in the mechanical properties of the muscle and not muscle activation. This is based on the findings that passive resistance of the plantarflexors was decreased following stretching and MVC was reduced initially but returned to control levels with additional stretching. Passive torque was reduced by 27% the end range of the movement following stretching as increased muscle length may increase muscle slack thus reducing cross-bridge interaction and MVC. With additional stretching, MVC returned to control levels and no decrease was reported in maximal activation suggesting mechanical changes for the reduction in MVC. Compound action potentials (M_{max}) were reduced following stretching but participants were not fatigued as twitch torque was normal after stretching suggesting a reduction in muscle activation was not the cause of the reduction in MVC. Additionally, motorneuron excitability was also not a limitation to MVC as participants were able to achieve maximal activation according to interpolated twitch data further supporting the theory that alterations in the mechanical properties of the muscle caused the reduction in strength which is in contrast to the hypotheses of Avela et al. (1999) but in agreement with Fowles et al. (2000).

Herda et al. (2008) compared the effects of static and dynamic stretching on peak torque, EMG, and MMG for the biceps femoris muscle. The static stretching protocol included three stretches that were held for 4 sets of 30 s each. The dynamic stretching protocol involved three stretches that were performed (12-15 repetitions) for 4 sets of 30 s each. The researchers reported a reduction in peak torque following static stretching supporting the results of previous researchers (Avela et al., 1999; Behm et al., 2001; Cramer et al., 2005, 2007; Evetovich et al., 2003; Fowles et al., 2000; Marek et al., 2005; Nelson, Allen et al., 2001; Nelson, Guillory et al., 2001). However, dynamic stretching did not result in any changes in peak torque. Additionally EMG amplitude was unchanged after static stretching but increased following dynamic stretching and MMG was increased after both protocols which is in agreement with Evetovich et al. (2003). Additional researchers (Behm et al., 2001; Cramer et al., 2005; Marek et al., 2005) have reported decreases in EMG activity following static stretching; whereas, MMG amplitude remained unchanged. The differences were possibly due to the different muscle utilized (quadriceps femoris vs biceps femoris). Herda et al. (2008) explained that the increase in EMG activity following both protocols indicated that either protocol does not decrease muscle activation but that both protocols increase muscle compliance as evidenced by increases in MMG amplitude as a result of post-activation potentiation or increased muscle temperature. The researchers concluded that dynamic stretching does not decrease muscle strength but strength is decreased following static stretching (Herda et al., 2008). In support of the use of dynamic stretching as part of a warm-up routine, Herman and Smith (2008) reported an 11% increase in peak quadriceps torque and improvements in other performance variables following 4 weeks of dynamic stretching warm-up. The performance variables were either not affected or adversely affected by the static stretching warm-up protocol indicating that the addition of dynamic stretching to a warm-up routine is advantageous to performance (Herman & Smith, 2008). Little and Williams (2006), McMillian, Moore, Hatler, and Taylor (2006), and Yamaguchi and Ishii (2005) similarly reported that performance variables exhibited the greatest improvements following a warm-up including dynamic stretching compared to static or no stretching, further supporting the theory that dynamic stretching improves performance compared to static stretching.

Stretching and Other Performance Variables

Behm, Bambury, Cahill, and Power (2004) hypothesized that changes in MTU characteristics following stretching could alter the ability of the MTU to detect and respond to changes in the immediate environment as characteristics of the MTU include characteristics of the muscle, tendon, and other connective tissue. Balance and proprioception are maintained and detected via intrafusal muscle fibers and Golgi tendon organs; therefore, any change in the MTU may be translated to changes in the intrafusal fibers and Golgi tendon organs thus affecting balance and proprioception. Additionally, changes in MTU stiffness along with altered muscular activation may affect reaction time and movement time. Changes in balance, proprioception, reaction time and movement time may affect performance in which these variables are important to success (Behm et al., 2004).

Behm et al. (2004) reported that balance, reaction time and movement time were significantly improved for a control group on posttest measures but treatment group did not demonstrate the same improvements following 3 sets of three different stretches that were held for 45 s. Stretching was performed during a 20 min rest between pre and posttest measurements of balance, reaction time, movement time, and force. The researchers speculated alterations in MTU stiffness may have caused the lack of improvement in balance, reaction time and movement time in the treatment group. The afferent input to the CNS and the subsequent mechanical output of the muscle are important for detecting changes in balance. A more compliant MTU may increase the electromechanical delay by slowing the transmission of forces from myofilament crossbridge interaction to the tension created by the MTU on the skeletal system. As a result, the detection and monitoring of increased tension by the Golgi tendon organs may also be delayed. Additionally, a more compliant MTU may alter the perception of the intrafusal stretch receptors thus changing the afferent responses to changes in muscle length, rate of length change, and tension; therefore, input to the CNS and the adjustment reactions by the muscle may be altered via stretch-induced increases in MTU compliance, a theory that is supported by the findings of Avela et al. (1999).

Alpkaya and Koceja (2007) examined the effects of acute stretching on reaction time and force utilizing a typical warm-up used in athletic settings as other researchers (Avela et al., 1999; Behm et al., 2001; Fowles et al., 2000) have stretched participants from 20 to 60 min. The warm-up included 5 min of cycling at 70 RPM following by either no stretching or a stretching protocol which required participants to perform 3 sets of stretches for the plantar flexors (Alpkaya & Koceja, 2007). Each stretch was held for 15 s with 15 s rest between each stretch. Reaction time and force were tested using a force platform immediately following the protocol. The researchers reported a 2% increase in reaction time and a 3.5% decrease in force following stretching but the changes were not statistically significant possibly due to the short duration of stretching (Alpkaya & Koceja, 2007).

Menstrual Cycle and Running Economy

Of the many factors influencing running economy, the menstrual cycle has often been ignored (Williams & Krahenbuhl, 1997). The menstrual cycle consists of the follicular (day 1 to day 14) and luteal phases (day 15 to day 28; Guyton & Hall, 2006). Progesterone levels in the luteal phase can increase 10 times above progesterone levels reported for the follicular phase (Guyton & Hall, 2006). Progesterone is associated with hyperventilation and a decrease in alveolar carbon dioxide tension during the luteal phase (Bonekat, Dombovy, & Staats, 1987;

Dombovy, Bonekat, Williams, & Staats, 1987; Janse de Jorge, 2003). Women also experience a hypercapnic ventilatory response during the luteal phase because progesterone may reduce the threshold and increase the excitability of the medullary respiratory center. Progesterone also exhibits a thermogenic effect, raising body temperature 0.3 – 0.5°C which also increases ventilation. An increase in ventilation is associated with an increase in oxygen consumption; therefore, oxygen consumption during steady state exercise in the luteal phase of the menstrual cycle should increase as a result of an increase in ventilation (Bonekat et al., 1987; Dumbovy et al., 1987; Janse de Jorge).

Williams and Krahenbuhl (1997) tested 10 moderately trained (VO_{2max} = 50.7 ± 2.8 ml·kg^{-1}·min^{-1}) female runners to determine the effects of menstrual cycle phase on running economy at 55 and 80% VO_{2max}. Running economy and hormone concentrations were recorded every three days beginning on the 7th day of the follicular phase. The researchers reported an increase in resting VO_2 from the early follicular to the midluteal phase (VO_2 = 3.9 vs. 4.8 ml·kg^{-1}·min^{-1}). Ventilation was also increased significantly from the early follicular to midluteal phase (VE = 10.3 vs. 12.4 L·min^{-1}).The authors speculated that the increase in ventilation was the result of the action of progesterone on the chemoreceptors (Williams & Krahenbuhl, 1997). In contrast, Smekal et al. (2007) reported that VO_2 and ventilation were not different at rest between the luteal and follicular phases in 19 eumenorrheic, aerobically trained females.

Williams and Krahenbuhl (1997) reported that no significant difference existed for running economy at 55% VO_{2max} as this speed was close to the transitional speed between walking and running. VO_2 increased when the running speed was uncomfortably slow and would have been more conducive as a walking speed; therefore, running at 55% VO_{2max} may have masked any differences in running economy (Williams & Krahenbuhl, 1997). Jurkowski, Jones, Toews, and Sutton (1981) and Stephenson, Kolka, and Wilkerson (1982) also reported that no significant differences existed between the luteal and follicular phases of the menstrual cycle while cycling at intensities less than 70% VO_{2max}. Similary, Smekal et al (2007) reported no differences for VO_2 on the cycle ergometer for power outputs between 50% VO_{2max} and VO_{2max}. Additionally, time to complete a 2000-m rowing time trial was not different between the phases of the menstrual cycle (Forsyth & Reilly, 2008). Significant differences in VO_2 and VE were reported for treadmill speed corresponding to 80% VO_{2max} during the midluteal phase (Williams & Krahenbuhl, 1997). DeSouza, Maguire, Rubin, and Maresh (1990) reported no significant differences in running economy between the luteal and follicular phase at running speeds greater than 80% VO_{2max}. DeSouza et al. tested participants once during each phase of the menstrual cycle suggesting that variations in levels of progesterone were not accounted for as progesterone levels fluctuate throughout the menstrual cycle; whereas, Williams and Krahenbuhl (1997) tested participants three times during each phase; thus, accounting for variations in progesterone levels.

Blood lactate measurement is another variable that may be affected by the menstrual cycle. Forsyth and Reilly (2005) examined the effects of time of day and menstrual cycle on lactate threshold in 11 endurance trained females (VO_{2peak} = 41.3 ± 6.1 $ml \cdot kg^{-1} \cdot min^{-1}$). Participants were tested during the midluteal phase (6-10 days after luteinizing hormone surge) and the midfollicular phase (6-10 days after menses). Resting blood lactate concentrations were significantly higher in the midfollicular phase (1.67 ± 0.60 vs 1.46 ±0.54 $mmol \cdot L^{-1}$). Additionally, blood lactate concentration was significantly lower in the midluteal phase at a fixed exercise intensity (3.17 ± 1.32 vs. 3.67 ± 1.85 $mmol \cdot L^{-1}$). The intensity, heart rate and VO_2 at which a blood lactate concentration of 4 $mmol \cdot L^{-1}$ occurred was significantly higher in the midluteal phase compared to the midfollicular phase. Possible explanations for the differences in blood lactate concentration include that the increased release of estrogen during the luteal phase (Guyton & Hall, 2006) may have a glycogen sparing effect (Zderic, Coggan, & Ruby, 2001) thus causing a decrease in lactate production (Forsyth & Reilly, 2005; Zderic et al., 2001). Estrogen has been shown to alter glucose and lipid metabolism which may have an effect on lactate production in the muscle (Zderic et al., 2001). Zderic et al. reported that the rate of glucose appearance (-14%) and disappearance (-15%), carbohydrate oxidation (-13%), and plasma lactate concentrations were lower while total fat oxidation (+23%) was higher in the luteal phase compared to the follicular phase when exercising at 90% of the lactate threshold but not at 70% of lactate threshold. The decreased carbohydrate oxidation was significantly related to the increased estrogen levels in the luteal phase. However, Smekal et al. (2007) did not report any significant differences in blood lactate concentration between the menstrual cycle phases for varying exercise intensities (50% VO_{2max} up to VO_{2max}) possibly due to methodological differences including testing protocols, equipment used, control of menstrual cycle phases, menstrual history and nutritional status compared to previous research.

Summary

Many factors affect running economy including fatigue, stride mechanisms, menstrual cycle phase, and flexibility. A commonly held belief is that increased flexibility improves performance. Improvements in flexibility are measured as increases in ROM which can be achieved through stretching exercises. Acute stretching prior to activity has been reported to be detrimental to sprinting activities, 1 RM, muscle strength endurance, and MVC. However, positive effects of stretching on performance have also been reported for both acute and chronic stretching. The most common explanation for a decrease in performance following stretching is a reduction in MTU stiffness and MUA. A reduction in MTU stiffness may affect running economy as a stiffer MTU has been reported to be more beneficial in terms of running economy by enhancing the ability of the MTU to store energy in the eccentric phase of the contraction to be used in the concentric phase of contraction, thus reducing the recruitment of additional muscles during the concentric phase which reduces VO_2. Additionally, performing a dynamic warm-up enhances performance when compared with static stretching or no stretching. Given that static stretching has been mostly reported to decrease performance due to decreases in MTU stiffness, a possibility exists that static stretching prior to running may affect running economy and a dynamic warm-up may be more beneficial to running performance.

CHAPTER III

METHODOLOGY

The current study was designed to determine the effects of three different stretching techniques on running economy. The effects of three stretching interventions on running economy were determined using highly trained female runners during the follicular phase of the menstrual cycle. Oxygen consumption was compared to determine the effects of the stretching interventions on running economy. A pilot study was completed to assess feasibility of all protocols and to determine participant number.

Participants

Participants (n = 12) included highly trained ($VO_{2peak} \geq 50$ ml·kg^{-1}·min^{-1}) female runners aged 18 – 49 years. A flyer (Appendix A) was emailed to local running clubs and posted on running club websites to recruit participants. Upon acceptance into the study, participants signed an informed consent form (Appendix B), and completed a medical history form (Appendix C). Participants were excluded from the study if they indicated on the medical history form that they were amenorrheic (less than three menstrual cycles per year) or had abnormal menstruation patterns (intermittent, irregular menstrual cycles), were pregnant, or had any other health concerns that may raise the risk level of the participant from low to moderate or high. All methods and procedures for this study were submitted to and approved by the Institutional Review Board at Texas Woman's University (Appendix D).

Determination of Peak Oxygen Consumption

Peak oxygen consumption ($ml \cdot kg^{-1} \cdot min^{-1}$) was determined prior to the running economy sessions. Prior to testing, participants were prepped for a 12 lead ECG which was also used to record heart rate via a Quinton Q4500 12 lead ECG (Quinton Instruments, Bothell, WA). The Modified McConnell (McConnell, 1988) progressive continuous treadmill test was used to assess VO_{2peak}. Participants were instructed to continue running as long as possible during the test. Participants began the test by walking at 4 mph, 0% grade for 1 min. Beginning at the 2[nd] min, the speed of the treadmill was increased by 1 mph at 0% grade every 2 min until 9 mph, where the grade was increased by 2% every 2 min until volitional exhaustion. The criteria to determine VO_{2peak} was volitional fatigue of the participant. VO_{2peak} was determined as an average of the final minute of the test. Respiratory gases were analyzed by a ParvoMedics Truemax 2400 metabolic cart (Consentius Technologics, Sandy, UT) in 30 s intervals, a system that was determined reliable and valid by Bassett et al. (2001).

Running Economy Session

Each participant completed four running economy sessions which were separated by at least 12 hr but not performed on the same day. Each session was randomly assigned. Participants ran each session at .5 mph less than the speed corresponding to 80% VO_{2peak}. Each session consisted of a 10-min run at a self-selected speed, the prestretching flexibility assessments, the stretching trial, the poststretching flexibility assessments, and the final 10-min run. Participants were instructed not to stretch prior to the warm-up run. Upon completion of the specified stretching protocol, participants were immediately prepped to analyze respiratory gases and ran for 10-min at 80% VO_{2peak}. Gases were sampled every minute beginning at Minute

3. Heart rate was continuously monitored via a Polar Vantage Heart Rate Monitor (Polar Electro OY, Kempele, Finland) and recorded each minute. Rate of perceived exertion was recorded every minute using the Modified Borg 0-10 scale (Borg, 1982). Respiratory gases were analyzed by the ParvoMedics Truemax 2400 metabolic cart. All sessions occurred during the follicular phase of the menstrual cycle as researchers (Williams & Krahenbuhl, 1997) suggested there may be an increase in oxygen consumption which negatively affects running economy due to increased progesterone during the luteal phase. The follicular phase was defined as the 7 – 10 days following the beginning of menstruation.

Stride Length

Stride length and stride rate was measured according to Gleim et al. (1990), as the time for 15 right foot contacts which was measured at Minutes 2, 5, and 9 of the 10 min running economy sessions. The three time points were averaged and used in the following equation. Steps per minute were determined by the following equation: 30/time(s) x 60. Step length was determined as the treadmill speed in meters$\cdot$minute^{-1} divided by the step frequency. Stride length was determined as the step length multiplied by 2.

Lactate

Blood lactate was measured within 1-2 min upon completion of the VO_{2peak} test and within 30 s following each running economy session. The finger was clean with an alcohol pad and blood was drawn using the finger prick technique via Unilets lancets (Ulster Scientific, Highland, NY). The first drop of blood was wiped clean with a gauze pad. The second drop of blood was analyzed using the Lactate Plus analyzer (Nova Biomedical, Waltham, MA).

Range of Motion

Range of motion was recorded using the sit-and-reach test as described in the ACSM guidelines (2010) immediately before and after each stretching protocol. Participants removed their shoes and placed their feet against the sit and reach box. Participants were instructed to places their hands on top of each other, take a deep breath, exhale, lower their head, and push the marker as far as they could without bending the knees. The best of three trials was recorded.

Ankle dorsiflexion was measured according to Palmer and Epler (1998). Participants were required to lie prone on the table with knees bent at 90°. The axis of the goniometer was placed 2.54 cm distal to the lateral malleolus. The stationary arm of the goniometer was placed parallel to the lateral malleolus toward the fibular head while the moving arm was placed parallel to the lateral midline of the calcaneus. The ankle was brought into a neutral position of 90°. Participants were instructed to dorsiflex the ankle as far as possible with the help of the technician (Palmer & Epler, 1998). The best of three measures was recorded.

Stretching Intervention

Participants were allowed a practice session for each stretching protocol prior to the beginning of testing but on a separate day from the running economy sessions. The protocols consisted of different exercises targeting the major muscle groups of the lower body used during running. All exercises were performed twice. Participants were instructed to stretch to the point of discomfort but not pain.

Control (CON): Upon completion of the 10 min run, participants were instructed to sit in a chair for 10 min.

Static Stretching (SS): Each stretch was held for 2 sets of 30 s with the other leg being stretched between repetitions.

Active Isolated Stretching (AIS): Active isolated stretching required each stretch to be held for 2 s and repeated for 30 s. Participants completed 2 sets of 30 s on each leg. A stretching strap was required for certain stretches to be specified below.

Dynamic Flexibility (DF): Dynamic flexibility involves performing dynamic movements to bring the limb through its full range of motion. Each dynamic movement was performed for 2 sets of 30 s.

Stretching Protocol

Static Stretching

The following stretches were adapted from Hayes and Walker (2007).

Standing Unilateral Quadriceps Stretch: Participants stood upright with the knee flexed, heel toward the buttock, and pulled the heel toward the buttock while extending the hip.

Standing Unilateral Calf Stretch: Participants maximally dorsiflexed the ankle while pushing against a wall for balance. The sole of the foot remained in contact with the floor.

Lunge: Participants placed the posterior knee on a mat with the hip extended. The anterior knee was flexed at a 90° angle. Participants were instructed to put their hands on their hips or floor.

Unilateral Hamstring Stretch: Participants were seated with one leg extended to the front. The opposite leg is abducted with the knee flexed and the lower leg internally rotated to ensure that the foot is touching the medial thigh. Participants stretched by actively flexing their trunk.

Gluteal Stretch: Participants sat on the floor with one leg extended to the front. The other leg was adducted, knee flexed, and the sole of the foot placed on the floor across to the lateral side of the extended leg, with the heel drawn as far as possible toward the buttock. Pressure was applied by the participant to the flexed knee to cause inward rotation and increase the stretch.

Active Isolated Stretching

The following stretches were adapted from Mattes (1995)

Lying Quadriceps Stretch: Participants lay on one side with the knee and hip closest to the floor flexed. Participants grasped the sole of the foot closest to the floor with the hand on the same side. The outer knee and hip were also flexed and kept in-line with each other. Participants grasped the top of the foot and extended the hip.

Seated Calf Stretch: Participants utilized a stretching strap. Participants were seated on the ground with one leg extended out. The strap was wrapped around the bottom of the foot. Participants pulled the toe toward the shin with assistance from the strap.

Lunge: Participants placed the posterior knee on a mat in line with the hip. The anterior knee was flexed at a 90° angle. Participants put their hands on their hips or floor. From this position, participants moved forward as they extended the posterior hip but keeping a 90° angle for the anterior knee.

Lying Hamstring Stretch: Participants laid on their backs with both legs straight. The stretching strap was placed around the sole of the foot on one leg which was lifted off the ground with assistance from the strap and pulled toward the trunk until a stretch was felt in the hamstring without bending the knee.

Abductor Stretch: Participants laid on the floor with the strap wrapped around the outside of one foot while holding the rope in the opposite hand. The other hand was placed out to the side. Participants lifted their leg across the body as far as possible with assistance from the strap to achieve a stretch.

Dynamic Flexibility

The following stretches were adapted from Jeffreys (2008):

Heel-Toe Walk: Participants performed a heel to toe walk by placing the heel on the ground for initial footstrike and performing an exaggerated plantarflexion upon toe off.

Figure Four: Participants lifted one leg off the floor while grasping the outside of the leg above the ankle and below the knee. The leg was externally rotated and abducted during the movement. The leg was gently pulled into the chest.

Straight-Leg Kick: Participants skipped while gently "kicking" the leg out to the front attempting to touch the fingertips of the extended hand.

Walking Heel-Up: Participants raised the heel of one leg towards the buttock and grasped the top of the foot applying a gentle pull. The opposite ankle was plantarflexed and this exercise was performed in a walking motion.

Lunge: Participants performed a moving lunge while attempting to place the elbow to the instep of the foot of the same leg. The opposite hand was in contact with the ground for balance. The posterior knee was not in contact with the ground but was slightly bent with the hip extended. Once the stretch was completed, the back leg was brought to front and the stretch repeated on the opposite side.

High Knee Pull: Participants lifted one knee toward the chest while grasping below the knee and pulling up toward the chest.

High Knee Run: Participants performed an exaggerated run by bringing the knees as high in the front toward the chest as possible. Arms moved in a natural running motion.

Butt Kicks: Participants raised and lowered the heel in a running motion similar to trying to "kick one's own buttocks". Arms moved in a natural running motion.

Skipping March: Participants performed a skipping motion while raising the knee and foot of one leg and lifting the opposite arm.

Karaoke: Participants performed a sideways run while alternately placing one foot to the front then to the back. Arms were held out to the side. The exercise was performed for 30 s in one direction and 30 s in the opposite direction.

Statistical Analysis

Differences in VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$), lactate, and stride length for each condition (control, DF, SS, AIS) were analyzed via a repeated measures multivariate analysis of variance (RM MANOVA). Sit and reach, and ankle dorsiflexion data were analyzed via a repeated measures factorial MANOVA. Pillai's Trace was used to interpret the MANOVA main effects. The following assumptions of the MANOVA were checked: univariate outliers, skewness, kurtosis, multivariate outliers, multicollinearity and singularity. Pearson Product Moment Correlation Coefficients were run to determine the extent of the relationship between the dependent variables. The alpha levels were set at .05. Power analysis was run with an alpha level at .05 at a power of 80%. All data was analyzed using the Statistical Package for Social Sciences 15.0 (SPSS Inc., Chicago, IL).

CHAPTER IV

RESULTS

A total of 12 participants completed the study, and all 12 participants were included in data analysis. Each participant read and signed the informed consent and completed a medical history questionnaire. All participants answered "no" to having a history of major health conditions and signs and symptoms of cardiorespiratory diseases . All participants reported having normal menstrual cycles (no more than 1 missed menstrual cycle per year). A total of five participants reported taking oral contraceptives (Microgestin Fe 1/20; Apri, Sprintec, Kariva, and Seasonale) and one participant was using the NUVARing. The average miles run per week was 19.09 ± 12.3 miles with a maximum of 40 and a minimum of 0 miles/week. Each running economy session was completed within 45 min. The running economy sessions were designed to be run at 80% VO_{2peak}. The average VO_{2peak} for the running economy sessions was 81.4 ± 4.55% VO_{2peak}. Descriptive characteristics of the participants are presented in Table 1.

Table 1

Descriptive Characteristics of Participants (N = 12)

	Mean ± SD	Maximum	Minimum
Age (years)	26.8 ± 7.3	42	20
Height (cm)	63.7 ± 3.5	67.5	54
Weight (kg)	57.9 ± 6.4	67	43.5
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	51.8 ± 4.3	59	45
MHR (bpm)	189 ± 6.5	200	180
Peak Lactate ($mmol \cdot L^{-1}$)	9.9 ± 2.6	13	2.9

Note. All values expressed as mean ± standard deviation. VO_2 = volume of oxygen; MHR = maximal heart rate; BPM = beats per minute.

All MANOVA assumptions were checked and met. Mean values for various physiological variables for each stretching intervention are presented in Table 2.

Table 2

Means Values for Physiological Data for Each Stretching Intervention (N = 12)

	CON	AIS	SS	DF
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	42.1 ± 4.7	42.4 ± 4.0	42.1 ± 4.1	42.7 ± 4.6
% VO_{2peak}	81.0 ± 5.2	81.4 ± 4.3	81.0 ± 4.1	82.2 ± 5.1
Lactate ($mmol \cdot L^{-1}$)	4.1 ± 1.6	3.4 ± 1.2	3.7 ± 1.4	4.6 ± 1.6
Stride Length (m)	2.2 ± .13	2.2 ± .13	2.2 ± .13	2.2 ± .13
RER	.88 ± .02	.87 ± .03	.88 ± .02	.88 ± .03
RPE	4.2 ± 1.4	4.1 ± 1.4	4.3 ± 1.5	4.5 ± 1.7
HR (bpm)	167 ± 9.0	167 ± 7.7	166 ± 9.8	172 ± 9.8
% MHR	88.5 ± 4.1	88.6 ± 3.6	88.2 ± 4.3	91.3 ± 3.8
PostStretch HR (bpm)	83.0 ± 13.3	81.3 ± 28.7	88.5 ± 12.0	160.5 ± 12.2
% MHR	43.8 ± 6.5	43.0 ± 15.1	47.0 ± 5.5	85.0 ± 5.3
Sit and Reach Pre (cm)	38.2 ± 5.9	37.8 ± 5.4	38.0 ± 5.9	38.4 ± 5.3
Sit and Reach Post (cm)	38.1 ± 5.3	39.4 ± 5.5	39.8 ± 5.8	40.1 ± 4.9
Left AD Pre (degrees)	6.9 ± 6.1	6.5 ± 6.3	6.8 ± 6.3	7.5 ± 6.8
Left AD Post (degrees)	6.5 ± 5.7	7.8 ± 7.1	7.8 ± 7.1	8.7 ± 7.2
Right AD Pre (degrees)	8.8 ± 7.0	8.1 ± 5.8	8.8 ± 7.3	8.8 ± 7.4
Right AD Post (degrees)	7.8 ± 6.2	9.4 ± 6.3	9.7 ± 7.6	10.0 ± 7.8

Note. All values expressed as mean ± standard deviation. CON = control; AIS = active isolated stretching; SS = static stretching; DF = dynamic flexibility; VO_2 = volume of oxygen; MHR = maximal heart rate; BPM = beats per minute; RER = respiratory exchange ratio; RPE = rate of perceived exertion; HR = heart rate; AD = ankle dorsiflexion.

Pillai's Trace was used to interpret the MANOVA main effects. A significant effect of identified for the multivariate tests. Pillai's Trace value was 0.479, the F value was 2.089 and *p* value was .037 for the stretching interventions (control [CON], active isolated stretching [AIS], static stretching [SS] and dynamic flexibility [DF]) for dependent variables (VO_2, lactate and stride length).

However, a significant difference did not exist for the univariate tests for each variable (VO_2, p = .110; lactate, p = .105; stride length, p = .095) as presented in Table 3. Additionally, the estimation of the treatment effect, Eta squared (η^2), was low for each dependent variable indicating that the stretching trials had little effect on running economy. The power for the univariate tests for each variable ranged from .50 to .53.

Table 3

Univariate Tests of Within-Subjects Effects

Source	Measure	Type III Sum of Squares	df	Mean Square	F	Significance	η2
Trials	VO_2	3.000	3	1.000	2.169	.110	.165
	Lactate	9.097	3	3.032	2.216	.105	.168
	Stride Length	.004	3	.001	2.308	.95	.173
Error (Trials)							
	VO_2	15.217	33	.461			
	Lactate	45.163	33	1.369			
	Stride Length	.020	33	.001			

Note. VO_2 = volume of oxygen; df = degrees of freedom; η^2 = Eta squared.

Correlations were run to determine the extent of the relationship between the dependent variables. The variables were not significantly correlated. The degree of the relationship between VO_2 and lactate was a moderate, positive correlation (r = .45 - .50) for the control, AIS and SS groups but changed to a weak, negative correlation (r = -.32) for the DF group. The change in the relationship for VO_2 and lactate for DF possibly lead to an erroneous significant multivariate effect when an actual significant difference did not exist. Correlation values are presented in Table 4.

Table 4

Pearson Correlation Coefficients for VO_2, Lactate, and Stride Length

DV	CON	AIS	SS	DF
VO_2 - Lactate	0.5	0.458	0.478	-0.322
VO_2 - Stride Length	-0.101	-0.167	-0.191	-0.207
Lactate - Stride Length	0.133	-0.349	-0.121	-0.067

Note. DV = dependent variable; CON = control; AIS = active isolated stretching; SS = static stretching; DF = dynamic flexibility; VO_2 = volume of oxygen.

The mean values for VO_2 (ml·kg^{-1}·min^{-1}) were not significantly different for each stretching trial. The mean values for each stretching trial, presented in Figure 1, are 42.13 ± 4.7 (CON), 42.4 ± 4.04 (AIS), 42.13 ± 4.06 (SS), and 42.75 ± 4.6 (DF).

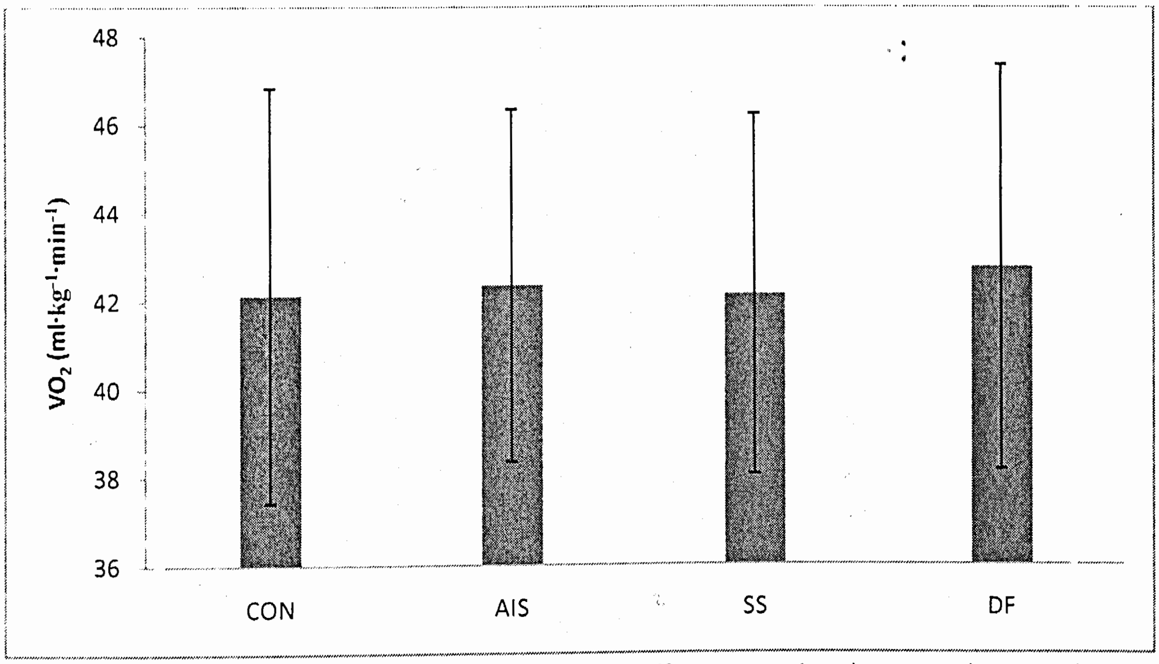

Figure 1. VO_2 mean values ± standard deviation. No differences existed among the stretching trials, p = 0.110.

The mean values for blood lactate concentration (mmol·L^{-1}) for each stretching trial, presented in Figure 2, were not significantly different. The mean values for each stretching trial were 4.1 ± 1.6 (CON), 3.4 ± 1.2 (AIS), 3.7 ± 1.4 (SS), and 4.6 ± 1.6 (DF).

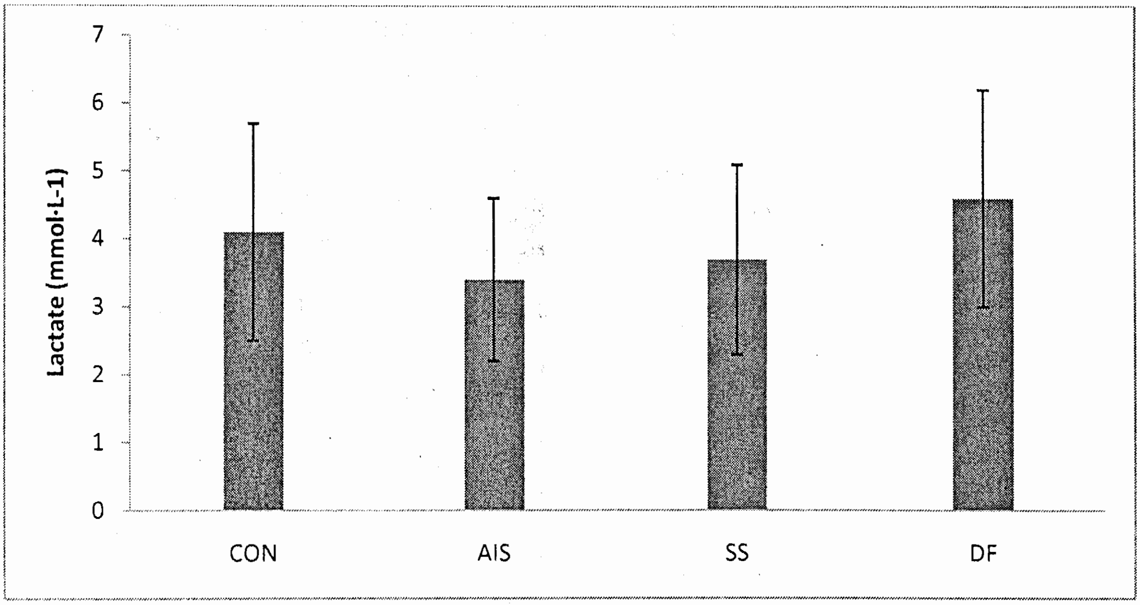

Figure 2. Lactate mean values ± standard deviation. No differences existed among the stretching trials, $p = 0.105$.

The mean values for stride length for each stretching trial were not significantly different. The mean values for each stretching trial, presented in Figure 3, were 2.2 ± .13 for all sessions (CON, AIS, SS, DF).

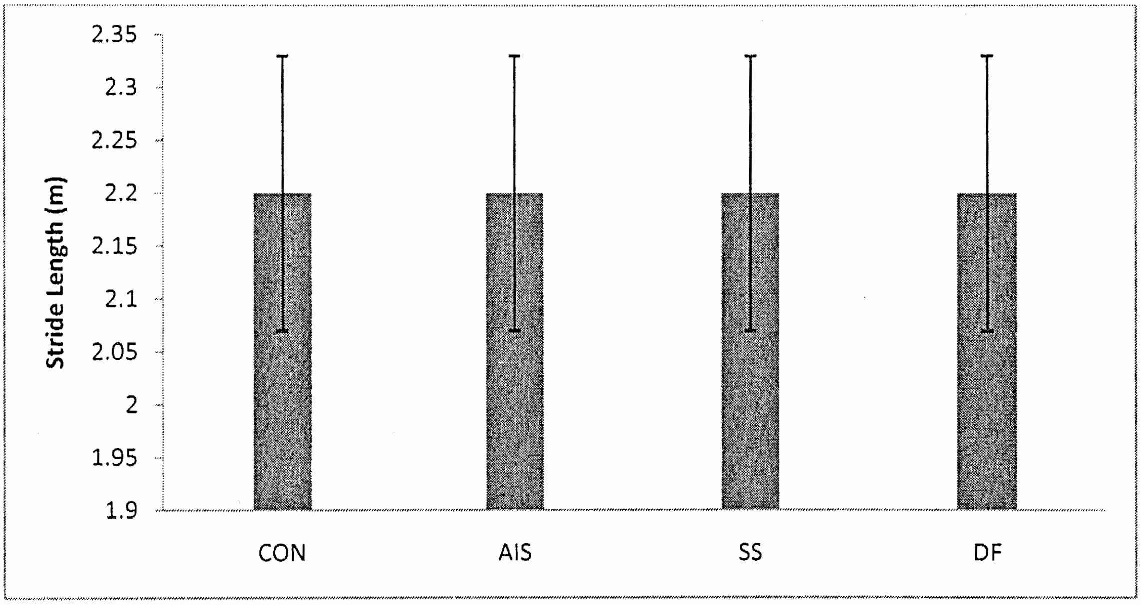

Figure 3. Stride length mean values ± standard deviation. No differences existed among the stretching trials, $p = 0.095$.

A significant ($p = 0.045$) interaction existed for all flexibility measures for time x trials. No differences existed for prestretching sit and reach, LAD and RAD values for CON, AIS, SS, DF, mean values of which are presented in Table 2. The mean values for the poststretching sit and reach measures for AIS, DF, and SS were all significantly (p = .012, .005, .002, respectively) greater than mean values for the poststretching sit and reach measures for the CON session. The mean differences were 1.35, 2.06, 1.77 cm for AIS, SS, and DF, respectively, when compared to the CON session as presented in Figure 4. The poststretching sit and reach values for AIS, DF, and SS were not significantly different from each other. No differences existed for the poststretching LAD and RAD values for the AIS, SS and control sessions. The poststretching LAD and RAD values for DF were significantly (p = 0.009, 0.021, respectively) greater than the poststretching LAD and RAD values for CON session. The mean differences for the poststretching

LAD and RAD values for DF when compared to the poststretching LAD and RAD values for the CON session were 2.167° and 2.250°, respectively as presented in Figures 5 and 6.

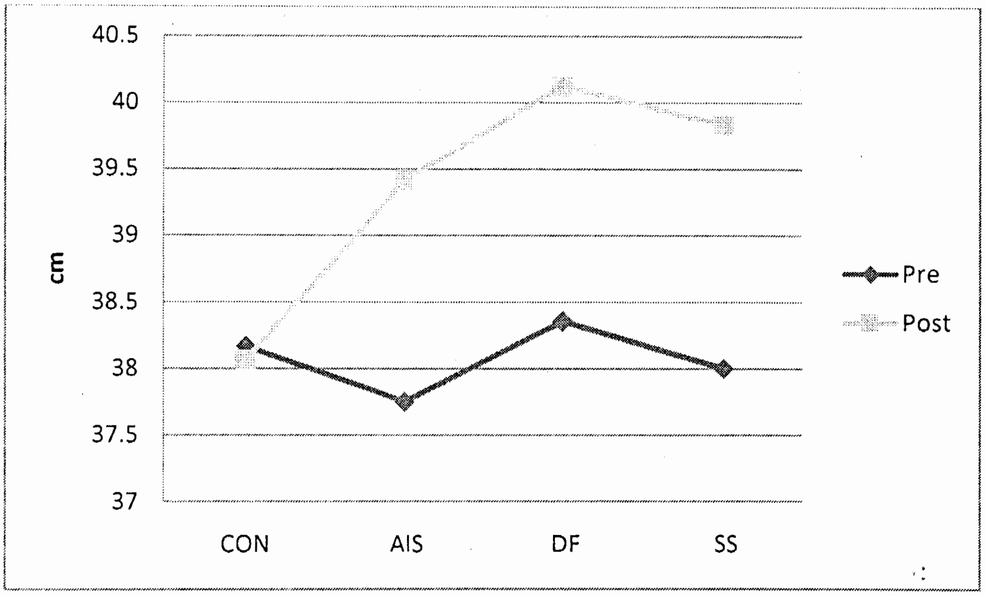

Figure 4. Interaction for trial and time for sit and reach values, $p = .003$.

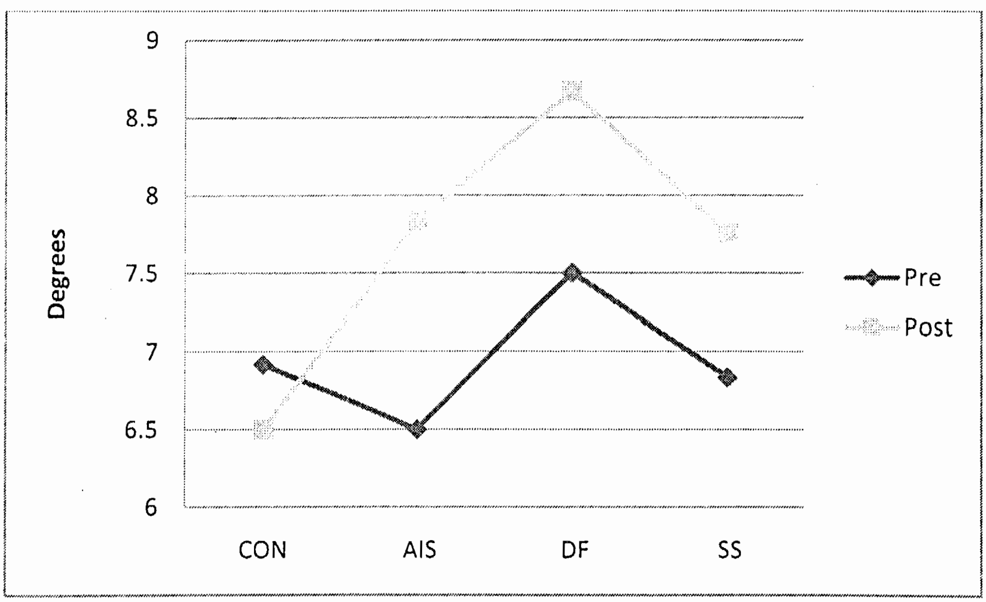

Figure 5. Interaction for trial and time for left ankle dorsiflexion values, $p = .008$.

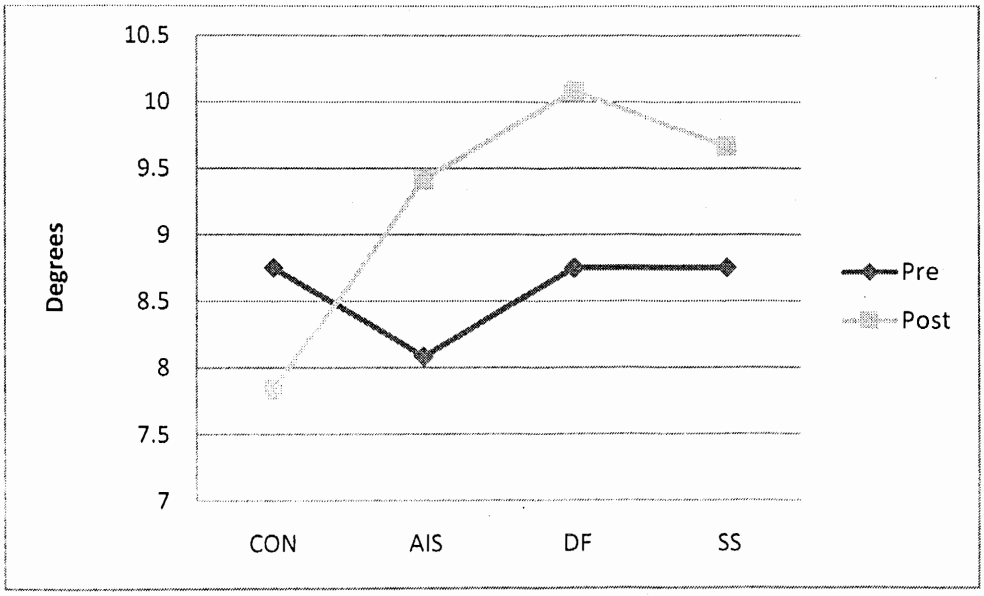

Figure 6. Interaction for trial and time for right ankle dorisflexion values, p = .006.

Summary

Three different stretching techniques did not have an effect on running economy, lactate or stride length which is consistent with the hypothesis. Range of motion as measured by the sit and reach test and ankle dorsiflexion was significantly increased poststretching.

CHAPTER V

DISCUSSION

The purpose of the current investigation was to determine the effects of three different stretching interventions (active isolated stretching (AIS), static stretching (SS) and dynamic flexibility (DF) on running economy in female distance runners. Twelve trained (VO_{2peak} = 52.1 ± 3.8 ml·kg^{-1}·min^{-1}) female participants completed all five testing sessions of the study. The VO_{2peak} value of the current study is lower than the typical minimum VO_{2max} value of 60 ml·kg^{-1}·min^{-1} reported for extremely highly trained female distance runners (Baechle & Earle, 2008; McArdle et al., 2001) but would fall between the 95th and 99th percentile for the 20-29 age group according to the ACSM guidelines (2010). The average VO_{2peak} of the current study is within the range reported for female soccer players of 49 – 53 ml·kg^{-1}·min^{-1} (Baechle & Earle, 2008). Additionally, the average miles run per week (≈ 20 miles per week) is lower than typically reported for female distance runners (≈ 50^{+} miles per week; Trehearn & Buresh, 2009). The lower VO_{2peak} and mileage values were due to difficultly in participant recruitment; therefore, not all participants were distance runners as four participants were soccer players. Previous research by Hayes and Walker (2007), Allison et al. (2008), and Zimmer et al. (2007) used male distance runners as participants; therefore, the current study is the first study to examine the effects of stretching on running economy in trained female athletes to the investigators knowledge.

When first examining the multivariate test statistics, the stretching protocols had a signficant effect on running economy. Upon further inspection of the univariate tests, the stretching protocols did not have an effect on running economy which is consistent with the literature for male participants (Allison et al., 2008; Hayes & Walker, 2007; Zimmer et al., 2007). When checking the correlation coefficients between VO_2, lactate and stride length, the relationship between VO_2 and lactate was different for the DF session than the CON, AIS, and SS sessions. The correlation coefficient between VO_2 and lactate for the CON, AIS, and SS sessions was a moderate, positive correlation; whereas, the correlation coefficient for the DF session was a weak, negative correlation. Bray and Maxwell (as cited in Warner, 2008) stated that "the magnitude and signs of the correlations among outcome measures influence the statistical power of MANOVA and the interpretability of results in complex ways" (p. 708). The change in the relationship between VO_2 and lactate for the DF session possibly resulted in an erroneous significant finding for the multivariate test statistic when, in fact, the stretching protocols appeared to have no effect on running economy. In further support, the stretching interventions only explained approximately 17% of the variance in running economy indicating a small treatment effect despite a significant multivariate effect.

Each stretching session was 10 min in duration, consisting of 2 sets of 30 s for five exercises for each limb for the AIS and SS sessions, 2 sets of 30 s for 10 active warm-up drills for the DF session, and a 10 min sit for the CON session. The CON session required minimal effort which was reflected with an average heart rate at the completion of the 10 min sit of 83 ± 13.3 bpm (44% MHR). The AIS and SS sessions were similar in nature except that in the SS session, each stretch was held for the entire 30 s and in the AIS session, repetitions of each stretch were performed for the 30 s period. The average heart rate at the completion of the AIS and SS sessions were 81.3 ± 28.7 and 88.5 ± 12 bpm (43 and 48% MHR), respectively. The DF session was much more active than the AIS, SS and CON sessions as it involved repeated bouts of running, skipping, and jumping. As a result, the average heart rate at the completion of the DF session was 160.5 ± 12 bpm (85% MHR). The mean VO_2 for the DF session was the highest of all the groups, though not statistically significant. Additionally, for six of the participants, the DF session resulted in the highest $\%VO_{2peak}$. The DF session had the highest mean blood lactate concentrations (4.6 ± 1.6 $mmol{\cdot}L^{-1}$ vs. 4.1 ± 1.6 [CON], 3.4 ± 1.2 [AIS], and 3.7 ± 1.4 [SS] $mmol{\cdot}L^{-1}$) and were the highest blood lactate concentrations for five participants. Although, the lactate values were not statistically significant, the higher values in the DF session resulted in a change in the relationship between VO_2 and lactate, thus possibly resulting in an erroneously significant multivariate effect. Finally, seven participants identified the run following the DF session to be the hardest which also had the highest RPE value (4.5 vs 4.2 [CON], 4.1 [AIS], and 4.3 [SS]; whereas, three participants said the run following the DF session was the easiest sessions.

The primary purpose of a warm-up is to increase body temperature which may serve to decrease the resistance of muscles and joints (Bishop, 2003) which may increase ROM (Henricson et al., 1984; Stewart & Sleivert, 1998; Wenos & Konin, 2004). Gregson, Batterham, Drust, and Cable (2005) reported significant increases in body temperature following 10 min of running at 70% VO_{2max}. The 10-min warm up in the current study was performed at a self selected speed below the speed corresponding to 80% VO_{2peak} and elicited a heart rate of 155 bpm (81% MHR). The run at 80% VO_{2peak} elicited a heart rate of 169 bpm (89% MHR). Given that the DF session elicited a poststretch heart rate of 160.5 bpm (85% MHR), it can be assumed that the DF session was performed between 70 and 80% VO_{2peak}, which is an adequate intensity to raise body temperature (Gregson et al., 2005). Furthermore, participants in the current investigation achieved the greatest sit and reach scores (40.1 ± 4.9 cm vs. 38.1 ± 5.3 [CON], 39.4 ± 5.5 [AIS], 39.8 ± 5.8 [SS])and ankle dorsiflexion measures (LAD: 8.7 ± 7.2 vs. 6.5 ± 5.7 [CON], 7.8 ±7.1 [AIS and SS]; RAD: 10.0 ± 7.8 vs. 7.8 ± 6.2 [CON], 9.4 ± 6.3 [AIS], 9.7 ± 7.6 [SS]) following the DF session. In support, Wenos and Konin (2004) reported the greatest increases in ROM following an active warm up of treadmill running at 70% heart rate reserve.

Increases in body temperature are associated with increased muscle glycogenolysis and lactate accumulation due to increased ATP turnover to meet the demands of the elevated body temperature (Febbraio, Carey, Snow, Stathis, & Hargreaves, 1996; Parkin, Carey, Zhao, & Febbraio, 1999). Blood lactate concentrations increase from rest to exercise during running (Morris, Nevill, & Williams, 2000) and were higher following an active warm up for kayaking (Bishop, Bonetti, & Spencer, 2003), cycling (Bishop and Maxwell, 2009), and running (Maxwell, Gardner, & Nimmo, 1999) compared to no warm up. Gray and Nimmo (2001), and Gray, DeVito, and Nimmo (2002) reported significantly higher lactate values following an active warm up consisting of 5 min of cycling at 40% of the power output achieved at VO_{2peak} (PO_{max}) followed by four 15 s sprints at 120% PO_{max} with 15 s rest compared to a control. In the current study, 9 participants had a blood lactate concentration of 4 $mmol \cdot L^{-1}$ or greater for the DF session. In addition, the average heart rate following the DF session was approximately 85% MHR. A blood lactate concentration of 4 $mmol \cdot L^{-1}$ has been used to represent lactate threshold (Sjödin & Jacobs, 1981) but after testing 75 male and female distance runners to determine lactate threshold, Daniels (personal email, Sept. 22, 2004) indicated that the blood lactate concentration at lactate threshold varied from 2.6 to 7.2 $mmol \cdot L^{-1}$. Additionally, Aunola and Rusko (1984) indicated poor reproducibility of a blood lactate concentration of 4 $mmol \cdot L^{-1}$ at anaerobic threshold. Daniels concluded that a lactate threshold of 4 $mmol \cdot L^{-1}$ corresponded to 86-88% VO_{2max} and a heart rate of 90-92% MHR which is in agreement with the findings of Dumke, Brock, Helms, and Haff (2006). Hoffman et al. (1997) reported that a lactate concentration of 4 $mmol \cdot L^{-1}$ corresponded to 81 to 88% MHR in 227 male athletes. Lajoie, Laurencelle, and Trudeau (2000) reported that lactate threshold occurred between 60-80% VO_{2max} for a group of trained cyclists. It is plausible that the DF session increased blood lactate concentration above lactate threshold, a value which was not directly measured, which was maintained throughout the 10-min running economy run to elicit a higher blood lactate concentration post run. Gray and Nimmo (2001) and Gray et al. (2002) reported higher blood lactate values following a 30 s sprint at 120% PO_{max} for the active warm up group. Fukuba et al. (1999) reported that peak blood lactate (9 $mmol \cdot L^{-1}$) was achieved approximately 2 min following an exhaustive ramp protocol on a cycle ergometer. The time period for blood lactate concentration to reach 4 $mmol \cdot L^{-1}$ during a passive recovery was approximately 20 min. After 30 min, the blood lactate concentration reached 2 $mmol \cdot L^{-1}$ (Fukuba et al., 1999). Gmada et al. 2005) reported that blood lactate values peaked between the 4th and 7th minute of recovery following three cycle exercise bouts at 120% maximal aerobic power for an average of 102 s separated by 5 min of recovery. The time period from the completion of the stretching protocol for the DF session to the start of the treadmill run was approximately 5 min. While the DF stretching protocol did not elicit maximal heart rates or maximal effort, given the plausibility that the stretching increased heart rates above lactate threshold, blood lactate concentration may have reached peak values or was not adequately cleared as the participant began the 10 min run at 80% VO_{2peak}. The 10 min run at 80% VO_{2peak} may have maintained or increased blood lactate resulting in higher blood lactate values than the other three sessions.

Another possibility for the higher lactate values in the dynamic flexibility session is the type of muscle recruited. Certain exercises in the dynamic flexibility session can be thought of as plyometric exercises including butt kicks, high knees, skipping march and karaoke which made of the last four exercises for the dynamic flexibility session of the current study. Plyometric exercise is defined as a quick, powerful movement used to increase the activity of the SSC and is used to increase both muscle force and power (Potach & Chu, 2008). Power type movements such as plyometrics rely on fast twitch motor units and muscle fibers (Moritani, 2003). Regardless of the type of activity, the recruitment of fast twitch muscle fibers results in the production of lactate (Brooks et al., 2005). Lactate production is increased in fast twitch muscle fibers due to a high glycolytic rate in which the M-type lactate dehydrogenase isoform readily converts pyruvate to lactate as due to the absence of mitochondria in these muscles, the pyruvate can not enter the mitochondria and is converted to lactate in the cytosol. It is plausible that the dynamic flexibility exercise recruited a high amount of fast twitch muscle fibers thus increasing lactate production.

In agreement with Hayes and Walker (2007), Allison et al. (2008) and Zimmer et al. (2007), the stretching protocols of the current study did not have an effect on running economy. Hayes and Walker (2007) used VO_2 data from the final 2 min of a 10 min run below lactate threshold to determine running economy. Zimmer et al. (2007) averaged the final 2 min of a 7 min at three different speeds (6.2, 7.5 and 8.7 mph) to determine running economy. Hayes and Walker (2007) and Zimmer et al. (2007) speculated that the length of the running economy sessions (10 and 7 min) may have negated any effects of the stretching protocols as Rosenbaum and Hennig (1995) suggested that 10-min of running may reverse the detrimental effects of static stretching on active peak force and rate of force development. Additionally, Magnusson et al. (2000) reported that energy absorption was not different from prestretch levels follow a 10 min run at 70% VO_{2max} suggesting that running after stretching may counteract the negative effects of preexercise stretching. To remedy the data collection limitations of Hayes and Walker (2007) and Zimmer et al. (2007), Allison et al. (2008) used mean values for Minutes 3-10 in a 10-min running economy session at 70% VO_{2peak} but still reported no difference in running economy, similar to the current study. All three studies plus the current investigation included SS as a stretching protocol. Hayes and Walker (2007) also included proprioceptive neuromuscular facilitation stretching and a dynamic warm up. Zimmer et al. (2007) used SS and DF. Stretching durations varied between the studies as Allison et al. (2008) had participants performed SS for 38 min; whereas, the protocols of Hayes and Walker (2007) were 10-min in length and Zimmer et al. (2007) used 20 min protocols. Similar to Hayes and Walker (2007) the current study used 10-min protocols for SS, DF and AIS. Despite differences in methodology, no significant differences were reported for any of the studies adding weight to the argument that the length of the run may negate any effects of the stretching protocols.

Stretching prior to activity is thought to improve performance and reduce the risk of injury by improving flexibility via increases in ROM (Herda et al., 2008). Stretching has been reported to positively increase ROM by possible lengthening of the connective tissue within the muscle (Bandy & Irion, 1994; Bandy, Irion, & Briggler, 1997; De Pino, Webright, & Arnold, 2000) Sit and reach, and ankle dorsiflexion measures were utilized to assess ROM pre and poststretching in the current study. All flexibility measures significantly increased from prestretching to poststretching in all trials which was also reported by Hayes and Walker (2007) and Allison et al. (2008). The averages of the sit and reach test for each stretching protocol would fall between very good and excellent for the 20-29 age group according to ACSM (2010). The ankle dorsiflexion values were well below (6.5 – 10.0°) the 15-20° normative range reported by ACSM (2010). Arampatzis et al. (2006) reported that the triceps surae was stiffest for the most economical runners which may be advantageous to runners as Craib et al. (1996) reported a significant correlation between ankle dorsiflexion and running economy. A stiffer triceps surae complex may enhance elastic return of energy through the Achilles tendon to the calf muscles which reduces subsequent muscle activation, thus decreasing the oxygen cost of running (Craib et al., 1996). In support, Gajdosik and Riggin (2005) indicated that distance runners had increased passive resistive properties compared to the general population suggesting adaptations to the triceps surae MTU resulting from the eccentric loading and stretching associated with the running stride.

Changes in ROM following stretching are thought to reflect changes in MTU stiffness or MUA activation (Cornwell et al., 2001). Jones (2002), and Trehearn and Buresh (2009) reported that less flexible runners, as measured by a sit and reach test, were more economical. The findings of Jones (2002), and Trehearn and Buresh (2009) would suggest that increases in ROM as measured by a sit and reach test may negatively affect running economy via reducing MTU stiffness or MUA activation which would be detrimental to running economy. Despite increases in ROM following the stretching protocols, running economy remained unaffected in the current study and the studies of Hayes and Walker (2007), and Allison et al. (2008). Hayes and Walker

(2007) speculated that since the sit and reach test is a measure of hamstring flexibility (Jackson & Baker, 1986; Minkler & Patterson, 1994; Youdas, Krause, & Hollman, 2008), and hamstring flexibility was not significantly correlated with running economy (Craib et al., 1996), that hamstring flexibility is not a strong determinant of running economy. Magnusson et al. (2000) reported that viscoelastic properties of the hamstring muscle were not changed following 10 and 30 min of running. However, the passive energy absorption of the hamstring muscle was immediately reduced 29% following passive static stretching but this effect was not present following 30 min of running. The current study also measured ankle dorsiflexion which increased significantly poststretching and was reported by Craib et al. (1996) to have a strong correlation (r = .65) with running economy. Additionally, stretching of the triceps surae via ankle dorsiflexion had been reported to reduce stiffness but increase elasticity similar to the hamstring muscle as reported by Magnusson et al. (2000). This would suggest that the opposing outcomes of stretching may prevent any changes in running economy as enhanced elasticity is beneficial to running economy (Kubo et al., 2001). Furthermore, running may decrease the stiffness of the MTU more effectively than stretching indicating that the addition of stretching has no effect on the already relaxed MTU (McNair & Stanley, 1996).

Previous studies that reported differences in performance following stretching involved maximal activities such as sprinting, and 1 RM lifts. Running for 10 min at 80% VO_{2peak} requires a submaximal effort. Hickson et al. (1988) reported that running at speeds of 3.62 - 4.0 $m \cdot s^{-1}$ has approximately 40-50% of the peak ground reaction forces of sprinting and 20% of the peak ground reaction forces of vertical jump. Participants in the current study all ran at speeds (3 to 3.8 $m \cdot s^{-1}$) slower than those reported by Hickson et al. (1988) suggesting that the detrimental effects of stretching are not evident with submaximal forces. Maximal activities heavily recruit Type II muscle fibers; whereas, submaximal activities rely more on Type I muscle fibers. The overall percentage of Type II muscle fibers was inversely correlated (r = -.61) to oxygen consumption at 7 $m \cdot s^{-1}$ in highly trained (VO_{2max} = 74.5 ± 5.1 $ml \cdot kg^{-1} \cdot min^{-1}$) middle distance runners as Type II muscle fibers are able to function in the absence of oxygen (Kyröläinen et al., 2003). Zimmer et al. (2007) suggested that the reliance on Type I muscle fibers allowed more time for the muscles to react to the stretching induced MTU changes, thus providing opportunity for the aerobic capabilities of the Type I muscle fibers to offset the detrimental effects of the stretching (Zimmer et al., 2007).

Stride mechanics have been reported to explain 54% of the variance in running economy (Williams & Cavanagh, 1987). Godges et al. (1989) reported an improvement in gait economy with an increase in hip ROM but did not measure stride mechanics. One could speculate that stride mechanics are altered with changes in hip ROM, thus altering the oxygen cost of the activity. Heise & Martin (1998) reported that more economical runners activated the rectus femoris as early as 55% of the swing phase compared to less economical runners who activated the rectus femoris as late as 80% of the swing phase. The more economical runners may activate the rectus femoris during hip flexion and knee extension whereas less economical runners may activate the rectus femoris during knee extension (Heise & Martin, 1998). Additionally, tight hip flexor musculature, which includes the iliopsoas, tensor fascia lata, and rectus femoris, may decrease hip extension flexibility (Schache, Blanch, & Murphy, 2000). The hip is in some degree (5° to full extension) of extension throughout the early, mid, and late swing phases of the running stride (Montgomery et al., 1994). Sufficiently tight hip flexor musculature may inhibit hip extensor musculature activation via reciprocal inhibition, thus altering the running stride. Excessively tight hip flexor musculature may also affect hip flexion via autogenic inhibition. The alteration of normal muscle recruitment patterns during the running stride may alter stride mechanism thus altering the oxygen cost of running (Cavanagh & Williams, 1982; Cavanagh et al., 1985; Heinert et al., 1988).

Despite performing stretches to increase the ROM of the hip joint, no differences in stride mechanics were reported for each stretching protocol in the current study which is in agreement with the findings of Allison et al. (2007). Cavanagh and Williams (1982) reported that well-trained runners will adopt an optimal stride length and stride frequency combination based on perceived exertion whether it is a conscious or subconscious alteration to minimize oxygen consumption (Cavanagh & Williams, 1982). Rating of perceived exertion looked similar in the current study for all sessions. It is possible that following a stretching protocol, runners were able to make slight adjustments to stride mechanics to keep stride length at an optimal length that were not visible through timing of 15 right foot contacts or video analysis. In support, Folland, Rowlands, Thorp, & Walmsley (2006) reported that despite changes in stride mechanics due to leg cooling, running economy was not altered indicating that the changes in stride mechanics were not sufficient enough to alter running economy.

Limitations of the Current Study

A few limitations exist in the current study. Due to difficultly in participant recruitment, not all participants were highly trained distance runners as four participants were soccer players and the weekly average mileage was lower than typically seen in trained distance runners. Additionally, not all participants achieved the desired minimal VO_{2peak} value of 50 $ml \cdot kg^{-1} \cdot min^{-1}$.

The results of the current study are limited to a similar population and cannot be generalized to the general population. Difficulty existed in estimating the speed corresponding to 80% VO_{2peak} from the VO_{2peak} test data as the percentage of VO_{2peak} for the final 10 min run ranged from 76 – 93%. Despite a best attempt by the investigator, the degree to which each participant felt each stretch could not be controlled and may have limited the study. Additionally, diet prior to each testing session was not controlled.

Summary and Conclusion

The current study investigated the effects of 10 min of active isolated stretching, static stretching, and dynamic flexibility on running economy, blood lactate concentration, and stride length at 80% VO_{2peak} in female athletes. The results of the current study were that no significant differences existed in running economy, blood lactate concentration and stride length as a result of the stretching interventions. Taken together with the current literature, a variety of stretching protocols appear to have no effect on factors associated with optimal running performance including running economy, blood lactate concentration and stride length.

Recommendation for Further Study

Although the published research relating to stretching and running have reported no effect, these studies were performed on highly trained male distance runners; therefore, more research should include highly trained female distance runners. Field studies on this topic may yield different results as racing a set distance may elicit different responses compared with running on a treadmill at given percentage of VO_{2peak}. Future researchers should investigate the effects of a combination of stretching techniques (i.e. static stretching and dynamic flexibility) on running economy.

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APPENDIX A

RECRUITMENT FLYER

Runners Needed for Research Project by TWU

Criteria:
Female Distance Runners
18-49 years old
Normal Menstruation Patterns

Purpose:
To Determine the Effects of Three Different Stretching Protocols on Running Economy

Benefits:
Determine your cardiovascular fitness (VO_{2max} Test)
Learn how efficiently you use oxygen while running
Identify the best stretching protocol for optimal performance
Free Massage

Participation is Requested but is Voluntary
If Interested, Please Contact Kelley Henry:
kelleyhenry03@yahoo.com

APPENDIX B

INFORMED CONSENT

Texas Woman's University
Consent to Participate in Research

Title: The Effect of Three Different Stretching Protocols on Running Economy

Investigator: Kelley Henry, M.S..
Advisor: David Nichols, PhD..940-898-2252

Explanation and Purpose of the Research

You are being asked to participate in research for Kelley Henry's dissertation at Texas Woman's University. The purpose of this research is to determine the effects of three different stretching protocols on running economy in female distance runners during the follicular phase of the menstrual cycle.

Research Procedures

The maximum time commitment is no more than 5 hours as each of the 5 sessions will last an hour each which will include the VO_{2max} session as well as going over the informed consent, filling out the Health History Questionnaire and explanation of the study. Additional time of up to 2 hours may be needed if you need additional time to adjust to wearing the mouth piece and nose clip during the testing sessions due to physical discomfort/anxiety.

The first session will involve measurement of VO_2max (the most amount of oxygen your body can use during exercise). Measurement of VO_2max involves running on a treadmill at increasingly faster speeds and inclines until you feel you can no longer run. The treadmill speed will begin at 4 mph at 0% grade and will increase in speed every 3 min up to 9 mph at which point the speed remains constant and the grade increases 1% every 3 min until cessation of the test. During the treadmill run, expired gases will be measured to determine VO_2max. This will require you to wear a breathing apparatus, nose clip, and mouth piece that will direct all expired air into the device which will measure the gas content of the expired air. Heart rate will be monitored via electrocardiogram (ECG) which requires you to wear electrodes. You will be prepped for the electrodes by a female researcher prior to the maximal testing and this involves rubbing the skin on the chest with alcohol and gauze pads to ensure proper bonding of the electrodes to the skin. Additionally, following each of the five sessions, blood will be taken from a simple finger prick using needle-like pin. Only a small amount of blood will be taken and only one finger prick will be performed.

Participant Initials______
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Sessions 2-5 involve measurement of running economy or how much oxygen you will use while running at a certain speed for 10 min. You will run at a comfortable pace for each session which will be determined from your VO_2max test. You will be outfitted with the breathing apparatus mentioned above to measure oxygen consumption. Each of these sessions will require you to warm-up by running on the treadmill for 10 min. In three of the remaining four sessions, you will perform one of three stretching protocols (static stretching, active isolated stretching and dynamic flexibility).

Static stretching will require you to hold a stretch for 30 s and repeat two times. You will be asked to stretch to the point of discomfort but not pain. For active isolated stretching, you will hold a stretch for 2 s and repeat this eight times. You will do 2 sets for each stretch. Dynamic flexibility involves performing different, sport specific movements for 2 sets of 30 s. The control session will require you to sit in a chair for the length of time it takes you to complete each stretching protocol. Your range of motion will be determined prior and following the stretching protocols. Upon completion of the protocols and/or rest period, you will be immediately prepped with the breathing apparatus and instructed to run at 8 mph for 10 min. You will wear a heart rate monitor to keep track of your heart rate during the runs.

Potential Risks

Potential risks related to your participation in this study include the following:

Fatigue, muscle soreness, and injury: Your training status should help reduce the risk of fatigue, muscle soreness, and injury during the running economy sessions as the testing is no more strenuous than daily training sessions. You will experience fatigue with VO_{2max} testing but you are allowed to stop the test at any point. Risk of injury from the stretching protocol should be limited as you will be instructed to the stretch to the point of mild discomfort but not pain. You will be allowed to practice each protocol prior to testing. A thorough familiarization with the lab setting and equipment should also limit the risk of injury.

Death: The risk of death during exercise is one death per year for every 769,000 women. The risk of death will be further prevented through screening for any cardiac abnormalities via a medical history form and by heart rate monitoring at rest and during exercise. Personnel trained in CPR/AED and First Aid will be present during each testing session. Defibrillators will also be present to minimize the risk of death is a cardiac event arises. All participants will be screened for existing and/or underlying cardiac abnormalities via a medical history form and will be excluded from the study if any abnormalities are present.

Participant Initials ____

Participants will be prepped for a 12 lead electrocardiogram (ECG) by a female researcher during the VO_{2max} test to detect any cardiac abnormalities that may arise. Additionally, only trained runners ($VO_{2max} \geq 50$ ml·kg^{-1}·min^{-1} with at least one year running experience) will be included in the study.

Infection/disease from finger prick for lactate measurement: You will experience some discomfort will each finger prick but the prick will be quick and will only be performed one time. Universal precautions including the use of alcohol pads prior to the finger prick and gloves will be worn by the researchers to reduce the risk of disease transmission and possible infection.

Irritation to skin via use of electrodes: Irritation to skin may occur due to the use of electrodes applied directly to the skin. You will be asked if your skin is sensitive to other types of gel or if there has been a past reaction to electrode preparation. Additionally, the skin will be cleaned via alcohol pads before and after use of the electrodes.

Physical Discomfort/Anxiety: You may experience anxiety/discomfort with the use of a nose clip and mouth piece for the breathing apparatus. You will be allowed to try on the mask prior to being prepped for testing to determine if discomfort/anxiety issues arise. If issues do arise, you will be given as much time as needed (up to two additional hours of total testing time) to adjust to wearing the mouth piece and nose clip.

Confidentiality: Confidentiality will be protected to the extent that is allowed by law. A number ID in place of your name will be used on all paperwork and data. All paper documents will be kept in a locked file cabinet in the investigator's office along with all electronic devices which contain data pertaining to your participation in this research. All paper documents will be shredded and electronic devices will be erased within 5 years of completion of the study. It is anticipated that the results of this study will be published in final paper as well as in other research publications. However, no names or other identifying information will be used in any publication. There is a potential risk of loss of confidentiality in all email, downloading and internet transactions.

Loss of time: In order to reduce time lost, the research team will arrive early to set up all necessary equipment for each session. Additionally, all research team members will be trained on all aspects of the study and equipment to prevent any delay in data collection. You should come prepared to run to further reduce loss of time. The research team will work quickly but effectively to ensure that you will only be at the lab for an hour each session.

Participant Initials______

The researchers will try to prevent any problem that could happen to you because of this research. You should let the researchers know at once if there is a problem and they will help you. However, TWU does not provide medical services or financial assistance for injuries that may happen because you are taking part in this research.

Participation and Benefits

Your involvement in this study is completely voluntary, and you may discontinue your participation in the study at anytime without penalty. The benefits of the study will be greater knowledge regarding the effects of different stretching protocols on running economy and possibly overall performance. Participants will also receive information regarding their running economy which may help identify a need to improve economy to improve overall performance. Additionally, participants will receive knowledge of their current fitness level via a free VO_2max test. Additionally, upon completion of the study, a summary of the results will be mailed to you upon request.* For your participation, you will receive a free 1 hour massage by a massage therapist upon completion of the study. The massage therapist performing the massages will be Kelley Henry, the researcher. You will receive her business card that will serve as a coupon to redeem your massage. There will be no expiration date for the free massage.

Questions Regarding the Study

If you have any questions regarding the research study, you may ask the researchers; their phone numbers are located at the top of this form. If you have questions about your rights as a participant in this research or the way the research is being conducted, you may contact the Texas Woman's University Office of Research and Sponsored Programs 940-898-3378 or via email at IRB@twu.edu. You will be given a copy of this signed and dated consent form to keep.

____________________________________ _______________

Signature of Participant Date

*** If you would like to receive a summary of the results of this study, please provide a mailing address or email address to which this summary should be sent:**

____

____

APPENDIX C

MEDICAL HISTORY FORM

MEDICAL HISTORY QUESTIONNAIRE

ID#__________________ Date_________

Age________

1. Do you have a history of any of the following conditions? (Check if "yes")

__ Abnormal ECG
__ Anemia
__ Diabetes
__ Disease of Arteries
__ Epilepsy
__ Heart Disease
__ High Blood Pressure
__ Muscular Illness
__ Heart Arrhythmia
__ Heart Murmur
__ High Blood Pressure
__ Lung Disease
__ Stroke
__ Heart Surgery
__ Heart Attack
__ Elevated Cholesterol

__ Other (please explain)______________________________
____

2. Cardio-respiratory History

Any heart disease now?	Yes	No
Any history of high cholesterol?	Yes	No
Any heart disease in past?	Yes	No
Heart murmurs?	Yes	No
Occasional chest pain?	Yes	No
Chest pain on exertion?	Yes	No
Fainting?	Yes	No
Daily coughing?	Yes	No
Coughing producing sputum?	Yes	No
High blood pressure?	Yes	No
Shortness of breath at rest?	Yes	No

3. Training and Menstruation Status

1. How many miles do you run per week? __________

2. How many days do you run per week? __________

3. Can you provide a log of your running miles?

If yes, please bring to next session.

4. How old were you when you started having your period? _________

5. Do you keep a calendar of your period?

YES NO

6. Have you had times when you missed periods other than when you were pregnant or breast feeding? YES NO

If yes, how long did you go without having a period?

Age	Number of Months without period
___________	__________________________
___________	__________________________
___________	__________________________
___________	__________________________

7. When was your last menstrual period? __________

8. When do you expect your next menstrual period? ________________

9. How many days does your period usually last? _________

10. What is the average interval from the start of one period to the start of the next?

____

11. Which statement best describes the character of your periods with respect to regularity (during a time when you have not been on the pill or using an IUD)

a. Amenorrheic: periods per year ___0, ____ 1, _____2

Spread out ____ yes, ____ no

Relation to time of year ____ yes, ____ no

Relation to training _____ yes, _____ no

Relation to body weight _____ yes, _____ no

b. Normal: something every month

c. Irregular

d. Intermittent

Spread out _____ yes, _____ no

Relation to time of year _____ yes, _____ no

Relation to training _____ yes, _____ no

Relation to body weight _____ yes, _____ no

12. Do you currently take any form of oral contraceptive (including birth control pills, patches, IUD, shots)? YES NO

If yes, please indicate what kind, the brand name, and for how long. Type

Brand Name For How Long

___________ ___________ ___________

4. Stretching Practices

Do you stretch? YES NO

If yes, please answer the following questions:

For how many years have you been stretching? _________

How many days per week to do you stretch? __________

How long is each stretching session? ________________

Specifically, what stretches do you perform? _________________

____

How long do you hold each stretch? ________________

Do you stretch before or after you run? Before   After   Both

APPENDIX D

IRB APPROVAL

TWU
TEXAS WOMAN'S UNIVERSITY
DENTON DALLAS HOUSTON

Institutional Review Board
Office of Research and Sponsored Programs
P.O. Box 425619 Denton TX 76204-5619
940-898-3378 Fax 940-898-34[illegible]6
e-mail: IRB@twu.edu

March 13, 2009

Ms. Kelley Henry
[redacted]

Dear Ms. Henry,

Re: *The Effect of Three Different Stretching Protocols on Running Economy*

The above referenced study has been reviewed by the TWU Institutional Review Board (IRB) and appears to meet our requirements for the protection of individuals' rights.

If applicable, agency approval letters must be submitted to the IRB upon receipt PRIOR to any data collection at that agency. A copy of the approved consent form with the IRB approval stamp and a copy of the annual/final report are enclosed. Please use the consent form with the most recent approval date stamp when obtaining consent from your participants. The signed consent forms and final report must be filed with the Institutional Review Board at the completion of the study.

This approval is valid one year from February 13, 2009. According to regulations from the Department of Health and Human Services, another review by the IRB is required if your project changes in any way, and the IRB must be notified immediately regarding any adverse events. If you have any questions, feel free to call the TWU Institutional Review Board.

Sincerely,

Dr. Kathy DeOrnellas, Co-Chair
Institutional Review Board - Denton

enc.

cc: Dr. Charlotte Sanborn, Department of Kinesiology
Dr. David Nichols, Department of Kinesiology
Graduate School

APPENDIX E

ORIGINAL DATA

Participant VO_2 Data for Minutes 3-10

N	CON	AIS	SS	DF
1	41.28	42.30	42.83	41.08
2	52.56	51.02	52.85	51.27
3	45.19	43.61	44.27	44.32
4	39.33	39.94	40.48	40.12
5	40.81	39.48	40.38	40.30
6	40.81	41.05	41.86	42.00
7	39.86	40.16	41.02	39.71
8	35.80	37.39	36.58	36.65
9	49.43	49.36	50.43	48.51
10	40.64	42.85	41.16	40.86
11	40.30	41.49	42.22	40.95
12	39.60	39.54	38.87	39.85

Participant VO_2 Data for Minutes 3-6

N	CON	AIS	SS	DF
1	40.56	41.65	42.35	40.63
2	51.26	49.83	51.57	50.12
3	44.06	42.92	43.52	43.35
4	38.77	39.20	40.03	39.75
5	40.16	38.99	39.91	39.55
6	40.57	40.58	41.52	41.61
7	39.63	38.92	40.31	38.94
8	35.26	36.67	36.26	36.05
9	48.95	48.68	49.53	48.31
10	40.45	42.15	40.87	40.14
11	39.81	40.91	41.40	40.06
12	38.82	38.59	38.31	39.12

Key:
N = Participant ID number
CON = Control
AIS = Active Isolated Stretching
DF = Dynamic Flexibility

Participant VO_2 Data for Minutes 7-10

N	CON	AIS	SS	DF
1	42.95	42.00	43.32	41.59
2	52.37	53.86	54.14	52.57
3	44.41	46.32	45.03	45.11
4	40.68	39.97	40.99	40.55
5	39.97	41.45	40.85	41.05
6	41.53	41.09	42.26	42.44
7	41.40	40.11	41.74	40.60
8	38.10	36.33	36.90	37.25
9	50.14	49.91	51.33	48.71
10	43.56	40.83	41.44	41.58
11	42.08	40.80	43.04	42.10
12	40.49	40.38	39.42	40.58

Participant Blood Lactate Concentration Data

N	CON	AIS	SS	DF
1	3	3.6	4.3	3.2
2	4.6	4.4	4.3	4.1
3	5.2	2.3	4	4.9
4	2.4	3.4	4.3	3.4
5	4.4	3.2	5.3	4.7
6	3.3	2.9	4.2	3.2
7	2.6	3	2.6	2.1
8	3.2	3.1	8.9	3.4
9	6.7	5.9	4.9	6.4
10	6.6	1.8	3.8	1.6
11	2.2	2.4	2.8	2.2
12	5	5	5.4	5

Key:
N = Participant ID number
CON = Control
AIS = Active Isolated Stretching
DF = Dynamic Flexibility

Participant Stride Length Data

N	CON	AIS	SS	DF
1	2.20	2.21	2.23	2.23
2	2.19	2.21	2.21	2.20
3	2.17	2.28	2.23	2.29
4	2.03	2.04	2.07	2.06
5	2.37	2.38	2.41	2.34
6	2.25	2.27	2.24	2.28
7	1.96	2.00	2.03	2.04
8	2.09	2.10	2.12	2.13
9	2.03	2.00	2.02	1.96
10	2.25	2.26	2.22	2.25
11	2.31	2.34	2.37	2.35
12	2.35	2.32	2.32	2.36

Participant Heart Rate Data

N	CON	AIS	SS	DF
1	171	168	174	172
2	175	176	177	173
3	162	159	164	153
4	158	161	170	169
5	173	171	178	166
6	173	170	177	171
7	162	166	163	161
8	176	175	188	176
9	180	171	183	178
10	162	165	161	159
11	149	150	155	146
12	162	173	179	173

Key:
N = Participant ID number
CON = Control
AIS = Active Isolated Stretching
DF = Dynamic Flexibility

Participant Poststretching Heart Rate Data

N	CON	AIS	SS	DF
1	95	110	81	155
2	76	86	89	143
3	94	0	82	158
4	58	67	102	166
5	82	86	87	170
6	88	96	105	167
7	76	86	90	137
8	97	104	99	171
9	94	92	77	177
10	81	100	97	153
11	61	69	62	157
12	94	80	91	172

Participant Respiratory Exchange Ratio Data

N	CON	AIS	SS	DF
1	0.87	0.87	0.90	0.86
2	0.88	0.90	0.89	0.89
3	0.86	0.87	0.90	0.89
4	0.87	0.90	0.88	0.88
5	0.85	0.88	0.89	0.91
6	0.90	0.90	0.88	0.90
7	0.85	0.87	0.87	0.84
8	0.90	0.89	0.88	0.94
9	0.93	0.87	0.89	0.86
10	0.86	0.81	0.82	0.84
11	0.87	0.86	0.87	0.86
12	0.87	0.86	0.86	0.89

Key:
N = Participant ID number
CON = Control
AIS = Active Isolated Stretching
DF = Dynamic Flexibility

Participant % VO_{2peak} Data

N	CON	AIS	SS	DF	Speed
1	84.41	86.51	84.00	87.59	7
2	93.86	91.10	91.55	94.38	8
3	79.28	76.52	77.75	77.67	7.5
4	77.12	78.32	78.67	79.37	7
5	81.61	78.96	80.60	80.76	6.5
6	77.01	77.46	79.24	78.99	7.5
7	83.03	83.66	82.73	85.47	6.5
8	76.16	79.55	77.98	77.83	6.5
9	83.77	83.67	82.22	85.47	8.5
10	76.68	80.85	77.09	77.66	7.5
11	76.05	78.29	77.26	79.65	6.5
12	82.50	82.38	83.03	80.97	6.5

Speed in mph

Descriptive Data

N	Age	Weight	Height	VO_{2max}	Peak Lactate	Miles Run/Week
1	33	54.5	62	49	9.3	30-50
2	42	55.1	67.5	56	9.8	25-35
3	27	60.5	67	57	8.9	0
4	24	57.7	63	51	11.2	13
5	20	66.5	65	49	10.7	10
6	22	67	63.1	53	13	10
7	39	64	54	48	9	25-35
8	20	53.7	63	48	12.7	2
9	23	43.5	63	58	11	35
10	24	55.4	66	53	2.9	15-25
11	25	58.5	66	53	9	15-20
12	23	57.8	65	45	10.7	6-8

Age in years; Weight in kg; Height in cm; VO_{2max} in $ml{\cdot}kg^{-1}{\cdot}min^{-1}$; Peak Lactate in $mmol{\cdot}L^{-1}$

Key:
N = Participant ID number
CON = Control
AIS = Active Isolated Stretching
DF = Dynamic Flexibility