THE EFFECT OF SHOE-LACING PATTERN ON RUNNING ECONOMY IN DIVISION-I ENDURANCE ATHLETES

By

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ABSTRACT

The purpose of this study was to assess the effect of different shoe-lacing patterns on running economy (RE) in collegiate distance runners. Kenyan endurance runners (*N* = 9) at a Division I University in the southeast United States participated in this study. Oxygen consumption was collected using a MOXUS metabolic cart during submaximal running trials to determine RE during 4 lacing conditions. Lacing pattern was manipulated by adjusting the number and order of eyelets laced in relation to a control condition. There was no significant difference in RE across the lacing conditions. Based on these findings, elite collegiate runners can be encouraged to lace their shoes in the pattern perceived as most comfortable without altering their RE.

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CHAPTER I

INTRODUCTION

Running economy (RE) is defined as energy expenditure or oxygen consumption (VO_2) at a submaximal, steady-state pace (Barnes, McGuigan, & Kilding, 2014; Saunders, Pyne, Telford, & Hawley, 2004). Physiology, anthropometry, training, environmental conditions, and biomechanics influence RE (Barnes et al., 2014; Shaw, Ingham, & Folland, 2014). Understanding RE is valuable for endurance and long distance running athletes because RE is the single most influential factor when predicting endurance running performance and success (Barnes & Kilding, 2015; Burgess & Lambert, 2010; Di Michele & Merni, 2014; Saunders et al., 2004). Running economy is measured at 50-70% of an individual's maximal oxygen consumption ($VO_{2\ max}$; Saunders et al., 2004). Trials are typically performed on treadmills using a metabolic cart to measure and record respiratory exchange ratio (RER) and oxygen consumption (VO_2).

Biomechanics is the combination of kinematics and kinetics of the human body during activity. Biomechanics of an endurance runner depend on an individual's gait, running style, kinematics, neuromuscular, and muscular properties. Gait analysis is used clinically as a functional assessment and diagnostic tool. There are three phases of gait: initial contact, stance phase, and swing phase (Cavanagh, 1987; Dugan & Bhat, 2005; Novacheck, 1998). A running gait includes another phase called the "float" phase where there is no ground contact. Speed and biomechanics during gait can determine energy cost, thus affecting RE (Dugan & Bhat, 2005)

Kinematics is the study of motion and movements, while kinetics is the study of forces creating and affecting kinematic patterns. Measurable kinematic variables of gait most commonly evaluated, manipulated, and recognized as factors affecting RE include the following: Ground reaction force (GRF), ground contact time (GCT), swing time (ST), stride length (SL), stride frequency (SF), and stride angle (SA). Generally, decreased GCT, freely chosen SL and SF, and decreased SA are kinematic indicators of improved biomechanical efficiency and better RE (Dugan & Bhat, 2005; Novachek, 1998; Santos-Concejero et al., 2014). Running style may contribute to natural variation of these factors.

Running style, or strike-type, is the pattern of how an individual strikes his or her foot on the ground while running. There are three different strike-types: rear-foot, mid-foot, and fore-foot. Rear-foot running is the most common strike-type for endurance runners (Novachek, 1998). Many elite endurance athletes are fore-foot strikers, but numerous studies indicate no difference in RE between fore-foot and rear-foot strike types (Di Michele & Merni, 2014; Gruber, Boyer, Derrick, & Hamill, 2014; Stearne, Alderson, Green, Donnelly, & Rubenson, 2014). Running style and kinematics are largely dependent on a runner's bone structure, neuromuscular adaptations, and muscular properties. Another factor that may influence running style and kinematics are shoe properties and lacing patterns.

Shoe fit around the foot and the amount of motion of the foot within the shoe will alter effectiveness of the supposed advantages to RE from shoes. Lacing tightness and patterns are manipulated for clinical and functional purposes. Lacing variations can improve shoe fit-to-foot, optimize biomechanical assistive components of footwear, and improve perceived comfort and stability (Hagan & Hennig, 2009; Hagan, Homme, Umlauf, & Hennig, 2008; Hong, Wang, Xian Li, & He Zhou, 2011). There is not ample evidence about shoe-lacing manipulation and its direct effect on RE, but some research has shed light on the effect of shoe-lacing on biomechanical efficiency. Shoe-lacing manipulation has produced biomechanical changes in favor of decreased energy cost and increased biomechanical efficiency, which improves RE. This justifies the necessity to investigate the relationship between shoe-lacing and RE.

Lacing pattern is manipulated by adjusting the amount and order of eyelets used. Previously manipulated lacing patterns for runners includes: bottom two eyelets laced (EYE12), 1st-3rd-5th eyelets laced (EYE135), all eyelets except for 6th eyelet laced (EYE57), and all 7 eyelets laced (ALL7); (Hagan et al., 2008; Hagan & Hennig, 2009). Notable differences between the lacing patterns occurred in relation to perceived comfort, dorsal pressures, kinematics, and kinetics (Hagan et al., 2008; Hagan & Hennig, 2009). Running economy can be affected positively or negatively depending on which biomechanical factors change.

Purpose Statement

The purpose of this study was to assess the effect of different shoe-lacing patterns on RE in collegiate distance runners.

Hypothesis

Different shoe-lacing patterns will affect RE in collegiate distance runners.

Delimitations

Participants were all of Kenyan origin and had all been training and competing at a Division I University in the Southeast United States for the entirety of the previous academic year. Individuals were not treating or rehabilitating an active injury, and each athlete had not experienced any orthopedic injury within the last 12 months. Participant’s medical history did not include asthma or other cardiovascular-related health problems. All participants were familiar with treadmill running or were given instruction and practice time on treadmills to become accustomed. All participants habitually train without orthotics or inserts.

Limitations

Results may only be generalized to runners at the same fitness level as those included in this sample, runners of Kenyan origin, and those running in shoes of similar weight and composition.

CHAPTER II

LITERATURE REVIEW

Running Economy

Running economy is defined as energy expenditure or VO_2 at a submaximal, steady-state pace (Barnes et al., 2014; Saunders et al., 2004). Steady-state refers to a submaximal running pace when the body is using aerobic metabolic processes to produce energy. Running economy is directly related to success as an endurance or long distance athlete (Barnes et al., 2014; Burgess & Lambert, 2010; Di Michele & Merni, 2014; Saunders et al., 2004). Running economy may be affected and manipulated through physiological, environmental, anthropometric, biomechanical, and training interventions.

Measurement of RE. Running economy is measured at a submaximal pace, approximately 50-70% of an individual's $VO_{2\ max}$. When measured at intensities greater than 85% of a trained endurance athlete's $VO_{2\ max}$, RE will not be accurate (Saunders et al., 2004). Most submaximal tests to determine RE include a series of 2-9 running trials at varying intensities lasting 3-5 minutes (Hanson, Berg, Deka, Meedering, & Ryan, 2011; Saunders et al., 2004; Shaw et al., 2014). The individual will run at a pre-determined steady-state pace based on $VO_{2\ max}$ measurements, velocity at $VO_{2\ max}$ ($vVO_{2\ max}$), or time trials of specific distances.

Submaximal protocols can be used to measure lactate accumulation, VO_2, RER, and estimate energy expenditure or cost. Lactate accumulation is measured by retrieving a capillary blood sample typically taken from the earlobe or fingertips (Shaw et al., 2014). Oxygen consumption and RER are measured using a metabolic cart. Treadmill running with a metabolic cart is a common mode used to measure RE, but portable options for VO_2 measurement are available too (Saunders et al., 2004).

Importance of RE. Running economy is the single most influential factor when predicting endurance running performance and success (Barnes & Kilding, 2015; Burgess & Lambert, 2010; Di Michele & Merni, 2014; Saunders et al., 2004). Maximal oxygen consumption values are associated with running success, but not as strongly as RE values. Endurance running consists of events from the 800M to the marathon. Endurance athletes can be divided into two categories: middle distance and long distance. Middle distance running is defined by competition lengths less than 3,000M; 800M, 1,000M, and 1,500M are some of these track events. Long distance running is defined as competition lengths greater than or equal to 3,000M; 5,000M, 8,000M, 10,000M, and marathons are within this class of running. A value like RE that can be measured to predict success is crucial to those training or aspiring to train for elite competition globally. Also crucial to success is to understand variables that affect RE, and how to manipulate these variables to improve RE.

Factors Affecting RE

Running economy can be affected by multiple factors. Physiology, anthropometry, training adaptations, environmental conditions, and biomechanics all influence RE (Barnes & Kilding, 2015; Shaw et al., 2014).

Physiological factors impacting RE. Blood lactate level, VO_2, energy cost, and RER are physiological factors affecting RE. These factors may be increased or decreased through training, environmental factors, or anthropometric influences. Changes in these values will elicit changes in RE.

Blood lactate level measurements indicate lactate present in the blood. Lactate accumulates when the amount of lactate produced exceeds the amount of lactate that the body is able to clear. This event occurs when the individual is no longer able to maintain steady-state aerobic exercise. Blood lactate levels greater than 8 mmol indicate that the individual is no longer predominately producing energy using aerobic metabolism (McArdle, Katch, & Katch, 2010). At this time, the individual is no longer running at a submaximal pace and RE assessment is compromised. Elite endurance athletes train to delay the onset of lactate accumulation.

Oxygen consumption is the amount of oxygen uptake during activity. Oxygen consumption has been shown to be independent of speed, whereas energy cost seems to increase as speed increases (Shaw et al., 2004). Energy cost is the amount of effort metabolically put forth for a given distance. Strictly measuring $VO_{2\,max}$ is not the best predictor of running success. Submaximal VO_2 is measured in conjunction with RER and heart rate (HR) values for RE calculations. According to Shaw et al. (2014), it may be necessary to start assessing underlying energy cost as another component of RE instead of depending on VO_2 alone for RE measurement.

Respiratory exchange ratio is a value that expresses the primary substrate, carbohydrates or fats, being metabolized for energy. Resting RER is approximately 0.70, indicating the main energy source comes from fat combustion. An RER above 1.0 indicates the individual is no longer at steady-state and the primary source of energy is carbohydrate. During a submaximal protocol to assess RE, it is important to monitor values and discontinue testing if the RER exceeds 1.0.

Anthropometric variables impacting RE. Genetics and body-type influence athletic performance and RE. Successful endurance runners typically have a narrow build at the hips and shoulders with smaller limb girth and a low body fat percentage; this physique is classified as ectomorphic (McArdle et al., 2010). Allometric measurements predicting endurance success are commonly reported in the literature about Kenyan runners with consistently low body mass, low body fat, and long, slender limbs (Kong & de Heer, 2008; Mooses et al., 2013). Body mass distribution has been recognized to affect middle distance runners more-so than long distance runners, and it has an inverse relationship to RE (Mooses et al., 2013).

The musculoskeletal system has fast-twitch, slow-twitch, and intermediate muscle fibers. Depending on the physical activity demand, an individual may need to recruit more of one muscle fiber type than another muscle fiber type to perform his or her specific running event. Fiber type distribution is correlated to RE (Hunter et al., 2011). Individuals with a higher percentage of slow-twitch fibers are at an advantage for endurance running events (McArdle et al., 2010). Endurance runners with more intermediate and fast-twitch fibers will be more suited to middle distance events versus long distance events.

Independent of muscle fiber type are muscular-tendon elasticity and flexibility elements of muscles, and these components have an inverse relation to RE (McArdle et al., 2010). Decreased flexibility in endurance runners improves RE, but tighter muscles and joints also correlate with higher injury rates which may affect training and RE (Barnes et al., 2014; Barnes & Kilding, 2015). Per its location and affect on human movement and gait, the Achilles tendon structure and properties are commonly studied in endurance runners. The moment arm of the Achilles tendon is the distance horizontally from the malleoli to the posterior aspect of the Achilles (Barnes et al., 2014). A longer moment arm and increased tightness are preferred, because the length provides more opportunity for energy storage, and the tightness allows for efficient energy transfer from potential energy (PE) to kinetic energy (KE) for forward progress (Barnes et al., 2014; Kunimasa et al., 2014).

Environmental factors impacting RE. The environment in which a person trains and competes may affect RE. Altitude is the most influential environmental factor affecting VO_2 and RE. There is a lower partial pressure of oxygen at higher altitudes. It is assumed that living in hypoxic environments, conditions with limited oxygen, will result in adaptations that improve oxygen delivery and consumption. Hypoxic training or living environments are incorporated into training programs for this reason (Barnes & Kilding, 2015). It is theorized that one reason Kenyan runners are successful endurance athletes is because of the high altitude at which they live and train (Kong & de Heer, 2008).

Environmental factors also include general outdoor weather conditions. It can be more difficult for the respiratory system to filter hot and humid air if the individual is used to breathing cold and dry air and vice versa. This can affect ease of oxygen delivery, which can increase metabolic cost and affect VO_2. In addition to air temperature and moisture values, more energy is required to run into the wind (McArdle et al., 2010). Being acclimatized to most inclement weather will make a person more economical in that setting versus training in one condition and racing in another. The same concept applies to those running on specific surfaces. Trails, concrete, blacktop, grass, and tracks produce different GRF that may affect RE directly, or indirectly, through biomechanical adaptations.

Impact of training on RE. Specificity dictates the most effective training mode for endurance runners is long distance running. However, literature highlights benefits of strength training for endurance athletes, especially for neuromuscular benefits (Barnes & Kilding, 2015; Piancentini et al., 2013; Saunders et al., 2006; Slawinski & Billat, 2004). Heavy strength training, resistance training, plyometric training, and high intensity interval training are all common strength programs used simultaneously with cardiovascular training to improve RE for endurance athletes.

Heavy strength training, also referred to as heavy weight training, indicates high loads and low repetitions at a certain percentage of an individual's measured one repetition maximum (1-RM), or the maximum weight an individual can lift one time for a specific lift. Heavy strength training will lead to increased strength and hypertrophy, or muscle size increases. Heavy strength training may be useful initially for untrained runners to gain neural adaptations beneficial to running biomechanics (Barnes & Kilding, 2015). Neural adaptations present as increased motor neuron recruitment and improved firing patterns within the muscles. Increased muscle recruitment improves ease of locomotion and decreases energy cost to result in improved RE. Heavy strength training should be implemented carefully and sparingly for long distance running populations to avoid excess weight gain that may be detrimental to RE. Strength-endurance training occurs via resistance training programs and plyometric programs with lower loads and higher repetitions during lifting. Resistance training will increase strength and improve neural adaptations without excessive hypertrophic effects and weight gain that heavy strength training causes. For this reason, it is acknowledged that short-term resistance training can be beneficial for endurance runners (Piancentini et al., 2013).

Plyometric training is a form of resistance training that incorporates explosive and quick movements to improve strength and neural adaptations. Improvements in RE with less hypertrophic changes than other strength training methods have been observed during plyometric training programs (Saunders et al., 2006). High intensity interval training is a training program combining strength training at intensities >85% 1-RM and cardiovascular exercises at velocities greater than an individual’s steady-state pace (Denadai, Ortiz, Greco, & de Mello, 2006; Ferley, Osborn, & Vukovich, 2014). Research indicates that high intensity interval training programs produce benefits similar to plyometric training adaptations in relation to muscle strength, muscle endurance, and neural adaptations that can elicit positive results concerning RE (Barnes et al., 2014). Interval training is not limited to the previous definition of a high intensity interval training workout and can include hill-running workouts. Hill-running workouts are a common addition in endurance training programs to incorporate strength and cardiovascular gains simultaneously (Ferley et al., 2014).

Endurance athletes perform long distance runs, tempo-runs at specific paces, or speed workouts on a track for cardiovascular benefits. Frequency, intensity, and duration of running and cardiovascular training performed can all affect performance in marathon events (Hagan, Smith, & Gettman, 1981). Endurance running training leads to aerobic system adaptations that cause improved RE. These physiological adaptations include increased left ventricular size, increased cardiac output, and increased aerobic enzymes and mitochondria count (McArdle et al., 2010). The literature about volume of cardiovascular training necessary to improve RE is not as consistent as with other training interventions like plyometric training, altitude training, or heavy strength training for neural adaptations. However, Saunders et al. (2004) determined there is a direct relationship between number of miles and workouts performed and RE improvement, respectively.

Running economy may be directly or indirectly affected by many factors. Researchers may manipulate factors related to anthropometrics, environmental conditions, or training to impact RE. Furthermore, biomechanical changes are frequently explored in the literature to determine the affects one or more biomechanical adjustments have on RE.

Biomechanical Factors Affecting RE

Biomechanics is the combination of kinematics and kinetics of the human body during activity. Biomechanics of an endurance runner depend on an individual's gait, running style, kinematics, and neuromuscular and muscular properties. The biomechanics of running primarily includes lower extremity dynamics, but also encompasses upper extremity movement and core stabilization (Novacheck, 1998). Biomechanical variables may be altered depending on running style and strike-type. Male and female runners have different biomechanics naturally, but ultimately, the factors of biomechanics are uniform for all endurance-trained athletes (Barnes et al., 2014).

Gait. The gait kinematics of running populations have been extensively analyzed and manipulated by researchers. Gait analysis is used clinically as a functional assessment and diagnostic tool. Improved equipment has enhanced gait study, but the general components and description of gait have remained the same. There are three phases of gait: initial contact, stance phase, and swing phase (Cavanagh, 1987; Dugan & Bhat, 2005; Novacheck, 1998). Initial contact is the point at which one foot comes into contact with the ground. Stance phase describes the time the foot remains in contact with the ground. During the stance phase, PE is transferred to KE to propel an individual's center of gravity forward. The swing phase begins when the involved foot leaves the ground after toe-off of the stance phase. The swing phase ends as the same foot comes into contact with the ground and begins a new gait cycle (Cavanagh, 1987; Dugan & Bhat, 2005; Novacheck, 1998).

Gait varies based on the velocity of the center of gravity. Slower velocities characterize a walking gait, and faster velocities transition into a running gait. A running gait includes another phase called the “float” phase wherein there is no ground contact. The float phase increases the limb movement and muscular forces required for biomechanical efficiency (Dugan & Bhat, 2005; Novachek, 1998). Biomechanical efficiency is the amount of mechanical energy spent to yield specific results. Speed and biomechanics during gait can determine energy cost (Dugan & Bhat, 2005). Increased energy cost during gait as a consequence of poor biomechanics can result in decreased biomechanical efficiency, and results of this will be unfavorable to RE.

Kinematics and kinetics. Kinematics is the study of motion and movements. Kinetics is the study of forces creating and affecting kinematic patterns. Measurable kinematic variables of gait most commonly evaluated, manipulated, and recognized as factors affecting RE include the following: GRF, GCT, ST, SL, SF, and SA. Ground reaction forces are the absorption and propulsion forces observed during the stance phase of gait (Novachek, 1998). The length of time spent in the stance phase is GCT. Stride length is the distance from initial contact of one foot to the next point of contact that same foot makes with the ground. Stride time is the time spent in swing phase of gait when the foot is not in contact with the ground (Dugan & Bhat, 2005). Stride length should not be confused with step length, which is the distance from one foot’s contact with the ground to the opposite foot’s contact point with the ground (Dugan & Bhat, 2005). Stride frequency, also known as cadence, is the number of steps in a given period of time measured as steps per minute (Dugan & Bhat, 2005; Novachek, 1998). Stride angle is the tangent created by making a parabola from initial contact point to initial contact point of a stride during swing phase (Santos-Concejero et al., 2014). To date, it is the least studied kinematic variable of gait. These kinematic variables of an endurance athlete are each affected by individual gait and kinetics of the muscles responsible for ambulation. Each factor can be manipulated and affect RE positively or negatively (Cavanagh, 1987; Dugan & Bhat, 2005; Novacheck, 1998).

Ground reaction forces include all PE and KE transferred, used, or lost while the foot is in contact with the ground. As running velocity increases, the GCT will decrease (Chapman et al., 2012). Trained endurance runners with less GCT have better biomechanical efficiency to indicate improved RE (Santos-Concejero et al., 2013). However, increased GCT at a slow pace has also elicited improved RE for endurance runners (Di Michele & Merni, 2014). These data appear contradictory, but the difference in speed renders these studies incomparable. It can be concluded that less GCT at faster velocities in elite endurance trained athletes generates improved RE. It is undisputed in the literature that a freely chosen SL renders the best RE (Barnes et al., 2014; Cavanagh, 1987; Dugan & Bhat, 2005; Saunders et al., 2004). Stride length and SF change simultaneously. As a runner’s SF increases, SL will decrease (Cavanagh, 1987). Freely chosen SF can also be assumed most economical because SF consistently varies inversely to SL. As SA increases, vertical momentum increases. Excess vertical motion, or vertical oscillation, is not economical because this indicates the individual is using energy to move the center of mass up rather than advancing the center of mass forward

(Cavanagh, 1987; Saunders et al., 2004). In support, Santos-Concejero et al. (2014) determined that decreased SA indicates better RE.

Decreased GCT, freely chosen SL and SF, and decreased SA are kinematic indicators of improved biomechanical efficiency and better RE. However, within these kinematic variables comes variation due to individual running style and strike-type.

Running style and strike-type. Running style, or strike-type, is the pattern of how an individual strikes his or her foot on the ground while running. There are three different strike-types: rear-foot, mid-foot, and fore-foot. Rear-foot runners strike the ground with the heel and then the entire foot rolls through and contacts the ground before toe-off of gait. Mid-foot runners strike in the middle of the foot and then advance into toe-off. Fore-foot runners strike and then push off from the ball of the foot. Rear-foot running is the most common strike-type for endurance runners (Novachek, 1998). There are mixed results in the literature about which running style is most economical.

Endurance athletes running barefoot or raised in barefoot societies are usually fore-foot runners (Kasmer, Ketchum, & Liu, 2014). A fore-foot strike type generates less impact peak. Impact peak is the highest measurement of GRF accumulated at a given time during the stance phase of gait. Decreased impact peak is an indicator of good RE (Perl, Daoud, & Lieberman, 2012). It is assumed fore-foot strikers have more elastic recoil in the Achilles tendon at initial contact and therefore utilize PE and elastic energy with more biomechanical efficiency (Di Michele & Merni, 2014). This brings into question whether no shoes or specific types of shoes influence a person to run fore-footed, and in theory, improve RE. Many elite endurance athletes are fore-foot strikers, but numerous studies indicate no difference in RE between fore-foot and rear-foot strike types (Di Michele & Merni, 2014; Gruber et al., 2014; Stearne et al., 2014). Hasegawa, Yamauchi, and Kraemer (2007) studied elite 15,000M runners during a competition and split the sample into groups. Strike-type differences were apparent when comparing groups of the faster runners to the slower runners. There was a higher percentage of mid-foot strike-type in the fast runner groups compared to the slow runner groups, collectively. However, it was not confirmed that better RE and faster times were due to strike-type of the top runners in this sample.

A rear-foot strike-type is the most common running style for long distance runners (Perl et al., 2012). Most running shoes are made to assist rear-foot striking patterns by adding more cushioning and support in the heel where initial contact and impact forces are made with the ground (Hasegawa et al., 2007). Theoretically, the cushion will minimize impact from GRFs. This could be negative for RE if the cushioning absorbs energy that could be used to propel the runner forward. Alternately, this could be positive for RE in that the runner's muscles are no longer responsible for work related to shock absorption. Rear-foot runners spend more time in contact with the ground, and this has been strongly related to an impaired RE (Di Michelle & Merni, 2014; Perl et al., 2012). Running style and strike-type are still being explored within research. Many variables need to be controlled to isolate results in studies about the relationship between running style and RE. However, within the current literature, it is suggested that footwear has a large influence on strike-type.

Neuromuscular adaptations and muscular properties. Running style and kinematics are largely dependent on a runner's neuromuscular adaptations and muscular properties. These adaptations refer to neural connections within the leg muscles for motor unit recruitment and muscle activation. Lower extremity neuromuscular adaptations take precedence over upper extremity importance with respect to RE. Biomechanical efficiency also depends on specific muscle properties that contribute to potential energy transformation. Elasticity and tension properties of a muscle refer to the amount, or lack of, stretch and flexibility of a muscle. The more PE that can be transferred into KE through the musculo-tendonous units of the lower body, the greater the improvement in RE (Barnes et al., 2014; Saunders et al., 2004).

Kinetics and kinematics at the lower extremity are heavily dependent on individual ambulatory patterns and muscular properties. The gait cycle's universal components can vary individually, especially because of the different strike-type variations that runners adopt. Strike-type and gait patterns are influenced by individual foot and ankle anatomy as well as footwear utilized during youth and initial running years.

Anatomy and Footwear Effects on Biomechanics at the Foot and Ankle

The foot is the first point of contact for the kinetic chain of the body during movement (Dugan & Bhat, 2005). Gait, kinematics, kinetics, and running style at the foot and ankle can be affected by the anatomy of the foot and footwear, which can affect RE.

Anatomy of the foot and ankle. Bone, muscle, tendon, and ligaments of the foot and ankle initiate and complete gait mechanics. The ankle is composed of three joints: talocrural, subtalar, and distal tibiofibular. Four bones meet to create the three joint structure of the ankle: the talus, calcaneus, tibia, and fibula. Ligaments on the medial and lateral aspect of the ankle serve as passive stabilizers (Dugan & Bhat, 2005). Muscles originate from the lower leg and insert as tendons at the foot and ankle to act as active stabilizers and movers. Tendons are the endpoint of muscles and attach onto bones to absorb and transfer energy during movement (Novachek, 1998). The primary motions performed at the ankle during gait are dorsiflexion and plantar flexion. The foot is described as divided into three sections: hind-foot, mid-foot, and fore-foot. The hind-foot refers to the calcaneus and talus. The mid-foot is composed of tarsal bones. The forefoot includes the metatarsals. The primary motions at the foot during gait are eversion and inversion, or pronation and supination (Dugan & Bhat, 2005).

*Movement of the foot and ankle during gait. S*ubtalar plantar flexion and dorsiflexion range of motion renders the subtalar ankle joint responsible for plantar pressure control and impact on the heel (Dugan & Bhat, 2005). Plantar pressure and heel impact are initial indicators of the amount an individual will pronate or supinate. As the ankle is dorsiflexed in stance phase, the arch is absorbing shock and pronation occurs eccentrically via the posterior tibialis and gastrocnemius-soleus complex. The foot ends stance phase in supination because of the "lock" mechanism of the foot bones. Ultimately, lower leg and foot muscles assist in propulsion of the body forward (Dugan & Bhat, 2005; Novachek, 1998). Too much pronation and shock absorption may lead an individual to enter supination and the lock phase too late, and this is why hyperpronation results in excess metabolic cost (Novachek, 1998). Too much or too little of one motion or movement within the foot and ankle can change biomechanics and affect RE positively or negatively.

Running shoe effect on biomechanics and RE. Shoe requirements for endurance athletes are unique per the individual based on his or her foot anatomy, kinematics, and strike-type (Novachek, 1998). Footwear characteristics that can affect RE include shoe mass, motion control, drop height, sole cushioning, midsole viscoelasticity, longitudinal bending stiffness, and perceived comfort (Fuller, Bellenger, Thewlis, Tsiros & Buckley, 2015). Shoe mass is a popular characteristic analyzed in relation to RE. Each 100g of additional weight added to the foot will increase VO_2 by 1% while running, barefoot or shod (Franz, Wierzbinski & Kram, 2012; Hanson et al., 2011). The increased VO_2 demand translates to an increase in RE, a negative side effect. Minimalistic running is favored, in part, due to the direct relationship between decreased shoe mass and improved RE, but there is no metabolic advantage when comparing minimalist running to shod running in lightweight, cushioned shoes (Franz et al., 2012). Running barefoot or in minimalist shoes, especially without experience, can significantly alter kinematics and kinetics at the foot and ankle which may be detrimental to metabolic cost, thus affecting RE negatively (Rao, Chambon, Gueguen, Berton, & Delattre, 2015). Finding a lightweight shoe to manipulate via shoe lacing techniques for improved RE would be beneficial.

Motion control at the hind-foot and the mid-foot are benefits of athletic shoes (McPoil, 2000). Orthotic intervention is implemented to decrease rear-foot eversion angle and internal ankle movement or pronation (MacLean, Davis, & Hamill, 2006). Orthotics and certain shoe styles may raise the heel. Elevated heels can alter lower limb and back muscle kinetics and change neuromuscular control (Murley, Landorf, Menz, & Bird, 2009). These kinematic and kinetic changes via neuromuscular control could be assumed to alter RE negatively due to excess energy cost. Some shoes and orthotics have drop height. Drop height is the distance from the ground to an elevated heel in relation to the distance from the ground to the surface of the sole at the forefoot. An increase or a decrease in drop height can affect biomechanics and foot-strike patterns. Eccentric contractions stabilize the foot each time it comes into contact with the ground during gait. An individual that needs more eccentric contraction and control to maintain optimal positioning of the foot expends more energy. Thus, the individual increases energy cost, decreases biomechanical efficiency, and compromises RE (Dugan et al., 2005). Shoes and footwear may support and provide motion control to decrease energy demand and eccentric contractions necessary, thus improving RE.

The midsole is the portion of the shoe between the upper of the shoe and the outsole (McPoil, 2000). Midsole cushioning can attenuate impact and provide shock absorption during the stance phase, but it can take away from sensory perception at the foot (McPoil, 2000). Additionally, midsole cushioning may dissipate PE that could have been transferred to KE to propel the runner forward. The term midsole viscoelasticity is used to describe the ability of these materials to absorb and return energy (McPoil, 2000).

Heat and friction created while running can degrade viscoelastic properties and decrease energy return characteristics, thus changing the shoe and affecting energy demands of the foot (McPoil, 2000). Because of the elastic properties the midsole possesses, the durability of materials making up the midsole can affect bending stiffness. Midsole longitudinal bending stiffness is the amount of flexibility allowed by the sole of the shoe. This characteristic has the most effect on the forefoot and the 1st metatarsal joint during toe-off in stance phase (McPoil, 2000). Roy and Stefanyshyn (2006) found a U-shaped curve represents the relationship between midsole bending stiffness and RE. This indicates there is an optimal amount of midsole stiffness, and too much or too little will be detrimental to RE (Roy & Stefanyshyn, 2006).

Most footwear characteristics mentioned may be altered independently and have further affects, positively or negatively, towards RE. Shoe fit around the foot and the amount of motion of the foot within the shoe will alter effectiveness of the supposed advantages to RE from shoes. There is not ample evidence and research about shoe-lacing manipulations and their direct effect on RE, but some research has shed light on the effect of shoe-lacing on biomechanical efficiency. Shoe-lacing manipulation produced biomechanical changes in favor of decreased energy cost and increased biomechanical efficiency, which improves RE. This supports the need to investigate the relationship of shoe-lacing to RE.

Shoe-lacing and RE

Lacing tightness and patterns are manipulated for clinical and functional purposes. Lacing variations can aid in injury rehabilitation and prevention, improve shoe fit-to-foot, optimize biomechanical assistive components of footwear, and improve perceived comfort and stability (Hagan et al., 2008; Hagan & Hennig, 2009; Hong et al., 2011). Lacing techniques for clinical purposes focus on different patterns to adjust foot structure and pressures to relieve pain and discomfort. Lacing techniques for functional purposes like endurance running are manipulated via tightness of lacing or number and placement of eyelets used (Hagan et al., 2008; Hagan & Hennig, 2009). Most literature about the relationship of shoe-lacing and running is directly related to the affect on biomechanical factors, and indirectly related to affects on RE. The direct relationship of shoe-lacing manipulation to RE should be explored to seek RE improvement via footwear variation without changing the shoe type or adding shoe mass.

Lacing tightness. Hagan et al. (2008) and Hagan and Hennig (2009) manipulated tightness by using a 6-eyelet pattern and instructing participants to lace shoes in regards to three classes of pull: weakest (WEAK6), regular (REG6), and tightest (TIGHT6). Tightness, or the amount of tension and pull on the shoelaces, was measured subjectively by perceived participant comfort. Hagan and Hennig (2009) investigated lacing affects on shock attenuation, rear-foot motion, and perceived stability and comfort of 20 experienced and symptom-free male rear-foot striking runners. Hagan et al. (2008) investigated dorsal pressures and perceived comfort of 14 experienced male rear-foot striking runners.

In the Hagan and Hennig (2009) study, TIGHT6 lacing produced the lowest amount of shock attenuation and rear-foot pronation. It was perceived as the most stable, but not the most comfortable. The TIGHT6 results had a better foot-in-shoe coupling dynamic, which is a good indicator of RE improvement (Hagan & Hennig, 2009). Regular tightness resulted in the same decreased rear-foot pronation as TIGHT6, but REG6 did not provide decreased shock attenuation or significant increased stability (Hagan & Hennig, 2009). Results for WEAK6 lacing tightness were poor along all measured variables. Perceived comfort was lowest in the TIGHT6, and highest in REG6 runs. Ultimately, the TIGHT6 trials had the most biomechanical changes to positively affect RE.

The Hagan et al. (2008) results for the WEAK6 lacing provided poor outcomes for all variables measured, and these results are comparable to Hagan and Hennig (2009). Weak tension at the shoelace constructs a loose fit of the shoe to the foot. The looseness allows foot slippage in the shoe, especially at the rear-foot, and may increase energy cost of the muscles during swing phase to keep the shoe on the foot (Hagan et al., 2008). The REG6 lacing is missing some quality components that the TIGHT6 lacing provides biomechanically, but it does give ideal perceived comfort and stability ratings from participants that can contribute to improved RE. In other research, improved perceived footwear comfort has been shown to reduce VO_2, thus improving RE (Luo, Stergiou, & Worobets, 2009). Ultimately, the WEAK6 pattern consistently provided poor results and should not be pursued or utilized for optimal running performance. The Hagan et al. (2008) and the Hagan and Hennig (2009) results indicate TIGHT6 to be the optimal option in reference to biomechanical factors promoting greater efficiency such as decreased pronation and shock attenuation.

Hong et al. (2011) investigated lacing manipulation using elastic covers in place of shoelaces in a group of 15 young adult, male, amateur runners. The elastic covers negatively influenced tightness and fit-to-foot quality (Hong et al., 2011). Pronation increased, pressure decreased, and perceived comfort decreased with the elastic shoe covering versus traditional laces. These adaptations at the foot negatively affected RE. A study on shoe-lacing tightness in healthy, adult participants while walking documented that looser shoe-lacing results in plantar pressure changes and in-shoe displacement, which negatively affects RE (Fiedler, Stuijfzand, Harlaar, Dekker, & Beckerman, 2010). This same group of researchers inadvertently found that in-shoe displacement and pressure values varied and corresponded with eyelet usage in shoes dependent on whether 6 versus 7 eyelets were available and utilized. However, it should be acknowledged that these results were obtained during walking trials, not running.

Lacing tightness as a manipulated variable provides consistent results among different demographics and different levels of runners. Looseness is not recommended and will not be beneficial to biomechanical factors that can improve RE. Tight fit is superlative for best shoe fit-to-foot to provide ideal coupling for positive biomechanical adaptations during activity. Runners that see improvement with perceived comfort may not want to utilize tighter options if uncomfortable. In these cases, a regular perceived tightness class should be applied for best biomechanical adaptations and performance.

Lacing patterns. Lacing pattern is manipulated by adjusting the amount and order of eyelets used. Hagan et al. (2008) and Hagan and Hennig (2009) previously manipulated lacing patterns for runners with the following techniques: EYE12, EYE135, EYE57, and ALL7. Notable difference between the different lacing patterns occurred in relation to perceived comfort, dorsal pressures, kinematics, and kinetics (Hagan et al., 2008; Hagan & Hennig, 2009).

Hagan and Hennig (2009) used lacing patterns EYE12, EYE135, and ALL7 to analyze changes in perceived comfort, foot pronation, tibial acceleration, and plantar pressure during contact with the ground while running. The EYE12 pattern was least favorable. The EYE12 pattern's looseness resulted in poor perceived comfort, decreased biomechanical efficiency, and altered gait patterns in similar ways to the trials of WEAK6 lacing. Slippage of the entire foot in the shoe during gait caused an increase in rear-foot pronation and decreased perceived comfort. Participants increased plantar flexion of the foot and ankle during swing phase in an attempt to keep the shoe on the foot. This extra movement increases metabolic demand to yield disadvantageous effects on RE (Fiedler et al., 2010; Hagan & Hennig, 2009). The EYE135 pattern produced insignificant results for rear-foot pronation, dorsal pressures, and perceived comfort. While ultimate pronation distance was not significant, this lacing did show significantly increased pronation velocities. The ALL7 pattern resulted in lower loading rates and the best perceived comfort rating. The ALL7 lacing pattern appears to have provided a better custom fit of the shoe for better foot-to-shoe coupling to allow optimal utilization of shoe properties like midsole cushioning, heel counter, and mid-foot support (Hagan & Hennig, 2009).

Hagan et al. (2008) used lacing patterns EYE135, EYE57, and ALL7 to analyze changes in dorsal pressures, plantar pressures, and perceived comfort. The EYE135 manipulation provided insignificant results. The EYE57 and ALL7 conditions produced decreased dorsal pressure at the talus and navicular, decreased plantar pressure at the calcaneus, and improved perceived comfort. In addition, the EYE57 lacing pattern had higher perceived comfort ratings than the ALL7 pattern. While this particular study by Hagan et al. (2008) did not assess as many biomechanical variables as Hagan and Hennig (2009) did, it may be possible to assume that the EYE57 results are comparable to ALL7 values in the Hagan and Hennig (2009) study.

Hagan et al. (2008) and Hagan and Hennig (2009) provided evidence that the EYE57 and ALL7 patterns produced the best results for improved biomechanics among experienced male runners. The EYE135 pattern may not be detrimental to biomechanical efficiency, but it does not show significant results for improvement either. It can be assumed that foot motion and biomechanics are affected by shoe-lacing style.

Lacing tightness and shoe-lacing patterns can be manipulated to directly affect a variety of biomechanical properties and perceived comfort. The literature provides evidence supporting that tighter lacing improves fit-to-foot coupling, and certain lacing pattern styles can have similar or identical affects to influence biomechanical variables. If biomechanics are affected, RE can be affected positively or negatively depending on which biomechanical factors changed.

Conclusions

Running economy is the single most influential factor when predicting endurance running performance and success (Barnes & Kilding, 2015; Burgess & Lambert, 2010; Di Michele & Merni, 2014; Saunders et al., 2004). Because of this, endurance athletes are constantly seeking ways to improve RE. Physiology, anthropometry, training adaptations, environmental conditions, and biomechanics all influence RE (Barnes & Kilding, 2015; Shaw et al., 2014). Of these factors, there are numerous biomechanical variables that can be manipulated and changed to affect RE. Biomechanics of a distance runner depend on an individual's gait, running style, kinematics, and neuromuscular and muscular properties. Because the foot is the first point of contact for the kinetic chain of the body during ambulation, biomechanical components can be affected by the anatomy of the foot and footwear (Dugan & Bhat, 2005).

Footwear characteristics that can affect RE include shoe mass, motion control, drop height, sole cushioning, midsole viscoelasticity, longitudinal bending stiffness, and perceived comfort (Fuller et al., 2015). In regards to shoe mass, each 100g of additional weight added to the foot will increase VO_2 by 1% while running, barefoot or shod (Franz et al., 2012; Hanson et al., 2011). It is for this reason that finding ways to manipulate footwear for biomechanical advantages without adding shoe mass are necessary. Shoelaces are an essential component of shoes. Adjusting shoelaces adds no mass and can affect biomechanical variables like pronation, shock attenuation, dorsal pressures, and plantar pressures during running (Hagan et al., 2008; Hagan & Hennig, 2009).

Lacing tightness and patterns are manipulated for clinical and functional purposes. Lacing techniques for functional purposes like endurance running are manipulated via tightness of lacing or number and placement of eyelets used (Hagan et al., 2008; Hagan & Hennig, 2009). The literature provides evidence to support that increased lacing tightness can produce biomechanical results favorable to increased RE.

In addition to increased tightness, the literature indicates that the EYE57 and ALL7 manipulations may influence biomechanical variables in a manner that would improve RE.

Most literature about the relationship of shoe-lacing and running is directly related to biomechanical affects, and indirectly related to RE affects. This is the reason that the direct affect of shoe-lacing on RE should be explored. Thus, the purpose of this study was to assess the affect of different shoe-lacing patterns on RE in collegiate distance runners.

CHAPTER III

METHODS

Participants

Participants included male and female athletes from Division-1 National Collegiate Athletics Association (NCAA) Cross Country and Track and Field teams at a University in the Southeast. All participants compete in endurance running events between 800M to 10,000M in distance. All participants were Kenyan in origin and between the ages of 20 and 26 years. The athletes were all cleared for endurance running competition prior to the season by a team physician. A consent form was completed by each participant before the individual began any trials. Participants had all been training and competing at the University for at least the entirety of the previous academic year. The individuals were not in the process of treating or rehabilitating an active injury, and had not undergone any orthopedic surgery within the last 12 months. Participant's medical histories did not include asthma or other cardiovascular-related health problems. Participants were familiar with treadmill running and habitually train without orthotics or inserts daily.

Materials and Measurements

Height and body mass. Participant body mass and height were measured prior to each trial. Height was measured using a SECA (Germany) stadiometer to the nearest 0.1 cm. Body mass was measured using a Health O meter® Professionals (McCook, IL) scale to the nearest 0.1 kg. Participants wore shoes and lightweight running attire to control for clothing mass variation. A Polar HR monitor (Kempele, Finland) was used to record HR.

Footwear and lacing patterns. Nike Vomero running shoes worn during trials were team shoes given to the athletes at approximately the same time during the 2015 Outdoor Track and Field season. The original laces that came with the shoes were used for each participant. The three lacing manipulations were chosen based on previously performed research: EYE135, EYE46, ALL6 (see Figure 1). Slight modifications of lacing pattern conditions were made because the Nike Vomero shoe is a 6-eyelet laced shoe rather than 7-eyelet laced shoe. The EYE135 pattern laces 1st-3rd-5th eyelets bilaterally. The EYE46 pattern laces all eyelets except for the 5th. The ALL6 pattern laces each eyelet available bilaterally. The control pattern consisted of the bottom 5 eyelets bilaterally. Each runner performed 4 submaximal trials. The participants were instructed to tie shoe tightness to preference to eliminate variation due to perceived comfort. A random number generator from an online source was used to produce the randomized order for lacing manipulation trials.

Oxygen consumption. Participants ran on a motorized treadmill. An AEI Technologies Moxus Metabolic cart (Naperville, IL) was used to measure expired gases for measurements of $VO_{2\,max}$, $vVO_{2\,max}$, and RE. The metabolic cart provided VO_2 and RER. The metabolic cart was calibrated to known high and low values for CO_2 and O_2, and calibrated for volume. Environmental variables were entered into the program per manufacturer specifications. A V2 Hans Rudolph face mask was used to collect expired gases for each participant.

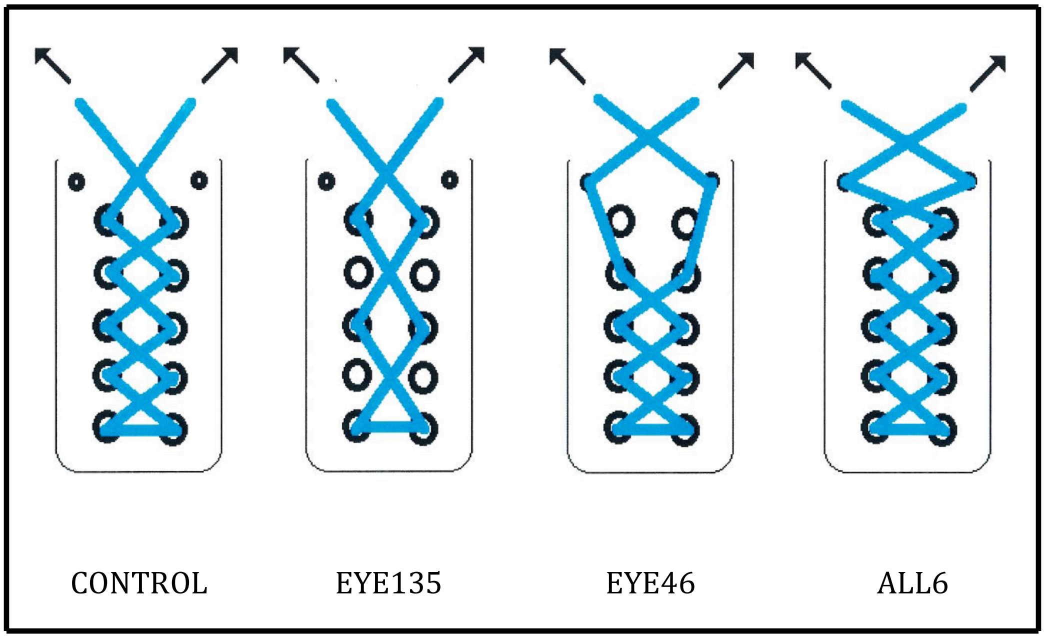

Figure 1. Running economy trial shoe-lacing manipulations. Adapted from “Effects of Different Shoe Lacing Patterns on Perceptual Variables and Dorsal Pressure Distribution in Heel-Toe Running,” by M. Hagan, A. Homme, T. Umlauf, & E. M. Hennig, 2008, *Journal of Foot and Ankle Research, 1*(Suppl. 1).

Maximal oxygen consumption. Maximal oxygen consumption was measured to determine $vVO_{2\ max}$, the speed at which the participant was traveling at the time $VO_{2\ max}$ was reached. The protocol by Hanson et al. (2011) in which 70% of $vVO_{2\ max}$ was used to predict RE trial paces was followed. During the VO_2 max protocol, individuals ran at an 80.5 m/min^{-1} pace initially and speed was increased by 26.8 m/min^{-1} every 2 minutes until the participant's HR reached 170 bpm. Once HR reached 170 bpm, the speed was increased every minute by 13.4 m/min^{-1} until the participant reached the point he or she could no longer continue physically, also known as volitional fatigue. Maximum oxygen consumption was considered achieved if the individual fulfilled at least two of the three criteria: HR within 10 bpm of maximum HR (age-220), RER value of 1.10 or greater, plateau of oxygen consumption measured via metabolic cart data. If $VO_{2\ max}$ was achieved, the $vVO_{2\ max}$ was determined at 60% to be used as the speed during submaximal trials. If a maximal value was not obtained, the participant was given the choice to remove his or herself from the study or come back at least 48-hours later to re-do the test. One participant did not achieve VO_2max on the first visit and elected to return for another attempt.

Submaximal oxygen consumption. The protocol selected for RE measurements was created by Morgan, Martin, Baldini, and Krahenbuhl (1990) and has been used subsequently for other submaximal testing. Treadmill grade was set to 1% because research indicates over ground running can be reproducible on the treadmill if 1% grade is used (Hanson et al., 2011). Submaximal trials were performed at 60% of vVO2max. Each lacing manipulation trial was performed, in random order, during the visit. Oxygen consumption was recorded every 10 seconds during the last 2 minutes of each trial to be averaged for accurate VO_2 recording. In addition, RER values were recorded during the last 2 minutes of each trial to assure values stayed below 1.0, indicating steady-state.

Procedures

Approval to collect data was obtained from the University Institutional Review Board (see Appendix A). Participants visited the laboratory on two or three occasions, at the same time of day. During the first visit, participants had the opportunity to acclimate his or herself to the treadmill if he or she wanted or needed to. After the participant felt comfortable, the maximal oxygen consumption test was run. If a maximal value was obtained, the data were used to determine the vVO_2max. If a maximal value was not obtained, the participant was given the choice to remove him or herself from the study or come back at another time to re-do the test. One participant did not achieve VO_2max on the first visit. The individual elected to return for another attempt, and the second VO_2max run was successful. For the second (or third) visit, each individual returned to the lab one week later at the same time of day for the submaximal runs with lacing manipulation conducted at a speed of 60% vVO_2max.

Running economy was obtained under 4 conditions: Standard 5-eyelet lacing for a control, EYE135, EYE46, ALL6 pattern (see Figure 1). Lacing patterns were adjusted by the researcher in between submaximal trials during a 5-minute mobile rest period. Order of lacing pattern trials was selected via a random number generator. Participants were instructed for each trial to tie his or her own shoe to comfort in relation to tightness to control for variation due to perceived comfort of the participant. Before the first submaximal trial, the participants had a 6-minute warm up on the treadmill at a selected pace with his or her regular lacing method (Lavcanska, Taylor, & Schache, 2005). Submaximal trials lasted 6-minutes. Between trials, participants had a 5-minute mobile rest period in the exercise science laboratory followed by a 5-minute walking period at 3.0 mph on the treadmill. Participants could begin the next trial as long as HR was less than 120 bpm (Hanson et al., 2011). The four submaximal runs were performed consecutively.

Data Analysis

Statistical Package for the Social Science (SPSS) software was used for data entry and statistical analysis. Oxygen consumption for each lacing condition was analyzed using a repeated measures analysis of variance (ANOVA) to determine if there were statistical differences in RE among the 4 lacing conditions. Additionally, mean and standard deviation values were calculated. This allowed for each participant to serve as his or her own control for best assessment of the impact of different lacing manipulations on RE during the randomized trials. Because participants are all on the same team, doing the same training, staying on similar schedules, living in the same location, and all coming from the same origin ethnically, these demographic and specificity of training factors had minimal impact on results.

CHAPTER IV

RESULTS

Members of a NCAA Division I Cross Country and Track and Field team ($N = 9$) agreed to participate in this study. The sample included 4 males and 5 females. All participants are Kenyan and have been training for distance, or endurance, running at the Division I setting on the same training schedule for at least one year. Additional participant characteristics are available in Table 1.

There was no statistically significant difference in mean oxygen consumption values across lacing conditions, $F(3, 6) = 1.113$, $p = .415$. Oxygen consumption values by condition are displayed in Table 2.

Table 1

Participant Descriptive Statistics (N = 9)

	μ	*SD*
Age (years)	23	2
Height (cm)	167.1	6.0
Body mass (kg)	55.0	5.6
$VO_{2\ max}$ (ml/kg/min)	56.7	6.5

Note. $VO_{2\ max}$ = maximal oxygen consumption.

Table 2

Oxygen Consumption Measures For Lacing Conditions (N = 9)

Condition	μ	*SD*
Control	36.28	5.12
EYE135	37.58	3.99
EYE46	36.92	4.80
ALL6	37.16	4.60

Note. Control = 1st 5 eyelets laced bilaterally. EYE135 = 1st -3rd -5th eyelets laced bilaterally. EYE46 = all eyelets except for the 5th. ALL6 = each eyelet available laced bilaterally.

CHAPTER V

DISCUSSION

The purpose of this study was to investigate the effect of alterations in shoe-lacing pattern on RE in trained endurance athletes. In this sample of Kenyan runners, there was no significant variation in RE across the lacing conditions. The lacing condition with the most variation from the control in relation to mean oxygen consumption was EYE135 followed by ALL6 and EYE46, from worst to best RE respectively.

Lacing tightness and lacing patterns are manipulated for clinical and functional purposes (Hagan & Hennig, 2009; Hagan et al., 2008). The amount of motion of the foot in a shoe can alter biomechanical efficiency and perceived comfort. The lacing patterns investigated in this study were selected based upon previous research indicating changes in relation to perceived comfort, dorsal pressures, kinematics, and kinetics (Hagan & Hennig, 2009; Hagan et al., 2008). Lacing variations can improve shoe fit-to-foot, optimize biomechanical assistive components of footwear, and influence perceived comfort and stability without affecting mass of the shoe (Hagan & Hennig, 2009; Hagan et al., 2008; Hong et al., 2011). This is important because each 100g of additional mass can decrease RE by 1% (Hanson et al., 2011). In contrast to adding mass, lightweight footwear options take away shoe mass at the expense of optimal foot support in the shoe. To account for impact of shoe mass on RE, the same brand and model of shoe was used by all participants in this study.

Lacing patterns within this study are similar to those investigated in previous research, although patterns were altered in relation to previous pattern manipulations because a 6-eyelet shoe was used instead of a 7-eyelet shoe. In the current sample, the EYE135 lacing pattern was the loosest fitting manipulation. This implies that the EYE135 pattern allowed the most foot movement within the shoe as it provided minimal support and stabilization across the entire foot, especially at the heel. The EYE46 lacing pattern allows for less pressure on the dorsal aspect while keeping the heel secured. This lacing pattern is different from all others in that the shoelace inserts into the 6th eyelet from the dorsal aspect after skipping the 5th eyelet without crossing over the tongue of the shoe. The locking mechanism of this lacing pattern at the upper midfoot and ankle secures the heel in the shoe more than any other lacing variation in this investigation. The EYE46 lacing pattern may provide the security and motion control of higher lacing patterns without losing the potential for improved perceived comfort of a looser lacing configuration. The ALL6 lacing pattern laces all of the eyelets in the normal direction, from bottom to the top of the shoe. In relation to the entire foot, this pattern ends at the highest point of the foot and provides the tightest manipulation. The ALL6 pattern is second to the EYE46 configuration in relation to heel lock and securing the heel.

Within a running shoe, some fore-foot motion control is helpful, but the rear-foot and mid-foot move more during gait and require more control and assistance from the shoe (McPoil, 2000). As such, running shoes are typically built to assist rear-foot runners and rear-foot stabilization more than fore-foot runners. Thus, lacing patterns that support the heel and secure the ankle in the shoe have potential to be beneficial for biomechanics and RE during running. Because of this, rear-foot strike type may be influenced by lacing patterns more-so than fore-foot or midfoot strike-types. While the strike-type of the runners in the current sample was not analyzed, endurance athletes running barefoot or raised in barefoot societies are usually fore-foot runners (Kasmer et al., 2014). As the participants in this sample were all of Kenyan origin and were raised in barefoot societies, it may be assumed the runners in this sample are primarily fore-foot strikers.

Fore-foot strikers have more elastic recoil in the Achilles tendon at initial contact and therefore utilize PE and elastic energy to a greater extent (Di Michele & Merni, 2014). A fore-foot striker generates less peak impact force, and this is an indicator of better RE (Perl et al., 2012). The current result indicated that lacing patterns did not result in a significant variation in RE in the runners. This lack of significance may be associated with the current participants being highly trained and efficient at running fore-footed, thus minimizing measureable changes in RE across the lacing conditions.

The fit, or tightness of a lacing pattern, may impact perceived comfort. While the runners in our study were not asked about the impression of the comfort in each lacing pattern, other research indicates that perceived footwear comfort reduces VO_2, thus improving RE (Fuller et al., 2015; Hagan & Hennig, 2009; Hagan et al., 2008; Luo et al., 2009). During the study, it was observed that participants arrived with their shoes laced in the control condition (the first 5 eyelets laced). Because of familiarity, the current participants may have perceived this to be most natural and most comfortable. While not statistically different, submaximal mean oxygen consumption was lowest in the standard or control lacing pattern. Running economy measurements may have been impacted by an improved perceived comfort of the familiar look and feel of the control lacing pattern.

In contrast to the 5-eyelet control condition, the EYE135 lacing pattern may be considered the most different lacing pattern from the control, both visually and physically. The EYE135 pattern was the loosest lacing condition in the study, which has previously been associated with lower perceived comfort (Hagan et al., 2008; Hagan & Hennig, 2009). This study provides further evidence that perceived comfort is an important variable to consider with respect to RE. Participants in this study were all of Kenyan origin and typically use a variety of descriptors unfamiliar to the researcher's first language. However, perceived comfort would be an important factor to incorporate in further studies.

Though biomechanical variables were adjusted without affecting shoe mass or integrity, modifying lacing patterns had no significant effect on RE in this population of elite endurance athletes. Mean RE values in this study were similar, ranging only 1.3 ml/kg/min from the lowest to the highest condition (see Table 2). Kenyan runners are known to be successful distance running competitors. Their success is commonly attributed to various allometric measurements, the high altitude at which they live and train, a consistently larger movement arm of the Achilles tendon, and the tendency for Kenyan's to run fore-footed (Kong & de Heer, 2008; Mooses et al., 2013). It has been reported that approximately 50% of interindividual RE can be attributed to kinematic variables (Williams & Cavanaugh, 1987). The small variation in the results may be due to predisposed biomechanical efficiency of this population. More significant changes may present in a less-trained population of rear-foot or mid-foot strike-type runners with more room for biomechanical error in his or her natural running style. This study could also be performed with elite rear-foot strike-type endurance runners to assess whether lacing variation would alter RE in that population. A practical application of this study involves the emphasis on endurance athletes running in his or her footwear style of choice to increase perceived comfort, and ultimately improve RE.

Conclusion

The affect of lacing variation on RE rendered no significant results in these elite Kenyan endurance athletes. This indicates that elite endurance athletes should select whichever lacing style is most comfortable to the individual, in part this conclusion is based on previous literature about the significance of perceived comfort on RE. Future research on lacing manipulations should include a recording of participant reported perceived comfort for each lacing pattern. Previous literature indicates that lacing manipulations have the greatest impact on rear-foot stabilization, thus influencing rear-foot strike type the most. The lacing manipulations may not have rendered significant results in this sample given the assumption that this group of Kenyan runners consists of primarily fore-foot strike-type runners. Further exploration is necessary to determine whether lacing pattern variation may affect RE in runners of different populations, different strike-types, or varied levels of experience.

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APPENDIX

APPENDIX A

IRB Letter of Approval

5/11/2015

Dear Investigator(s),

The MTSU Institutional Review Board, or a representative of the IRB, has reviewed the research proposal identified above. The MTSU IRB or its representative has determined that the study poses minimal risk to participants and qualifies for an expedited review under 45 CFR 46.110 and 21 CFR 56.110, and you have satisfactorily addressed all of the points brought up during the review.

Approval is granted for one (1) year from the date of this letter for **20 (TWENTY) participants.**

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

You will need to submit an end-of-project form to the Office of Compliance upon completion of your research located on the IRB website. Complete research means that you have finished collecting and analyzing data. **Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date.** Please allow time for review and requested revisions. Failure to submit a Progress Report and request for continuation will automatically result in cancellation of your research study. Therefore, you will not be able to use any data and/or collect any data. Your study expires **5/11/2016**.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to complete the required training. **If you add researchers to an approved project, please forward an updated list of researchers to the Office of Compliance before they begin to work on the project.**

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

Sincerely,

Institutional Review Board Middle Tennessee State University