The Effect of Minimalist footwear on Running Economy following Exercise-Induced Fatigue

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Abstract

Running economy (RE) is the oxygen utilization during a steady state submaximal running bout. The purpose of this study was two-fold: (a) to determine if running in minimalist footwear results in better RE (mL kg^{-1} km^{-1}) compared to conventional footwear and to identify any relationships between RE and lower limb muscle activation; (b) to determine whether any changes in RE related to minimalist footwear are sustained following exercise-induced fatigue. In a fully randomized, counterbalanced fashion, ten well-trained male distance runners (age 29.0±7.5; BMI 38.6±6.5 kg m^{-2}; $\dot{V}O_{2max}$ 61.6±7.3 mL min^{-1} Kg^{-1}) completed a RE test pre- and post-fatigue on a motorized treadmill in both conditions using identical footwear (minimalist 178g; conventional 349g). The fatiguing protocol consisted of high-intensity interval training (7 X 1000-m at 94-97% $\dot{V}O_{2max}$) on a 200-m, unbanked, Mondo surface, indoor running track. Cardiorespiratory, muscle activation, and kinematic parameters as well as, the rate of perceived exertion and blood lactate were measured throughout the experimental sessions. A significant main effect of footwear on running speed during intervals (p=0.041) was found. Participants ran faster during the minimalist compared to conventional footwear condition (3:24±0:44 vs. 3:30±0:47 (mm:ss), respectively). While fatigue was induced, no other effect of time or footwear on RE, muscle activation or stride frequency occurred. The results of this study suggest that the characteristics of the minimalist footwear did not differ enough from the conventional shoes to induce acute changes in metabolic, kinematic and muscle activation variables during the submaximal runs.

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List of Abbreviations and Symbols

CR	**Cost of running**
EIF	**Exercise induced fatigue**
EMG	**Electromyography**
HIIT	**High-intensity interval training**
HR	**Heart rate**
MAS	**Maximal aerobic speed**
MI	**Minimalist index**
MIN	**Minimalist footwear**
MVC	**Maximum voluntary contraction**
RE	**Running economy**
RER	**Respiratory exchange ratio**
RPE	**Rate of perceived exertion**
SHOD	**Conventional running shoes**
$\dot{V}CO2$	**Volume carbon dioxide output**
$\dot{V}O2$	**Volume oxygen uptake**

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Chapter 1: Introduction and Overview

1.1 Background of Study

Running is one of the most prevalent activities for both sporting and fitness purposes. Despite the high popularity of conventional running shoes (SHOD) historically, there is currently a shift towards minimalist footwear (MIN) the characteristics of which are in complete contrast to (Fleming, Walters, Grounds, Fife, & Finch, 2015; McCallion, Donne, Fleming, & Blanksby, 2014; Sobhani et al., 2014). Designed to be lightweight with modest cushioning and motion-control technologies, the belief is that their use will positively impact a runner's health and performance via improvements in running economy (RE) (Jenkins & Cauthon, 2011; Rothschild, 2012). However, relatively little is known about how the minimalist models of footwear impact running economy and there are conflicting reports within the scientific community (Jenkins & Cauthon, 2011; Paulson & Braun, 2014).

Running economy is an accepted physiological parameter for efficient distance running performance and is thought to be a greater predictor than the previous "gold standard" $\dot{V}O_{2max}$ (Anderson, 1996; Conley & Krahenbuhl, 1980; Daniels, Oldridge, Nagle, & White, 1978). Defined as the rate of oxygen uptake ($\dot{V}O_2$) at a given submaximal running velocity (Daniels & Daniels, 1992; Morgan & Craib, 1992), RE is expressed as the $\dot{V}O_2$ per unit of mass (kg) relative to the distance covered (km) or time (min). More specifically, RE is the submaximal, steady-state rate of oxygen uptake (Altman & Davis, 2012; Gruber, Umberger, Braun, & Hamill, 2013; Pinnington & Dawson, 2001). Although there is a shift towards the use of MIN with the belief that they will positively impact running performance (McCallion et al., 2014; Sobhani et al., 2014), conclusive reports of how MIN influence running performance, and more specifically RE, represent a gap within the scientific literature. However, there is a well-established body of research on the mass effect of footwear that reports a positive relationship between footwear mass and energy expenditure (Cheung & Ngai, 2016; Fuller, Bellenger, Thewlis, Tsiros, & Buckley, 2015). Additionally, the interrelationship between fatigue, footwear, and RE is also not well understood.

1.2 Purpose of Study

This study aims to determine if there is an effect of minimalist shoes on RE and if it is altered by exercise-induced fatigue (EIF). It also seeks to identify if changes in RE are reflected by differences in muscle activation as quantified using electromyography (EMG). As such, the research question is organized into the following sub-questions:

A) What is the effect of minimalist footwear on RE?

B) Do muscle activation patterns reflect these differences?

C) Is there a change in RE with fatigue?

D) Is there an attenuation of fatigue in minimalist shoes?

The hypothesis is that wearing minimalist shoes will lead to a lower oxygen uptake at a submaximal speed resulting in improved RE, in both the non-fatigued and fatigued states. It was also hypothesized that the $\dot{V}O_2$ will reflect the differences in mass between footwear conditions and changes in muscle activation amplitude will reflect the metabolic differences. No shoe effect on EMG is expected, however, a fatigue effect is.

1.3 Significance of Study

Although a substantial number of studies (De Wit, De Clercq, & Aerts, 2000; Greensword, Aghazadeh, & Al-Qaisi, 2012; Lieberman et al., 2010; Olin & Gutierrez, 2013) demonstrate changing footwear will alter kinematics, muscle activation and other variables that influence RE, the majority of these studies were conducted without the use of MIN. Inconsistent reports of the effects of wearing MIN on RE and muscle activation present a gap within the literature (Kahle, Brown, Shaw, & Shaw, 2016; Kasmer, Ketchum, & Liu, 2014; Khowailed, Petrofsky, Lohman, & Daher, 2015; Rao, Chambon, Guéguen, Berton, & Delattre, 2015; Sobhani et al., 2014; Squadrone & Gallozzi, 2009). Fatigue is also known to influence the aforementioned characteristics, but few direct observations on RE have been identified (Collins et al., 2000; Guezennec, Vallier, Bigard, & Durey, 1996; Xu & Montgomery, 1995; Zavorsky, Montgomery, & Pearsall, 1998), none of which used MIN. Therefore, the manifestation of fatigue while wearing minimalist compared to conventional footwear represents another gap within the literature.

With growing participation in running activities each year and a high prevalence of running-related injuries per year between 19-79% (van Gent et al., 2007), it is of no surprise that a large breadth of research has focused on footwear characteristics and running-related injuries. The comparison of lower-limb muscle activation patterns between footwear conditions while in the fatigued state may help elucidate the relationship between shoe characteristics and injury trends. Most notably, the footwear used in this study are on either side of the heel-toe drop range amongst popular running shoes. There is also debate on the performance advantages of wearing MIN. The comparison of RE will help identify if any benefits exists and if it is sustained through fatigue.

Chapter 2: Review of Literature

2.1 Background

The evolution of human locomotion began approximately 4.4 million years ago with australopithecines being the earliest-known bipeds followed by endurance-based running capabilities of Homo erectus nearly 2 million years later (Bramble & Lieberman, 2004). As running evolved from a means of survival into an athletic and recreational activity, it is likely to have been done "barefoot" or in primitive footwear (such as sandals) made from nominal quantities of material (Lieberman et al., 2010; McCallion et al., 2014). The advent of protective footwear did not occur until nearly 30,000 years ago (Rixe, Gallo, & Silvis, 2012).

Before 1968, approximately 100,000 Americans were habitual runners. Following a so-called "running boom" in the 1970s, participation levels grew steadily with an estimated 10-20% (30-60 million) of Americans running annually

(Fields, Sykes, Walker, & Jackson, 2010; Novacheck, 1998). In 2011, more than 47,000 runners participated in the New York Marathon (Tam, Astephen Wilson, Noakes, & Tucker, 2014). Prior to this boom in participation rates, the development of running shoes was not considered a profitable venture for manufacturers. In response to the increased number of participants, athletic apparel companies increased their attention on research and development of running shoes (Rixe et al., 2012). However, a recent review reported that no clinical-based evidence is available to validate a positive effect of cushioning and motion-control technologies on a runner's health or performance (Richards, Magin, & Callister, 2009).

Today's multibillion-dollar running shoe industry is a good indicator of the footwear used by the endurance running community and shows that running shoes with built-in cushioning and motion-control features have become a standard in conventional running footwear. However, more recently, it appears that many runners have shifted their preference towards minimalist shoes that are lighter, contain lessor cushioning and feature little to no heel-toe drop. This shift is an effort to simulate barefoot running with the belief that it will improve performance (Fleming et al., 2015; McCallion et al., 2014; Sobhani et al., 2014). While this shift has occurred among both manufacturers and runners alike, relatively little is known about how running barefoot impacts runners' health or performance (Tam et al., 2014). The impact of MIN is also yet to be supported conclusively within the literature. Similarly, while running performance is known to be negatively impacted by fatigue, the interrelationship between fatigue, footwear, and RE is not well understood. As such, this research endeavors to augment current understandings of how footwear impacts RE as well as the effects of fatigue while running in MIN versus SHOD.

2.2 Running Economy

This review will focus primarily on how MIN impacts RE, the submaximal aerobic cost of running. By definition, RE is the relationship between oxygen uptake and submaximal running velocity (Burgess & Lambert, 2010; Daniels & Daniels, 1992; Martin & Morgan, 1992). As such, it is the $\dot{V}O_2$ relative to mass at a steady-state running speed and can be expressed per kilometer ($mlO_2 \cdot kg^{-1} \cdot km^{-1}$) or minute ($mlO_2 \cdot kg^{-1} \cdot min^{-1}$). Therefore, RE can simply be viewed as a submaximal, steady state rate of oxygen uptake (Gruber et al., 2013; Pinnington & Dawson, 2001). To be a true RE, it is reported that the respiratory exchange ratio must be ≤ 1.0 (Morgan, Martin, & Krahenbuhl, 1989). Anderson (1996) has also described RE as an accepted physiological criterion for efficient performance and a critical element of distance running. In addition to $\dot{V}O_2$, RE can also be expressed as the metabolic demand of running also known as the energy cost of running (CR) (kcal or joules) (Di Prampero et al., 1993; Nicol, Komi, & Marconnet, 1991). Indeed, some authors have challenged the sensitivity of $\dot{V}O_2$ as it does not account for the respiratory exchange ratio and instead have concluded that the energetic cost of running is a more appropriate measure of RE (Fletcher, Esau, & MacIntosh, 2009). Further, some authors have expressed RE relative to time (Collins et al., 2000; Xu & Montgomery, 1995; Zavorsky et al., 1998), or to distance (Di Prampero et al., 1993; Shaw, Ingham, Atkinson, & Folland, 2015). It would appear that RE is best expressed relative to distance to allow for inter-study comparisons as this method accounts for differences in running speed used within each study (Shaw, Ingham, & Folland, 2014). In fact, the metabolic demand expressed as the energy spent per unit distance has been referred to as CR whereas the energy demand at a given running speed has been referred to as RE (Lacour & Bourdin, 2015). As such, when $\dot{V}O_2$ is measured at a given submaximal speed for a given time (or distance) changes in CR would reflect changes RE (Hausswirth & Lehenaff, 2001). Therefore, studies reporting changes in $\dot{V}O_2$ during submaximal runs of standardized duration are referred to as changes in RE. Any change in RE is based on the change in $\dot{V}O_2$ during submaximal running whereby a decrease in $\dot{V}O_2$ indicates an improved RE and vice versa.

Although some authors have discussed RE and endurance running capacities in relation to their importance to evolution (Bramble & Lieberman, 2004; Raichlen, Armstrong, & Lieberman, 2011), the primary application of RE has been to assess endurance capabilities. Runners with good RE are known to favor lipids as a fuel source at a high work rate while minimizing the accumulation of metabolites and sparing carbohydrates while running at a race pace (Saunders, Pyne, Telford, & Hawley, 2004). Therefore, a good RE will allow a runner to use less energy and have lower $\dot{V}O_2$ at a fixed submaximal workload compared to a runner with a “poor” RE (Burgess & Lambert, 2010; Nummela, Keränen, & Mikkelsson, 2007). In other words, an individual with better RE will uptake lower volumes of oxygen at similar speeds and in theory, be able to run faster or longer than a competitor with a poorer RE (Burgess & Lambert, 2010).

Although RE is a useful measure, it is noted that considerable differences exist between and within individuals at a given submaximal speed (Daniels, 1985). In fact, intra-individual variations of 2-11% (Morgan, Martin, Baldini, & Krahenbuhl, 1990) and 30% (Daniels, 1985; Saunders et al., 2004) are reported. It is also well-established that comparisons of RE between individuals are only valid amongst similar populations (Burgess & Lambert, 2010; Daniels, 1985; Daniels & Daniels, 1992; Daniels et al., 1978; Morgan, 1992; Morgan & Craib, 1992)

2.3 Running Economy and Performance

Although an athlete's ability to reach maximal oxygen uptake ($\dot{V}O_{2max}$) has been well correlated with performance during distance running (Conley & Krahenbuhl, 1980; Daniels et al., 1978; Saunders et al., 2004), the measurement of RE also offers a reliable measure for predicting performance (Pinnington & Dawson, 2001; Tartaruga et al., 2012). In fact, research has indicated that RE is the better predictor of performance in similar runners during an endurance event (Conley & Krahenbuhl, 1980; Costill, Thomason, & Roberts, 1973; Daniels et al., 1978; Mooses et al., 2013; Saunders et al., 2004; Tartaruga et al., 2010). A study by Di Prampero and colleagues (1993) reported that a 5% improvement in RE (lower oxygen cost) might result in an approximate 4% increase in performance during a distance running event. These outcomes were replicated by Hanson and colleagues (2011). Hence, understanding how to improve the capacity to spare energy (or optimize energy production) may provide the most benefit to competitors. A review by Cavanagh and Kram (1985) notes that considerations of improved economy are most relevant to athletes at the elite level. That is, changes of even a small magnitude could have a major effect on performance in endurance events. Conversely, for a novice or unskilled performer, modifications are not likely to show because other factors increase at the same time.

2.4 Factors that Influence Running Economy

Studies measuring RE ranging from populations of elite runners (e.g. Olympians) to recreational runners have identified various physiological (Moore, Jones, & Dixon, 2012; Pate, Macera, Bailey, Bartoli, & Powell, 1992; Tartaruga et al., 2010) and biomechanical (Anderson, 1996; Burkett, Kohrt, & Buchbinder, 1985; Gruber et al., 2013; Raichlen et al., 2011) variables that influence RE. The main factors are presented below.

2.5 Runner Characteristics

As previously noted, comparisons of RE can only be made amongst similar runners. To accurately compare RE, differences in each individual must be accounted for because many characteristics are known to influence RE including: variations in anthropometrics (Morgan et al., 1990) training history (Burgess & Lambert, 2010; Dallam, Wilber, Jadelis, Fletcher, & Romanov, 2005; Daniels & Daniels, 1992; Morgan et al., 1990) metabolic profile (Basset & Boulay, 2003), treadmill running experience and nutritional status (Burgess & Lambert, 2010;

Conley & Krahenbuhl, 1980; Moore et al., 2012; Saunders et al., 2004). Therefore, the comparison of long-distance runners and sprinters is an inappropriate application of RE (Basset & Boulay, 2003). In fact, improved RE is associated with long-distance as opposed to those of middle- and short-distance runners (Daniels, 1985).

2.6 Running Speed

Running speed is positively correlated with $\dot{V}O_2$ (Burkett et al., 1985; Conley & Krahenbuhl, 1980; Daniels & Daniels, 1992). The interplay between biomechanical factors and the physiological response to running speed has been under scrutiny since the first generation of exercise physiologists, and its relation to performance is the topic of many investigations.

To understand the effect of running speed on $\dot{V}O_2$ we should first consider the influence of stride frequency and stride length on oxygen uptake. An increase in speed can be achieved by manipulating either stride length or stride frequency (Elliott & Roberts, 1980; Kyröläinen, Belli, & Komi, 2001; Kyröläinen, Komi, & Belli, 1999; Luhtanen & Komi, 1978; Nummela et al., 2007), but the product of both will best determine a runner's velocity (Luhtanen & Komi, 1978; Nummela et al., 2007). For example, stride length is considered to be responsible for increases of up to 90% of an individual's maximal speed (Nummela et al., 2007). However, at higher speeds, stride frequency becomes predominant factor for increases of speed close to maximal aerobic speed (Luhtanen & Komi, 1978; Nummela et al., 2007). In fact, Mero and Komi (1986) showed that both stride length and stride frequency increased as a function of running velocity. Furthermore, this relationship was reported to be nonlinear for both variables at all aerobic speeds.

A decline in RE with an increase in running speed is reported within the literature (Burgess & Lambert, 2010; Conley & Krahenbuhl, 1980; Daniels, 1985; Daniels & Daniels, 1992; Gimenez, Kerhervé, Messonnier, Féasson, & Millet, 2013). For example, Nicol, Komi, and Marconnet (1991) observed that distance runners' RE declined (increased energy cost) as speeds increased from 75% to 100% of their marathon running speeds. Likewise, Davies and Thompson (1986) followed ultra-marathoners during a four-hour run on a motorized treadmill. They reported that a 9% decline in RE (increase in $\dot{V}O_2$) occurred with a 0.41 $m \cdot s^{-1}$ (~9%) increase in speed. In other words, a negative linear relationship between running speed and RE has been shown in the literature (Burgess & Lambert, 2010; Daniels, 1985; Davies & Thompson, 1986; Gimenez et al., 2013; Kyröläinen et al., 2001). Furthermore, as speeds reach 80% of $\dot{V}O_{2max}$, this relationship becomes curvilinear (Burgess & Lambert, 2010; Daniels, 1985). As such, a trade-off between speed and RE exists (Burkett et al., 1985; Gimenez et al., 2013). However, the studies mentioned above have reported RE relative to time. When RE has been expressed relative to the distance covered, no trade-off between RE and speed has been observed. For example, Di Prampero and colleagues (1993) followed 16 intermediate level runners during steady state track running. This group reported that energy cost per body mass per distance ($J\ kg^{-1}\ m^{-1}$) was insensitive to changes in speed demonstrating no trade-off between RE and running speed was present. Similarly, Shaw and colleagues (2014) evaluated the validity of oxygen cost versus energy cost as a measure of RE. This group compared the sensitivity of RE expressed as energetic cost (kcal kg^{-1} km^{-1}) and oxygen cost (mlO_2 kg^{-1} km^{-1}) to an increase in running speed. Indeed, this group reported an increase in the energetic cost and respiratory exchange ratio with increasing speed. However, there were no changes in oxygen cost as speed increased. After close examination, several factors may account for this disparity. RE is the measure of the aerobic cost of submaximal running and is only valid with a respiratory ratio ≤ 1.0 and may be expressed relative to distance or time. Therefore, it is important to be cognizant of the speeds used when testing RE as those approaching or above an individual's upper submaximal limit impact absolute $\dot{V}O_2$ as well as the respiratory exchange ratio. Further, when reporting changes in RE, it may be wise to report relative to distance to normalize for different speeds used within the RE tests within and across studies.

2.7 Environment

Similar to recreational running, it is often impractical to conduct research using traditional surfaces such as a track or an outdoor field. As such, a treadmill is commonly used in lieu of overground surfaces. Despite the methodological benefits, inconclusive reports within the literature suggest that caution must be used when comparing results taken from studies using different surfaces. Further more, environmental factors such as surface compliance and air resistance are likely responsible for some differences in RE. However, making adjustments to the testing protocol can mitigate the effect of these environmental components.

Preliminary studies have suggested that the running surface does not affect RE. For example, McMiken and Daniels (1976) demonstrated that at low-to-moderate speeds (2.27-4.77 $m \cdot s^{-1}$), no change in RE occurred between level track and treadmill running. Similar results have corroborated these reports (Burkett et al., 1985; Hanson et al., 2011). However, conflicting results have also been reported (Davies, 1980; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002; McMahon & Greene, 1979; Pugh, 1970, 1971). Two specific environmental aspects have been identified as possible reasons for these discrepancies: surface compliance and air resistance.

McMahon and Greene (1978, 1979) reported that the compliance of a running surface affects RE. Results from these studies have demonstrated that very compliant surfaces (with spring stiffness being much less than that of running humans) considerably reduce performance. Conversely, surfaces of intermediate compliance (160-320 $kN \cdot m^{-1}$) can potentially improve performance. In fact, Kerdok and colleagues (2002) studied eight males running on a customized surface that allowed for changes in stiffness (75.5 - 945.7 $kN \cdot m^{-1}$). A 12% decrease in RE was observed during a 12.5-fold reduction in surface stiffness.

Although the reports of McMiken and Daniels (1976) have since been contested, they did recognize one important variable: air resistance (or drag), a force that, depending on direction, can either impede or augment a runner's efforts and consequently impact RE. For example, air resistance can equate to approximately 5-10% of total energy expenditure during running that is dependent on ground speed. However, in situations of calm air (such as indoors on a treadmill) this resistance is negligible and can be ignored (Di Prampero, 1986). Furthermore, Davies (1980) has demonstrated that the cost of overcoming air resistance outdoors was ~8% for sprinting (10 $m \cdot s^{-1}$), 4% for middle-distance (6 $m \cdot s^{-1}$) and 2% during long-distance (5 $m \cdot s^{-1}$) running. Reviews comparing treadmill and over ground running (Bassett et al., 1985; Morgan & Craib, 1992) have also elaborated on the effects of air resistance; as speeds increase, a greater difference of oxygen cost during over ground versus treadmill running occurs. This data are said to demonstrate the relationship between velocity and fluid drag (Anderson, 1996).

Although differences in kinematics (Nigg, de Boer, & Fisher, 1995; Riley et al., 2008), kinetics (Riley et al., 2008), surface compliance (Frederick, 1986; McMahon & Greene, 1978, 1979), air resistance (Anderson, 1996; Bassett et al., 1985; Davies, 1980; Di Prampero, 1986; Pugh, 1970, 1971), and RE (Burkett et al., 1985; Hanson et al., 2011; Kerdok et al., 2002; McMiken & Daniels, 1976; Nigg et al., 1995) have been reported, running on a treadmill is considered similar to over ground running (Riley et al., 2008). In fact, two recommendations have been used to mitigate any differences that may be present. Providing a familiarization period (Matsas, Taylor, & McBurney, 2000) and increasing running grade (Davies, 1980; Jones & Doust, 1996) have been demonstrated to be beneficial when using a treadmill during testing. For example, Davies (1980) expanded on Pugh's (1970, 1971) work by observing the effect of wind with and against a runner on level and graded running. It was suggested that the energetic cost of running on a treadmill grade of 1% is approximately equal to air resistance while running outside on a calm day at an endurance pace. Furthermore, Jones and Doust (1996) compared overground and graded treadmill running at six different velocities (2.92-5.0 $m \cdot s^{-1}$). They also demonstrated that a 1% gradient could be used to account for the energy cost of air resistance at running speeds between 2.92 and 5.0 $m \cdot s^{-1}$.

2.8 Spatiotemporal Variables

Considerable research has examined how the spatiotemporal characteristics of an individuals' running pattern impact their RE. While many variables exist, the two most frequently analyzed are stride length and stride frequency (Tartaruga et al., 2012). As manipulations of these variables were previously demonstrated to alter running speed, it is not surprising that both correlate with RE. Furthermore, the balance of these two variables appears to correspond with a natural optimization in RE.

Early investigations of spatiotemporal variables primarily focused on stride length. Although these studies have reported conflicting effects on RE (Cavanagh & Kram, 1985; Cavanagh, Pollock, & Landa, 1977; Dillman, 1975), it appears both stride length and the runner's ability to "fine-tune" it influence RE. For example, Dillman (1975) suggested that better runners tend to have longer strides at any given velocity compared to less skilled runners. Conversely, Cavanagh et al. (1977) reported that elite distance runners took shorter absolute and relative strides than good distance runners. A well-established relationship between RE and stride length has since been reported and a freely chosen stride length has been found to be most economical (Cavagna, 1977; Cavagna, Willems, Franzetti, & Detrembleur, 1991; Cavanagh & Kram, 1985, 1989; Cavanagh & Williams, 1982; Kaneko, Matsumoto, Ito, & Fuchimoto, 1987; Knuttgen, 1961). Furthermore, deviations from a freely chosen stride length result in a decrease of RE (Cavagna, 1977; Cavagna et al., 1991; Cavanagh & Kram, 1985, 1989; Cavanagh & Williams, 1982; Heinert, Serfass, & Stull, 1988).

Comparatively, a naturally selected stride frequency correlates with better RE. Anderson (1996) summarized the basic relationship between spatiotemporal variables and RE. A stride too long would require considerable energy due to power needs during propulsion and an increase in muscle contraction to control the body during heel strike. Furthermore, a stride too short would result in an increased amount of work due to the increased frequency of movements. In fact, Tartaruga et al. (2012) demonstrated that stride frequency and stride length had significant relationships with RE corresponding to 28% and 23% of the overall biomechanical influence, respectively. Therefore, it is believed that runners will naturally select a stride ratio that minimizes metabolic cost and optimizes mechanical efficiency (Cavagna, 1977; Cavanagh & Williams, 1982; Kaneko et al., 1987). This preferred stride ratio has also been termed self-optimization (Hunter & Smith, 2007). However, some studies have used mathematical models to quantify what change in preferred stride characteristics are optimal for RE. Indeed, RE values are reported to be highest with an approximate 2-3% reduction in stride length (Cavanagh & Williams, 1982; Connick & Li, 2014), and a 2-3% increase in stride frequency (de

Ruiter, Verdijk, Werker, Zuidema, & de Haan, 2014). As such, deviations from the optimal stride patterns have a negative impact on RE (Hunter & Smith, 2007) and can be described as an inverted-U relationship. Therefore, considering the relationship between running speed and these spatiotemporal variables, an individual running slower or faster than their preferred speed may exhibit reduced RE. This relationship may explain why sprinters, for example, exhibit very poor running economy while most endurance runners have exceptional RE. This interaction also highlights the importance of testing RE near individuals' preferred cadence at submaximal running speeds. Requiring individuals to run at a pre-determined speed that may be less than optimal for them would likely result in inaccurate estimates of RE.

2.9 Ground Reaction Forces

The correlation between ground reaction forces and RE is a common topic in biomechanical analysis of distance running (Heise & Martin, 2001; Martin & Morgan, 1992; Morgan, 1992; Morgan & Craib, 1992; K. R. Williams & Cavanagh, 1987). During ground contact, the primary functions of the lower limb musculature are to provide stability and maintain forward propulsion. It is believed that ground reaction force reflects muscle activation and segment acceleration while the foot is in contact with the ground (Heise & Martin, 2001; Martin & Morgan, 1992; Saunders et al., 2004). Lower ground reaction force would therefore be associated with reduced muscle activations and potential avoidance of unnecessary movements, both of which would result in reduced wasted energy. For example, any excess movements in the vertical, anterior-posterior and medial-lateral directions would represent the need for increased muscular activity to maintain stability and hence, can be viewed as a wasteful or uneconomical use of metabolic energy. Studies have identified correlations between ground reaction force and changes in RE. Further, Heise and Martin (2001) reported that more economical runners exhibit lower total vertical impulse and net vertical impulse. In this study, 38% and 36% of the variability in RE was explained by total and net vertical impulse, respectively. These results are consistent with other studies that observed a correlation between variations in vertical oscillations of the center of mass and RE (Tartaruga et al., 2012; Williams & Cavanagh, 1987). Although relationships between runners with better RE and lower peak vertical forces have also been established, it must be noted that these relationships are moderate at best (Martin & Morgan, 1992).

2.10 Foot Strike Patterns

Current observations of human gait have identified three distinct strike types. Each foot strike pattern is characterized by the part of the foot that contacts the ground first (Hasegawa, Yamauchi, & Kraemer, 2007; Lieberman et al., 2010). A rear-foot strike and fore-foot strike occur when initial contact with the ground is made by the heel and ball of the foot, respectively. However, a mid-foot strike occurs when the heel and ball of the foot land simultaneously (Altman & Davis, 2012; Hasegawa et al., 2007; Lieberman et al., 2010). It has been suggested that a fore-foot strike is a more natural foot strike pattern (opposed to a rear-foot strike) and some authors consider it a more efficient movement pattern (Altman & Davis, 2012;

Divert, Mornieux, Baur, Mayer, & Belli, 2005; Lieberman et al., 2010; Nunns, House, Fallowfield, Allsopp, & Dixon, 2013; Squadrone & Gallozzi, 2009) Although the foot strike pattern used by a runner reflects the amount of energy expended while running (Daniels, 1985), and the mechanics of each are well documented (Altman & Davis, 2012; Cavanagh & Laforune, 1980; Williams, McClay, & Manal, 2000), there continues to be debate regarding the impact on RE remains (Hasegawa et al., 2007).

An alteration in foot strike pattern is a common recommendation by distance running coaches when trying to improve running performance (Hasegawa et al., 2007). Furthermore, recommendations within the scientific literature have also suggested that a shift from a rear-foot strike to a fore-foot strike will improve RE (Hasegawa et al., 2007; Jenkins & Cauthon, 2011; Lieberman et al., 2010). However, there is no consensus within the literature as to the effectiveness of these recommendations because some have reported no change in performance as a result of altering foot strike pattern (Aridgo, Lafortuna, Minetti, Mogoni, & Saibene, 1995; Cunningham, 2010; Gruber et al., 2013; Perl, Daoud, & Lieberman, 2012). In fact, the mechanics of running with a rear-foot strike have been associated with better RE (Heise & Martin, 2001; Williams & Cavanagh, 1987). Common systematic flaws in previous studies are believed to explain these conflicting reports (Gruber et al., 2013). Small sample sizes and the absence of habitual cohorts for each foot strike pattern hinder the detection of significant changes in RE. Furthermore, it is expected that observing runners at a self-selected foot strike pattern would eliminate any effect of performing a novel task on $\dot{V}O_2$ measurements. Runners would have already acclimated to the unique mechanical and physiological aspects of their habitual foot strike pattern. Therefore, comparing groups rather than requiring each group to alter their preferred foot strike pattern may provide a better model to assess the effects of foot strike pattern on RE. In recognition of this gap within the literature, Gruber et al. (2013) compared RE at three different speeds (3.0, 3.5, and 4.0 m s^{-1}) between a habitual fore-foot strike and rear-foot strike. The rate of carbohydrate contribution to total energy production was also determined. The results showed no difference in $\dot{V}O_2$ and carbohydrate contribution to energy production between groups running at their habitual foot strike pattern. Although not concomitant, a rear-foot strike resulted in either lower $\dot{V}O_2$ or carbohydrate contribution compared to a fore-foot strike for the two slowest speeds (3.0 and 3.5 m s^{-1}). However, at a speed of 4.0 m s^{-1}, a fore-foot strike had higher $\dot{V}O_2$ than a rear-foot strike with no difference in carbohydrate contribution. It was concluded that a fore-foot strike was no more economical than a rear-foot strike. Thus, no particular advantage of foot strike pattern on RE was present. Although the mechanics of a rear-foot strike are reported to be characteristic of a more economical runner (Gruber et al., 2013; Heise, Smith, & Martin, 2011; Williams & Cavanagh, 1987), debate within anecdotal and scientific literature remains. A review by Gruber et al. (2013) demonstrated that while there appears to be some relationship between RE and foot strike pattern, this relationship is not well understood. Therefore, the foot strike pattern is a factor that should be considered when comparing RE between different models of footwear.

2.11 Fatigue

An early review by Daniels (1985) suggests that fatigue has a clear influence on the aerobic demand of running and thus RE. A more recent review by Burgess and Lambert (2010) has supported this notion. The majority of studies that have investigated the relationship between RE and fatigue have shown that a decline in RE is associated with fatigue (Brueckner et al., 1991; Cavanagh & Kram, 1985; Collins et al., 2000; Hunter & Smith, 2007; Nicol et al., 1991; Sproule, 1998; Xu & Montgomery, 1995; Zavorsky et al., 1998). Several studies have further shown that this decline in RE is positively correlated with the intensity and duration of exercise (Brueckner et al., 1991; Cavanagh & Kram, 1985; Davies & Thompson, 1986; Hausswirth, Bigard, Berthelot, Thomaidis, & Guezennec, 1986; Hausswirth, Bigard, & Guezennec, 1997; Sproule, 1998; Woledge, 1998; Xu & Montgomery, 1995). Although some studies have reported no change in RE with fatigue (Millet, Millet, Hoffman, & Candau, 2000; Morgan, Baldini, Martin, & Kohrt, 1989; Morgan et al., 1990), this may be due to the difference in fatiguing protocols used. Studies on the prolonged (Kyröläinen et al., 2000; Morgan et al., 1990; Nicol et al., 1991) and acute response (Brueckner et al., 1991; Collins et al., 2000; Hunter & Smith, 2007; Sproule, 1998; Xu & Montgomery, 1995; Zavorsky et al., 1998) of fatigue during both maximal (Brueckner et al., 1991; Morgan et al., 1990) and submaximal (Candau et al., 1998; Collins et al., 2000; Hunter & Smith, 2007; Morgan et al., 1990; Sproule, 1998; Xu & Montgomery, 1995) running have been conducted. However, this section of the review will focus on acute effects of fatigue and discuss any apparent discrepancies between experimental protocols. Studies observing intensities of 80% of $\dot{V}O_{2max}$ or less will be considered near- or sub-maximal, respectively, and therefore grouped. Furthermore, studies observing running at intensities above 80% will be examined separately.

Prolonged running events (such as marathons or ultra-marathons) are generally run at submaximal paces. Studies investigating these events have reported a decrease in RE (increased oxygen uptake) in the range of ~8%-15% (Davies & Thompson, 1986; Gimenez et al., 2013; Kyröläinen et al., 2000). However, no change in RE was reported during ultra-marathons (duration of 65 km) (Millet et al., 2000). Studies conducted on shorter, submaximal events have reported decreases in RE but only in the range of ~3 to ~9% (Brueckner et al., 1991; Hunter & Smith, 2007; Nicol et al., 1991; Xu & Montgomery, 1995).

Fatiguing protocols of high (above 80% $\dot{V}O_{2max}$) intensities such as sprinting bouts have also reported declines in RE. For example, Zavorsky, Montgomery, and Pearsall (1998) have observed significant reductions in RE during running bouts at speeds of 3.33 and 4.47 m s^{-1} following intense interval training at approximately 100% $\dot{V}O_{2max}$. Using the same protocol and dataset, Collins and colleagues (2000) observed small but consistent decreases in RE (~5%, ~2% at 3.33 and 4.47 m s^{-1}, respectively).

Although many of these studies on fatigue showed a detrimental effect of running speed on RE, contradictory results may be attributed to differences in individuals' fatigue response as well as testing protocol (Hunter & Smith, 2007). For example, measurements obtained during running bouts are not considered valid to test RE (Hanley & Mohan, 2014). Furthermore, some fatiguing protocols require running at a constant pace until exhaustion. However, this pacing strategy is not commonly used by distance runners, and in fact, variations in pace are common during endurance events (Hunter & Smith, 2007). Hunter and Smith (2007) showed that maintaining stride kinematics outside their preference may disrupt an individual's optimization process. Therefore, caution should be used when comparing studies.

While the relationship between RE and fatigue appears to be relatively straightforward, fatigue induced by running affects many physiological and biomechanical variables. It is also important to note that responses to fatigue differ from one individual to another. Thus one can hypothesize that variations in physiological and biomechanical variables may hinder the measurement of RE or, be the underlying cause of a decrease observed with fatigue (Candau et al., 1998; Hunter & Smith, 2007). For example, alterations in gait characteristics (Candau et al., 1998; Hanley & Mohan, 2014; Hausswirth et al., 1997; Kyröläinen et al., 2000; Nicol et al., 1991; Williams et al., 2000), increased respiratory muscle effort (Candau et al., 1998; Davies & Thompson, 1986; Nicol et al., 1991), and increased activation of the lower limb musculature (Davies & Thompson, 1986; Nicol et al., 1991; Williams et al., 2000) due to fatigue have been suggested to influence RE.

2.12 Footwear

The influence of footwear during running events has received considerable attention. In fact, a variety of variables affected by footwear choice have been identified. Although the number of studies investigating the effect of shoe condition on RE is relatively limited, other variables, known to influence RE, have received a significant amount of attention. The majority of studies concerned with RE have compared barefoot to SHOD conditions (Burkett et al., 1985; Divert et al., 2008; Franz, Wierzbinski, & Kram, 2012; Hanson et al., 2011; Jenkins & Cauthon, 2011; Nigg, 2009; Perl et al., 2012) but few studies have investigated the impact of MIN on RE and how they compare with other footwear conditions. In fact, a recent meta-analysis and a systematic review (Cheung & Ngai, 2016; Fuller et al., 2015) provide a comprehensive understanding of the effects of footwear on RE during distance running. Indeed, the lack of studies observing MIN, and the number of variables affected by footwear have contributed to the obscure relationship between RE and MIN. Before a review of footwear conditions, an outline of standard definitions that will be used to describe various footwear classifications is given.

2.12.1 Barefoot

Barefoot running is best described as running with the absence of footwear, not necessarily with bare feet. For example, running barefoot can be performed with nude feet or wearing items such as yoga or diving socks (Divert et al., 2008). There is little argument that running barefoot changes many aspects of gait compared to wearing shoes (Hatala, Dingwall, Wunderlich, & Richmond, 2013; Jenkins & Cauthon, 2011). Two advantages well supported by evidence in the literature include reduced impact at contact (Hatala et al., 2013; Jenkins & Cauthon, 2011; Perl et al., 2012) and improved proprioception (Altman & Davis, 2012). Barefoot runners have higher stride frequencies; shorter stride lengths; and forefoot strike patterns (Altman & Davis, 2012; De Wit et al., 2000; Divert, Baur, Mornieux, Mayer, & Belli, 2005; Hamill, Russell, Gruber, & Miller, 2011; Lieberman et al., 2010). The most cited motive for switching to barefoot is the promise of improved CR (Burkett et al., 1985; Divert et al., 2008; Divert, Mornieux, et al., 2005; Hanson et al., 2011; Paulson & Braun, 2014), or RE. Furthermore, running barefoot has gained additional exposure due to the interest in injury prevention. In fact, the general belief is that running barefoot can enhance performance while reducing the risk of overuse injuries (Altman & Davis, 2012; Goss & Goss, 2012; Jenkins & Cauthon, 2011; Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009; Nunns et al., 2013; Paulson & Braun, 2014). However, Nigg (2009) has questioned the validity of claims that barefoot running has fewer running related injuries. In fact, the author dismissed this claim as speculation with no epidemiological support. Regardless, is much needs to be determined about barefoot running before medical professionals can make informed decisions about what to recommend to their running patients (Altman & Davis, 2012; Jenkins & Cauthon, 2011).

2.12.2 Minimalist

The term minimalist running tends to be used synonymously with barefoot running, despite debate regarding their dissimilarity (Bonacci et al., 2013; Luo et al., 2009). As a hybrid of barefoot and convention footwear, minimalist shoes intend to mimic the barefoot condition. Indeed, Nigg (2009) has summarized variations of the minimalist shoe concept and how each focuses on a different characteristic - either mimicking the kinematics or sensation of barefoot running or simply the shape of the foot. As such, the term "minimalist footwear" is used within the marketplace without standardization due to the numerous minimalist shoe models produced. Indeed, in a survey of over 700 American runners (Rothschild, 2012) the Vibram Five Finger, Nike Free, Saucony Kinvara, and New Balance Minimus were the most commonly used minimalist shoes. While acknowledging the need for a standard definition, Esculier and colleagues (2015) have used a modified Delphi method to establish a standard definition based on the consensus of 42 experts in 11 countries. Indeed, 95% of respondents agreed that the minimalism of a shoe should be based on five criteria. As such, a minimalist shoe is defined as a running shoe that is light in weight, with a low heel-to-toe drop and stack height, with no motion-control technologies; and does not impede the natural movement of the foot (Esculier et al., 2015).

Examples of footwear examined in the literature include Nike Free, Nike VIVO, Adidas Feet You Wear (Nigg, 2009), Merrell Pace Glove (Sobhani et al., 2014), and Vibram FiveFinger (Jenkins & Cauthon, 2011; Squadrone & Gallozzi, 2009).

Common comparisons between MIN and SHOD conditions include training responses; performance outcomes, associated injuries and kinematic adjustments. However, it should be noted that, due to the high degree of variability within the five characteristics that define a minimalist shoe, a comparison between footwear studies requires caution. To aid runners with the transition from a conventional to minimalist shoe and improve the validity of intra-study comparisons, Esculier and colleagues (2015) have also developed a rating scale based on an equal weighting of the five characteristics identified within the standard definition of a minimalist shoe. The minimalist index (MI) covers the spectrum of running shoes to quantify the degree of minimalism – with a higher score being more minimalist, and a lower score being more maximalist. To help establish the minimalist index of footwear, Esculier and colleagues (2015) provide a detailed explanation and how-to guide. Esculier and colleagues also provide a useful resource for determining the minimalist index for a wide variety of footwear models at https://therunningclinic.com/en/shoes/. Readers with interest in learning more about the minimalist index determination are encouraged to go to this website.

2.12.3 Conventional

Modern conventional running shoes are known to have a significant amount of cushioning material used to provide comfort, support, protection, and correct movement patterns (Altman & Davis, 2012; Divert, Mornieux, et al., 2005; Warne & Warrington, 2014). Furthermore, a dual-density midsole, elevated and cushioned heel, as well as, arch support is standard in many SHOD models (Altman & Davis, 2012; Bonacci et al., 2013).

2.12.4 Does Footwear type Affect Running Economy?

The number of studies investigating the effect of shoe condition on RE is relatively limited compared to other variables. Considering the aforementioned variability in footwear, the minimalist index in addition to the mass of the footwear will be provided when possible. This will aid the reader to address possible disparities when discussing comparisons of footwear models and their effect on RE.

Although the majority of studies have reported improved RE in barefoot compared to shod condition (Burkett et al., 1985; Divert et al., 2008; Franz, Wierzbinski, & Kram, 2012; Hanson et al., 2011; Jenkins & Cauthon, 2011; Nigg, 2009; Perl, Daoud, & Lieberman, 2012), some evidence of a decrease or even no change in RE (Divert et al., 2008; Franz et al., 2012; Frederick, Clarke, Larsen, & Cooper, 1983; Pugh, 1970; Squadrone & Gallozzi, 2009; Warne, Moran, & Warrington, 2015) have been reported. Regardless, it appears that the type of footwear a runner chooses to wear may impact their efficiency and thus, performance. In fact, the preference of the shoe alone has been shown to influence RE (Burke & Papuga, 2012; Luo et al., 2009) . These studies show that a runner's RE significantly improved while wearing shoes with a higher comfort rating.

Many of the investigations studying RE between footwear conditions have compared barefoot to SHOD with the majority reporting improved RE while barefoot. Burkett and colleagues (1985) measured the oxygen cost of 21 runners under three conditions: barefoot, SHOD, and SHOD with orthotic inserts. Improvements of ~1% to ~3% in RE occurred from SHOD to barefoot conditions, regardless of orthotic inserts. It is important to note that these significant differences in oxygen uptake were only found when absolute values were considered- no differences were observed when the relative (normalized to mass) was examined. Similarly, improvements of ~4% to ~6% in RE from SHOD to barefoot conditions have also been reported (Divert et al., 2008; Hanson et al., 2011; Jenkins & Cauthon, 2011; Nigg, 2009; Paulson & Braun, 2014). However, results favoring the SHOD condition were also observed. For example, although Franz and colleagues (2012) reported increases in RE with the barefoot condition, they also identified a ~3-4% increase in RE in one SHOD condition compared to barefoot. In fact, these authors concluded that running barefoot had no metabolic advantage over running in lightweight shoes. Furthermore, Squadrone and Gallozzi (2009) reported a greater than 1% reduction in oxygen uptake while wearing a shoe of approximately 150 grams. Some studies have reported no change in RE between SHOD and barefoot conditions. For example, while wearing a shoe of approximately 150 grams, Divert and colleagues (2008) observed no change in oxygen uptake. Similarly, Pugh (1970) and Frederick et al. (1983) showed no difference in oxygen cost.

Considering mainstream MIN use has only recently occurred, it is of little surprise that the literature studying RE while MIN is limited. Nonetheless, observations focused on comparing RE from MIN to barefoot and SHOD conditions show that similarities amongst footwear models do exist, but disagreement within the literature remains. For example, while investigating a minimalist shoe (the Vibram FiveFinger – MI= 90%, ~148g), both Squadrone and Gallozzi (2009) and Paulson and Braun (2014) reported a non-significant difference in RE compared to barefoot. In the former study, a ~1% improvement in RE from barefoot to MIN was reported, whereas the latter study reported a ~2% reduction in RE from barefoot to minimalist footwear condition. Further, RE has been shown to increase in the minimalist footwear condition. Squadrone and Gallozzi (2009) reported a significant ~3% improvement, as well as, Paulson and Braun (2014) from SHOD to minimalist conditions. However, the latter was not statistically significant. Of the studies examining minimalist footwear, several accounted for habitual footwear use and its influence on RE (Perl et al., 2012; Sobhani et al., 2014; Squadrone & Gallozzi, 2009; Warne & Warrington, 2014). Amongst these studies, runners that did not habitually wear SHOD were significantly more economical in the minimalist condition (Perl et al., 2012; Squadrone & Gallozzi, 2009). For example, Perl et al. (2012) observed a ~2-3% better RE while wearing minimalist footwear (MI= 90%, ~148g). Similarly, Squadrone and Gallozzi (2009) reported a significant ~3% RE improvement from the SHOD to minimalist condition. Conversely, Sobahni et al. (2014) reported a non-significant ~1% improvement in RE with the minimalist footwear condition compared to SHOD in habitually SHOD runners with no experience in minimalist footwear. A study by Warne and Warrington (2014) followed a group of runners with no barefoot running experience and reported that following a 4-week minimalist footwear habituation period, RE while wearing minimalist footwear improved by 8% and RE while SHOD only improved by ~2%. Furthermore, the magnitude of improvement in RE from SHOD to minimalist conditions also increased by ~7%. However, specific details of the shoe's characteristics are unavailable in both studies. Further, the study by Warne et al. (2015) also followed 23 male trained runners over an eight-week gait retraining program in minimalist footwear. Although the gait retraining intervention did not affect on RE, a ~3% mean differences in RE was reported at both pre- and post-tests compared to SHOD (Bellar & Judge, 2015). Therefore, it does appear that experience with minimalist footwear influences RE and may account for the differences in RE between minimalist and SHOD conditions.

2.12.5 Mass Effect

An obvious difference between barefoot and SHOD running is that in the former, the runner does not have to carry the additional shoe mass. As shown in a review by Anderson (1996), a variety of anthropometric dimensions can influence the useful application of muscular activity towards locomotion and, hence, the energy cost of running. For example, an early investigation by Myers and Steudel (1985) showed that the aerobic demand of running increased significantly with increased distal mass. Their results found that for every kilogram carried on the trunk, the aerobic demand of running increased by 1% as opposed to an approximate 10% increase when the mass was carried on the shoe. Likewise, Frederick (1984) concluded that at a given speed, the cost of transport ($mlO_2\ kg^{-1}\ m^{-}$

^{1}) increased by approximately 1% for every additional 100g in shoe mass. Divert et al. (2008) conducted a similar study of the effects of shoes and mass on energetics and mechanical factors during running over six conditions. In this study, the mass was controlled by using weighted socks. A significant mass effect was present as runners were 3% less efficient (decrease in RE) with 350g shoes and socks versus barefoot. Further studies have also reported similar findings (Burkett et al., 1985; Franz et al., 2012; Squadrone & Gallozzi, 2009). While acknowledging some variation in results, Nigg and Enders (2013) also described shoe mass as a predominant characteristic of running shoes that influences RE. Indeed, reviews by Fuller and colleagues (2015) and Cheung et al (2016) have both identified an effect of footwear mass is commonly recognized within the literature.

Despite these conclusive findings related to the effect of shoe mass on RE, research has highlighted the fact that mass alone does not account for all of the observed differences in RE when footwear is altered (Cheung & Ngai, 2016; Franz et al., 2012; Frederick et al., 1983). Below is a review of additional factors thought to impact RE.

2.12.6 Shoe Sole Characteristics

Frederick and colleagues (1983) suggested that discrepancies in results examining the mass effect of running shoes could be explained by shoe cushioning. This group developed a study to test the notion of an energetic cost of cushioning, and their results demonstrated that a lower oxygen cost is expected with a softer shoe condition. These findings are consistent with others (Frederick, Howley, &

Powers, 1986; Tung, Franz, & Kram, 2014). Essentially, a ~3% energy savings in well-cushioned shoes compared to a lesser-cushioned shoe of comparable mass is seen. Additionally, Frederick, Howley and Powers (1986) studied ten well-trained male distance runners who ran on a treadmill at their approximate race pace (3.65-4.55 $m \cdot s^{-1}$). The authors aimed at demonstrating that soles mechanical properties (ability to deform and recoil) might influence RE. Indeed, the softer, more compliant and resilient shoe soles decreased oxygen uptake by ~2%. Although the more compliant shoe was 31 grams heavier, the authors concluded that changes in oxygen uptake were the result of a change in the shoe's mechanical properties. Conversely, Burke and Papuga (2012) reported a 2% improvement in RE when midsole longitudinal bending stiffness was orthotic inserts compared to the shoe fitted insoles was improved. Roy and Stefanyshyn (2006) reported a 1% improvement in RE with increased longitudinal bending stiffness (38 N mm^{-1}) compared to the control (18 N mm^{-1}) conditions. However, the stiffest midsole (45 N mm^{-1}) showed no improvements to RE. Although sole characteristics can reduce the amount of energy absorbed by a shoe's sole, these studies have failed to define this relationship. Taken together, these studies show that the cushioning properties of a shoe's sole may influence the mechanical work performed and, thus, the economy of movement. These changes could be achieved by altering movement patterns and muscle activity. The identification of these variables and their effect on RE point out the complex interaction between footwear and oxygen cost. While SHOD certainly represents a more compliant condition than a bare heel, foot strike patterns often change in barefoot or in minimalist shoes. As discussed below, this has also been shown to have an impact on RE.

2.12.7 Spatiotemporal

The effects of running footwear have also focused on changes to spatiotemporal variables. As such, De Witt and colleagues (2000) reported that barefoot runners took significantly shorter strides, at a higher frequency with reduced contact time over three velocities (3.5, 4.5, 5.5 m s^{-1}) compared to their SHOD counterparts (MI=14%, 335g). In fact, barefoot stride frequency was ~3% greater than SHOD and minimalist footwear conditions. Indeed, stride length while barefoot was reduced by ~4% and ~5% compared to SHOD and minimalist conditions, respectively. Conversely, Paulson and Braun (2014) reported no significant differences in stride length, stride frequency, or contact time between three footwear conditions [barefoot, minimalist (MI=96%, 167g) and shod (characteristics unknown)]. Thus, footwear worn by the runner has the potential to alter spatiotemporal variables.

Stride length decreases in barefoot condition compared to any other footwear condition. The highest increase in stride length occurs in SHOD. As shown by Squadrone and Gallozzi (2009) barefoot stride length significantly decreases by ~5% and ~7% compared to minimalist (MI=>90%, 48g) and SHOD (341g) conditions, respectively. Ahn, Brayton and Martin (2014) also demonstrated a ~2-5% decrease in stride length when barefoot compared to neutrally SHOD (MI=16%,

~260g) conditions. Others have also shown similar results (Cronin & Finni, 2013; Fleming et al., 2015; Komi, Gollhofer, Schmidtbeicher, & Frick, 1987).

Alterations in stride frequency displayed an inverse trend. That is stride frequency increases in barefoot compared to other footwear conditions. For instance, Divert, Baur and colleagues (2005) reported a significant 5% larger stride frequency while barefoot compared to SHOD. Further, Tung, Franz and Kram (2014) and Ahn, Brayton and Martin (2014) reported a ~2% and ~2-5% increase on the same parameter in barefoot compared to SHOD, respectively. These results are corroborated by others reporting similar results (Fleming et al., 2015; Komi et al., 1987). Furthermore, stride frequency was higher in a stepwise fashion (McCallion et al., 2014), from higher (barefoot) to lower (SHOD) frequency (Lussiana, Fabre, Hébert-Losier, & Mourot, 2013). Indeed, Squadrone and Gallozzi (2009) showed ~3% and ~6% stride frequency differences in minimalist (148g) and SHOD footwear, respectively compared to barefoot. A significant positive effect of running velocity has also been reported (Fleming et al., 2015).

Contact time also appears to be altered by footwear conditions. In fact, barefoot locomotion is associated with a decrease in contact time in both walking and running (Cronin & Finni, 2013) compared to SHOD(Divert, Mornieux, et al., 2005; Fleming et al., 2015; McCallion et al., 2014). Furthermore, Lussiana and colleagues (2013) reported decreased contact time with minimalist (MI=86%,187g) compared to SHOD (333g) footwear.

2.12.8 Foot Strike Pattern

A common belief is that barefoot runners typically use a fore-foot strike (Ahn et al., 2014) whereas SHOD conditions promote a rear-foot strike, primarily due to the additional cushioning beneath the heel (Ahn et al., 2014; Hatala et al., 2013; Lieberman et al., 2010). Observations following habitually SHOD (Hasegawa et al., 2007; Kerr, Beauchamp, Fisher, & Neil, 1983; Larson et al., 2011) and habitually barefoot (Hatala et al., 2013; Lieberman et al., 2010) runners have, in fact, identified various rates for each foot strike pattern in both conditions.

An early observation of recreational SHOD runners during a 10 km race and at two points during a marathon (20 km & 35 km) reported all three types of foot strike patterns (Kerr et al., 1983). Approximately 80% ran with a rear-foot strike, 20% with a mid-foot strike and only three runners in total (<1%) had a fore-foot strike. However, it should be noted that the data was collected at a rate of 60Hz, which is not considered sufficient to accurately capture foot strike pattern during dynamic movements such as running. Furthermore, proper controls to categorize runners were missing. Therefore, differences between recreational and elite runners might have induced discrepancies in this report. Recent investigations on SHOD runners report similar rates of foot strike pattern with a slightly higher number of fore-foot strikes. For example, Hasewaga and colleagues (2007) observed elite level runners during a half-marathon and reported that ~75% ran with a rear-foot strike, ~24% mid-foot strike, and ~1% fore-foot strike. Another study following half-, relay- and full-marathon runners reported ~94% rear-foot strike, ~4% mid-foot strike, and ~2% fore-foot strike (Larson et al., 2011). The data in this study was collected using a 300Hz camera. It was also noted that their sample was mostly recreational runners wearing mostly typical modern running shoes. This may also explain why a rear-foot strike was more common and a mid-foot strike was less frequent than previous reports. Furthermore, the authors noted that the best runners in their study were not elite as those in the other studies; the fastest runners in this study would not rank within the top 100 of the marathon runners examined by Hasegawa and colleagues (2007). Further, the lower-end speeds reported by Kerr et al. (1983) was faster than 85% of the marathoner runners of this study. Filming speed 2- (Hasegawa et al., 2007) and 5-times (Kerr et al., 1983) faster than other studies is another possible reason for the differences observed.

An understanding of habitually barefoot runners may provide some insight into the mechanisms, and potential advantages and/or disadvantages of barefoot running for modern runners. Only two studies have addressed this aspect (Hatala et al., 2013; Lieberman et al., 2010). The seminal work of Lieberman and colleagues (2010) reported a higher incidence of a fore-foot strike pattern in contrast to a rear-foot strike. At self-selected endurance running speeds, 75% of adult and 66% of adolescent Kalenjin runners of northern Kenya, adopted a fore-foot strike while 25% and 12% used a rear-foot strike, respectively. Further, it was shown that less (0% and 2%) exhibited a mid-foot strike. This trend, a large percentage of the runners using a fore-foot strike, was also observed in the SHOD condition for each group. Advocates for barefoot running often cite the results of this study when promoting the benefits of the barefoot condition. However, Hatala and colleagues (2013) observed a different habitually barefoot group, the Daasanach, also of northern Kenya. The authors reported at preferred endurance running speeds, 72%, 24%, and 4% adopted a rear-foot, mid-foot, and fore-foot strike, respectively. In fact, at no point in this study did the majority of runners use a fore-foot strike. This finding challenges the notion that habitually barefoot individuals exhibit a fore-foot strike pattern when running at self-selected speeds. The influence of speed on foot strike pattern was also statistically significant in this study. In fact, variation in speed was proposed to account for the difference in preferred foot strike pattern between each study. The Daasanach averaged 3.3 $m \cdot s^{-1}$ at their preferred endurance speed whereas the Kalenjin runners ranged 5.1-5.9 $m \cdot s^{-1}$. Similar to habitually SHOD runners, this demonstrates that habitually barefoot runners may alter their foot strike pattern as running speeds increase. Running speed has previously been shown to affect foot strike pattern selection. In a study by Nigg and colleagues (1987) habitually SHOD runners altered the position of their foot at strike as running speed increased. In fact, Keller and colleagues (1996) reported that 86% of habitually SHOD runners, who predominantly used a rear-foot strike when running at speeds 5 $m \cdot s^{-1}$ or slower, preferred either a mid-foot strike or fore-foot strike at 6 $m \cdot s^{-1}$ or higher. An interesting finding of the Larson (2011) study showed that as running distance increased (and presumably speed decreased), a speed threshold for a switch towards a mid-foot strike was apparent. This study followed 936 runners during a half-marathon/marathon road race and found that ~92% of fore-foot strikers changed foot strike pattern to a mid-foot strike or rear-foot strike. During the race, ~60% of runners who exhibited a mid-foot strike at the 10km mark (~3% of runners) switched to a rear-foot strike at the 32km point. Furthermore, ~98% of those with a rear-foot strike at 10 km (~89% of runners) remained rear-foot strike at the 32 km point. Similarly, this shift in foot strike pattern due to running speed observed in habitually SHOD runners has also been reported in habitually barefoot runners (Hatala et al., 2013; Lieberman et al., 2010). The percentage of mid-foot strike/fore-foot strike also increased significantly with speed indicating an anterior shift in foot strike pattern occurs from speeds of 5 to 6 m s^{-1}. This suggests that other factors such as running speed, influence the selection of a foot strike pattern.

Of the few studies that have observed the effect of changing footwear on foot strike pattern, mixed results have been reported. Cronin and Finni (2013), as well as McCallion and Colleagues (2014), have reported no significant effect of footwear on foot strike pattern. That is, no change in foot strike pattern was observed from barefoot to SHOD conditions. However, Hamil and colleagues (2011) reported that runners appeared to alter foot strike pattern from rear-foot strike to mid-foot strike from SHOD to barefoot conditions, despite changes in speed. Recently, Ahn, Brayton and Martin (2014) observed 40 recreational and highly trained runners at four standardized running speeds (2.5, 2.8, 3.2 and 3.5 m s^{-1}) on a motorized treadmill while barefoot (five-toed socks) and SHOD (neutral running shoes). Eleven runners (~28%) consistently ran with a fore-foot strike, and 11 runners (~28%)

consistently ran with a rear-foot strike, regardless of footwear. Furthermore, the remaining 18 runners (45%) shifted from a rear-foot strike while SHOD to a fore-foot strike while barefoot. To further advance on this topic, Fredericks and colleagues (2015) recently followed 26 recreational runners in barefoot, minimalist (MI=100%; 312g) and SHOD (96%; 167g) running conditions and reported a clear influence of footwear on foot strike pattern. For instance, there was a higher incidence of a mid-foot strike and fore-foot strike while barefoot and wearing minimalist footwear compared to SHOD. In fact, within this study, the minimalist footwear condition exhibited an intermediate distribution of fore-foot strike between barefoot and SHOD conditions. As such, the foot-strike-pattern of a runner may be influenced by several factors, such as running speed, but the influence of footwear models on foot-strike-pattern is unclear based on the current literature.

2.13 Muscle Activation

Considering various kinematic adjustments (e.g., stride length, stride frequency, & foot strike pattern), known to influence RE, are altered by footwear, an obvious consideration would be changes in muscle activation during these movements. That is, does footwear worn by a runner effect muscle activation and is there an effect on RE as a result? Indeed, a large number of studies have examined changes in muscle activation across footwear conditions and a good overview of these studies-including the effects of foot posture, footwear, and orthoses on muscle activation-is available in a systematic review by Murley and colleagues (2008). Indeed, scientific evidence suggests changes in muscle activation may account for changes in RE (Barnes & Kilding, 2015). For example, Kyrolainen and colleagues (2001) and Numela et al. (2007) showed that improvements in RE and running performance correlate with increased lower-limb muscle pre-activation.

These studies have focused on changes in muscle activation amplitude (Greensword et al., 2012; Kasmer, Wren, & Hoffman, 2014; Nawoczenski & Ludewig, 1999; Olin & Gutierrez, 2013), timing (Ervilha, Mochizuki, Figueira, & Hamill, 2017; Von Tscharner, Goepfert, & Nigg, 2003) and the co-activation of the lower-limb musculature (Ervilha et al., 2017; Rao et al., 2015; Von Tscharner et al., 2003). Although the aforementioned studies have shown changes in muscle activation, others have reported no change in either the magnitude (Burke & Papuga, 2012; Nawoczenski & Ludewig, 1999; Roy & Stefanyshyn, 2006) or timing (Ahn et al., 2014; Burke & Papuga, 2012; Nawoczenski & Ludewig, 1999; Roy & Stefanyshyn, 2006). However, it appears that the differences reported are likely due to high variability of footwear used in each study.

Some studies have evaluated the use of orthotic inserts (Ahn et al., 2014; Burke & Papuga, 2012; Nawoczenski & Ludewig, 1999) while others have compared shoes of a differing heel and sole construction (Greensword et al., 2012). Few have compared barefoot (Ahn et al., 2014; Olin & Gutierrez, 2013; Von Tscharner et al., 2003) or minimalist footwear (Kasmer, Wren, et al., 2014) to SHOD conditions. Regardless, it does appear that the footwear worn by an individual can affect muscle activation of the lower limb, specifically that of the shank.

The analysis of muscle activation has been conducted on an assortment of the lower-limb musculature, depending on the purpose of the study. However, EMG is commonly sampled from the *Gluteus Maximus*, *Vastus Lateralis*, *Rectus Femoris*, *Biceps Femoris*, *Tibialis Anterior*, *Soleus* and medial and lateral *Gastrocnemius*. Their reported activation throughout the running gait cycle is well documented (Cavanagh, 1990; Elliott & Blanksby, 1979; Kasmer, Ketchum, et al., 2014; Komi et al., 1987; Kyröläinen et al., 2001, 1999; Mero & Komi, 1986).

Modified shoe conditions have also been used to manipulate the footwear of participants. Mixed results are also available for this footwear modality. Roy and Stefanyshyn (2006) observed the *Soleus*, medial *Gastrocnemius*, *Biceps Femoris*, *Vastus Lateralis* and *Rectus Femoris* activation of runners in running shoes of three different sole stiffness levels. This group reported no changes to the root-mean-square EMG over the three shoe conditions. Conversely, Greenwood, Aghazadeh, & Al-Qaisi (2012) observed individuals walking in modified track shoes with a removable heel. This group reported that EMG activity of the *Tibialis Anterior* and *Gastrocnemius* decreased by ~22% and ~24%, respectively, while walking with the heels attached at 0.89 $m \cdot s^{-1}$. Similar results were demonstrated at a walking speed of 1.34 $m\ s^{-1}$.

Studies comparing barefoot to SHOD conditions also have mixed results. Von Tscharner, Goepfert, and Nigg (2003) reported delayed onset of the *Tibialis Anterior* following foot contact while SHOD compared to barefoot, whereas, Olin & Gutierrez (2013) reported both average and peak muscle activation of the Tibialis Anterior were significantly lower barefoot than SHOD. Conversely, average *Gastrocnemius* activation was significantly higher in barefoot versus SHOD conditions, while there were no statistically significant differences in peak *Gastrocnemius* activity. However, Ahn, Brayton and Martin (2014) reported no difference in the offset times of the medial and the lateral *Gastrocnemius* when barefoot and SHOD.

Relative to SHOD running, fewer studies have compared muscle activation with minimalist footwear. In fact, four recent studies examined muscle activation between minimalist footwear and SHOD conditions (Kahle et al., 2016; Kasmer, Wren, et al., 2014; Khowailed et al., 2015; Rao et al., 2015). Khowalied and colleagues (2015) compared muscle activation in females following both an acute and 6-weeks minimalist footwear exposure. An increase in the lateral *Gastrocnemius* during the swing phase following both acute and chronic running in minimalist footwear was reported. However, a decrease in *Tibialis Anterior* during the swing phase was only seen after six weeks of training. Rao et al. (2015) compared peak muscle activation between shoes with a 16 mm (SHOD) and 0 mm (MIN) heel-toe-drop and found a non-significant increase in the lateral and medial *Gastrocnemius* and *Soleus* from SHOD to minimalist conditions. However, a reduction in *Tibialis Anterior* activation was observed in the minimalist footwear condition. Kasmer et al (2014) reported significantly greater root-mean-square activity of the *Tibialis Anterior* before foot contact in SHOD compared to the minimalist condition following a 4-week training period. Participants were randomly assigned to minimalist footwear or SHOD training condition and then completed a 50-km trail run in the opposite shoe condition. They were then crossed over into the remaining footwear condition for a second 4-week training period, after which they completed a second 50-km trail run. Conversely, no differences in muscle activation were reported by Kahle and colleagues (2016) between the minimalist footwear (MI=88%; 107g) and participants' own SHOD footwear condition. The authors also reported no difference in RE between footwear conditions.

Although there remains a gap within the literature regarding the acute changes in muscle activation from footwear conditions, it appears that foot strike pattern may be a more predominant effecter of muscle activation. Recent research has shown differences in muscle activation with alterations in foot strike pattern without changes in footwear. For example, significant increases in muscle activation throughout both the swing and stance phases were associated with a change from fore-foot strike to rear-foot strike, with no change from barefoot to SHOD conditions (Shih, Lin, & Shiang, 2013). Similarly, no differences in muscle activation were reported between SHOD and minimalist conditions for both fore-foot strike (Ervilha et al., 2017) and rear-foot strike (Divert et al., 2008) running. Therefore, both disagreement in the literature and a paucity of studies examining minimalist footwear, make it difficult to establish a relationship between muscle activation and footwear. Although changes in RE are related to muscle activation (Barnes & Kilding, 2015; Nummela et al., 2007; Tartaruga et al., 2012), other factors such as footwear or foot strike pattern may be responsible.

2.14 Summary of Footwear

Knowledge of the effect of footwear choice on performance would be invaluable to endurance runners and coaches looking to gain an advantage over competitors. However, it appears that research to date is inconclusive, and somewhat limited, in establishing the optimal footwear condition. The only exception to this is related to footwear mass, where it is clear that lighter footwear is optimal. Reports of improved, decreased and even no change in RE are available. Furthermore, a large number of variables-both known to influence RE, and also affected by footwear condition- demonstrate the need for further investigation. A clear understanding of the influence of footwear on lower limb muscle activation is also void. Therefore, both the disagreement within the literature and the relatively small numbers of studies examining minimalist footwear indicate a specific gap within the literature in need of further examination. As such, this study aims to determine if the use of minimalist footwear (MI=70%, 178g) has an effect on RE and muscle activation and if this effect is magnified after exercise-induced fatigue. Further, this study aims to determine if trends in EMG reflect changes in RE. Therefore, the research question is organized into the following sub-questions:

A) What is the effect of minimalist footwear on RE?

B) Does muscle activation amplitude reflect these differences?

C) Is there a change in RE with EIF?

D) Is there an attenuation of fatigue in minimalist footwear compared to SHOD?

It is hypothesized that minimalist footwear will lead to a better RE in both the rested and fatigued state, but the $\dot{V}O_2$ will reflect the differences in mass between footwear conditions. Changes in muscle activation amplitudes will reflect any metabolic differences. No footwear effect on EMG is expected, however, a fatigue effect is.

Chapter 3: Materials and Methods

3.1 Experimental Procedures

A total of ten male distance runners partook in this study. To be eligible for this study, participants were required to be training a minimum of five days a week, with one session being high-intensity interval training over 70% of maximal aerobic speed (MAS). Also, they were required to run a minimum of 50 km, per week. This study consisted of three sessions; one familiarization and two counterbalanced experimental conditions (MIN and SHOD) separated by at least 72 hours (Figure 3.1). Before each session, participants were instructed to refrain from strenuous exercise and resistance training for 36 hours and to avoid caffeine, alcohol, and other stimulants or supplement intake for 24 hours. Participants were also asked to arrive well rested for each testing session.

All sessions were conducted in the morning at the same time of day for each participant. During the familiarization session (Day one), participants read and signed the consent form, and answered a long-form physical activity readiness questionnaire to screen for health and injury risks in addition to completing a questionnaire that determined training status and minimalist shoe experience. If eligible, anthropometric measurements were recorded and participants underwent a fitness appraisal. All participants were given identical footwear to ensure they were all exposed to the same conditions during their running session. The minimalist footwear (Altra "one") weighed 178 g with 0 mm heel-toe drop and a minimalist index of 70%. These characteristics correspond with the definition established in the literature (Esculier et al., 2015). The SHOD footwear (Brooks "Glycerine 13") weighed 349 g, with a 12 mm heel-toe drop with a minimalist index of 30%. Both models of footwear were neutral. That is, no anti-pronation or anti-supination elements in the outsole. Appropriate footwear was provided prior to each experimental session. During sessions two and three (Day two and three), participants underwent a pre- and post-treatment running economy test interspaced with the treatment consisting of exercise-induced fatigue in both SHOD and minimalist footwear conditions.

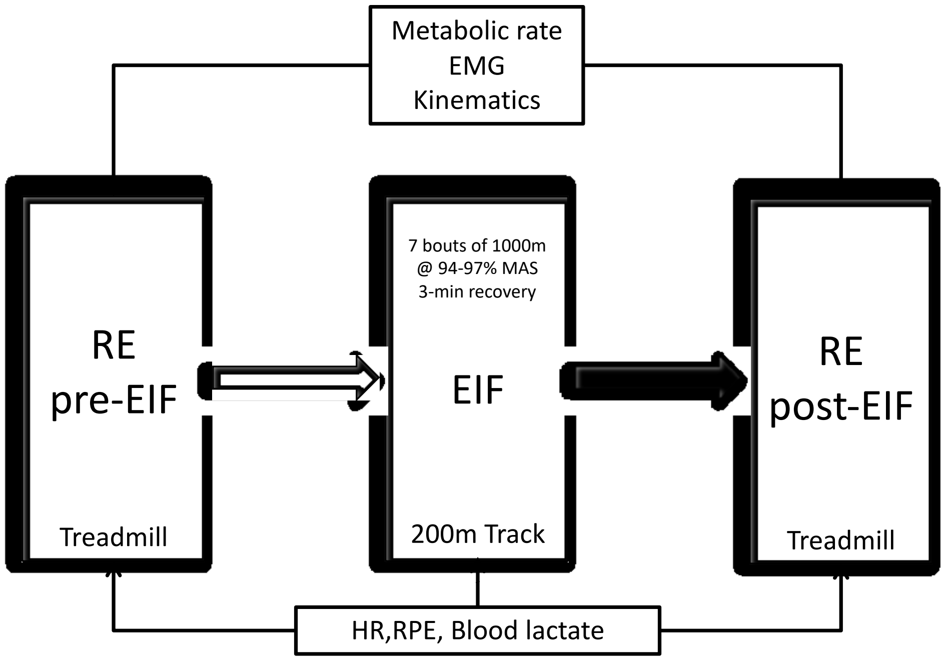

Figure 3.1: Experimental design and time line. Each participant completed two experimental trials in randomized order. Each experimental trial consisted of pre- and post-exercise induced fatigue (EIF) running economy test interspaced by the fatiguing session that consisted of seven bouts of 1000 m with 3-min recovery between each run.

DAY ONE: Maximal oxygen uptake ($\dot{V}O_{2max}$) was tested to characterize the participants' aerobic fitness and to determine MAS. The incremental test was performed on a motor-driven treadmill at a constant 1% slope. Before the test, a warm-up, consisting of running at a self-selected speed for 5-min was provided. Afterward, the fitness test started at an initial speed of 7 km h^{-1} and increased by 1 km h^{-1} every 2-min until volitional exhaustion was reached (Basset & Boulay, 2003; Leger & Boucher, 1980). Participants were then given a 5-min rest before undergoing a verification phase consisting of running at 105% of the speed reached at $\dot{V}O_{2max}$ until volitional exhaustion. This procedure was implemented to ensure the participants reached $\dot{V}O_{2max}$ (Rossiter, Kowalchuk, & Whipp, 2006). A recovery period followed, until participants' heart rate decreased to 120 bpm.

Day Two and Three: Before the start of data collection on both days participants were prepared for electromyography data collection. A Trigno wireless acquisition system (Delsys Inc., Boston, MA, USA) was used for all EMG collection. Data were sampled at 2000 Hz for all trials. Participants had electrodes affixed to the right leg to record muscle activation. Electrodes were placed over five muscles: *Biceps Femoris*, medial *Gastrocnemius*, *Gluteus Maximus*, *Tibialis Anterior*, *Vastus Lateralis* as per Criswell (2010). The skin was shaved, gently rubbed with medical sandpaper, and cleaned with an alcohol swab. Following electrode placement, participants performed maximum voluntary isometric contractions (MVCs) of each muscle. These contractions lasted for approximately 5-sec and were repeated twice for each muscle. Participants were given 1-min rest between each contraction. Verbal encouragement was provided during all contractions to ensure all participants' maximal effort.

Participants then underwent a running economy test consisting of three randomized 8-min treadmill runs at 2.79, 3.33, and 3.89 m s^{-1} with a 1% grade and 2-min rest period between runs. Metabolic rate, EMG, heart rate (HR), video data, blood lactate concentrations and rate of perceived exertion (RPE) were recorded throughout. An optional self-selected warm-up was provided (Shaw et al., 2014) prior to the RE test. All runners opted to complete a 5-10 min warm-up before pre-fatigue tests.

Upon completion of the first RE test, the participants were then directed to a 200-m, unbanked, Mondo-surface, indoor running track to perform the EIF protocol consisting of 7 bouts of 1000-m at a running pace between 94% and 97% of MAS with a 3-min recovery between bouts. Throughout each interval, participants were given verbal feedback to help maintain their pace within the assigned range. The MAS corresponded to the speed reached at $\dot{V}O_{2max}$ and was determined as per Basset and Boulay (2003). These bouts continued until the participants reached on RPE of 18, at which time the EIF trial was stopped. If the participant did not reach an RPE score of 18 at the end of the 7th running bout, they were asked to run "all-out" until they reached this criterion (Dishman, 1994). During the EIF trials, blood lactate, HR, RPE and time to completion of each interval were collected. Muscle activation data was also recorded, but these results were not included in this particular study. The intensity of the bouts corresponded with a typical endurance runner's training session with the aim of developing aerobic power (Basset & Chouinard, 2002). Upon completion of the EIF, participants returned to the laboratory to undergo the second RE protocol as described above. On average this transition time took 22:28 ± 5:24 min. Participants were permitted to consume only water throughout the entirety of these sessions.

3.2 Data Collection

3.2.1 Rate of Perceived Exertion (RPE)

The RPE was recorded using the Borg's category-ratio scale 6-20 (Borg, 1973). Subjective ratings of effort were determined at the end of each EIF interval as well as before each RE test.

3.2.2 Blood Lactate

Blood lactate was sampled following the first, fourth and last interval as well as before each RE test. Blood samples were approximately 15-20 μL each for a total of 210-280 μL. Lactate was sampled as an indicator of fast-glycolytic energy production and fatigue occurrence. The blood was assayed on site with a lactate analyzer (Lactate scout+, EKF diagnostics, Cardiff, U.K.).

3.2.3 Heart Rate

The HR values were recorded for the entirety of each session with a heart monitor (Suunto, model Ambit2, Suunto OY, Vantaa, Finland) and uploaded to MovesCount (www.movescount.com) before being transferred to Igor Pro 6.3 (WaveMetrics Inc., Lake Oswego, Ore, USA) for determination of peak HR of each running bout.

3.2.4 Muscle Activation

During the RE trials, 10s of EMG data were collected every min. This resulted in 24 EMG trials (8 for each of the three running speeds). The EMG data was synced to video data that was required for signal processing. This syncing was done using a light that was placed within the video frame and connected to the Delsys system. When EMG data acquisition was initiated, the light turned on enabling frame "0" of EMG data to be identified in the video. See below for more details.

3.2.5 Cardiorespiratory Measurements

Cardiorespiratory parameters were recorded during incremental and running economy tests. Oxygen uptake, carbon dioxide output ($\dot{V}CO_2$), breathing frequency, and tidal volume were continuously recorded through real-time breath-by-breath sampling using an automated respiratory system (Oxycon Pro, Jaeger, Hochberg, Germany). Respiratory exchange ratio (RER) and minute ventilation were calculated as the quotient of $\dot{V}CO_2$ on $\dot{V}O_2$ and as the product of breathing frequency by tidal volume, respectively. Prior to testing, gas analyzers and volume were calibrated with medically certified gases and automated flow calibration, respectively.

3.2.6 Video Data

A video camera (Casio, Exilim HS ex-zr1000, Casio computer co ltd., China) was used to capture lower limb motion during the RE tests. This camera was placed perpendicular to the treadmill. Video trials were collected during all EMG data collection and as described above, were synced with EMG data. The camera sampled at a rate of 240 Hz.

3.3 Data Analysis & Reduction

3.3.1 Metabolic

All metabolic data were transferred to Igor Pro 6.3 (WaveMetrics Inc., Lake Oswego, Ore, USA) for further analyses. All cardiorespiratory parameters from both the incremental test and the RE tests were smoothed before further analysis. This was done using the Loess smoothing method from the "Smoothing" command in Igor. Options selected in the Loess method were a quadratic polynomial with a window size of 0.03 of the total frame number.

Incremental test data was then examined to determine maximal $\dot{V}O_2$ and its corresponding values of $\dot{V}CO_2$, breathing frequency, tidal volume as well as, peak oxygen uptake of the verification phase. Secondly, the equivalent of oxygen and carbon dioxide were calculated and plotted over $\dot{V}O_2$ to determine ventilatory threshold by identifying when the equivalent of oxygen, abruptly departs from the equivalent of carbon dioxide as a function of $\dot{V}O_2$ (Cooper & Storer, 2001).

For the RE test, the data was examined to ensure the RER was $\leq$1.0. Then total $\dot{V}O_2$ and $\dot{V}CO_2$ were computed using the area-under-the-curve method applied on the middle 4-min of the 8-min running bouts. RE was calculated according to Daniels and Daniels (1992). In brief, RE was expressed as ml kg^{-1} km^{-1}, and the energy cost was expressed as kcal kg^{-1} km^{-1} to normalize for different running velocities and to allow for comparisons with the existing literature.

3.3.2 Heart Rate

For the RE test, heart rate was calculated as the average heart rate across the middle 4-min of each running bout to coincide with the metabolic data. Heart rate peak was determined using the FindPeak function from Igor Pro 6.3 (WaveMetrics Inc., Lake Oswego, Ore, USA). Peak HR was detected from the HR signal. First, the signal was smoothed using a Box smoothing procedure that averaged an equal number of points before and after the averaged output (or smoothed value). Then, the peak HR was detected [with a minimum peak amplitude of 5% and a maximum peak window of 100] at the first derivative zero-crossing, where the second derivative was negative (Igor Pro Manual – volume III- chapter 9 Signal processing, 2017).

3.3.3 Video

All video data analysis was done using Kinovea (Version 2.0). Videos were visually examined to identify the frame of foot-contact and toe-off and to separate the gait cycle into stance and swing phases. This analysis was done for a total of 5 strides from the start of the trial. The identified frame numbers were recorded and used to assist with EMG analysis. They were also used to calculate contact time (toe-off frame – foot-contact frame). The foot strike pattern of these five strides was classified as being either a rear-foot strike or fore-foot strike. Stride frequency was also estimated by counting the number of full strides of the right leg (i.e., foot-contact through swing to subsequent foot-contact) for 10-s of video data. This value was then multiplied by six to calculate stride frequency (strides min^{-1}).

3.3.4 Electromyography

Due to technical issues, resulting in a poor signal to noise ratio, several trials of data were removed. In total, all SHOD pre-trials for *Biceps Femoris* were removed for one subject, for another subject 7 minimalist footwear pre-trials and all minimalist footwear post-trials were removed for *Tibialis Anterior,* and 2 SHOD post trials for *Vastus Lateralis* were not used for another subject.

The EMG data were windowed from heel-contact to toe-off for the each of the strides examined. This windowing was done using data from the video analysis. All raw EMG data was filtered using a 20 Hz dual-pass, high-pass filter to remove movement artifact (De Luca, Gilmore, Kuznetsov, & Roy, 2010). Prior to amplitude analysis, the raw EMG was normalized to the maximum value of the MVC data. Root-mean-square was calculated using a 100-ms moving window. Integrated EMG was calculated using area-under-the-curve (trapezoid rule). Both values were determined for the duration of stance (from heel contact to toe-off). The resulting root-mean-square and integrated EMG measures were then averaged across the first five strides in each trial. These average activations were used for all statistical analysis.

3.4 Statistical Analysis

All values are reported as a mean ± standard deviation unless otherwise specified and an alpha level (α) of 0.05 was used to indicate statistical significance.

Tests for statistical assumptions (i.e., normality and homogeneity of variance) were performed, that is, the homogeneity of variance was tested using Levene's test, and normality was tested using Kolmogorov-Smirnov test. First, descriptive statistics were conducted on all parameters of interest (body mass, height, age, training profile parameters, $\dot{V}O_{2max}$, and MAS). Second, all data corresponding to the RE tests were collapsed for speed and a 2-way [2 conditions (MIN vs. SHOD) X 2 times (pre- vs. post-EIF) ANOVA with repeated measures was performed on RE, HR, RER, stride frequency, contact time and root-mean-square and integrated EMG. Third, a 2-way [2 conditions (MIN vs. SHOD)) X 5 time (pre- and post-EIF and for the first, fourth, and last interval)] ANOVA with repeated measures was conducted on blood lactate and RPE. Finally, a 2-way [(2 conditions (MIN vs. SHOD) X 3 time (first, fourth, and last interval)] ANOVA with repeated measures was performed on peak HR and interval pace during the EIF. IBM SPSS Statistics 20 (IBM Corporation, Armonk, New York, USA) was used for statistical analyses.

Chapter 4: Results

4.1 Participant Characteristics

The following results are based on ten subjects except for metabolic data, blood lactate, years of training and interval training (n=9). Results of the fitness appraisal, as well as anthropometric measurements, are provided in Table 4.1. Participants' $\dot{V}O_{2max}$ corresponded to the 95th to 99th percentile (American College of Sports Medicine (ACSM), 2013), which puts them well above the average recreational runner. Further, the aerobic fitness of participants is confirmed by the velocity (MAS) reached at exhaustion (18.1 km h^{-1}) and HR_{max} that reached 100% of the age-predicted (220-age).

4.2 Participant Training Profile

The training profile of all participants was screened to ensure training status was sufficient to achieve the high EIF metabolic demand. Indeed, the participants had to train a minimum of five days a week and have one of their weekly training sessions at an intensity higher than 70% MAS. In addition, they had to run at least 50 km per week and had to follow a structured training program, as shown in Table 4.1. As such, they represent a good cluster of runners as demonstrated by their 10k personal best corresponding to an average running performance score of 478.1 ± 185.6 based on world records (Mercier & Beauregard, 1994). Further, the runners were classified as ”regional class” according to the USA Masters Track and Field online calculator (http://www.usatfmasters.org/fa_agegrading.htm). This calculator uses the age and sex matched world record for 10 km and dividing it by the participants' recent 10 km race time. Regional class runners are defined as 70% to 79.9% of the age and sex normalized world record for a 10 km race. This group has a score of ~74%.

Table 4.1: Summary of the participants' characteristics and training profile.

Measure	Mean	SD	Range
Age (years)	28.3	8.4	19 - 41
Mass (kg)	71.1	4.9	59.4 - 76.8
Height (cm)	176.4	6.5	167 - 187
Body Mass Index (kg m^2)	23	2	21 - 25
VO_{2max} (ml min^{-1} kg^{-1})	61.6	7.3	48.3 - 75.1
Respiratory Exchange $Ratio_{max}$	1.14	0.04	1.11 - 1.23
$Ventilation_{max}$	160.3	16.5	137 - 191
Ventilatory Threshold (% max)	78.8	6.9	68.6 - 86.8
HR_{max} (beats min^{-1})	190.3	9.0	178 - 208
MAS (km hr^{-1})	18.0	1.1	15.3 - 19.3
Structured Training (years)	4.4	4.7	0 - 17
Training Load (km $week^{-1}$)	104.0	63.5	40 - 210
10K Personal Best (mm:ss)	36:02	4:22	30:43 - 44:10
Weekly Training Sessions	7.1	2.7	3 - 13
Weekly Interval Training Sessions	1.5	0.7	0 - 2

4.3 Exercise-Induced-Fatigue

As displayed in Figure 4.1, blood lactate increased as a function of running intervals. Similar increases were observed for RPE score and HR_{peak}, therefore confirming fatigue occurrence. Statistical analysis revealed no significant interaction for blood lactate. However, a significant main time effect was observed for blood lactate ($F_{(4, 32)}$ = 57.376, p=0.001). Pairwise comparison showed that all blood lactate measurements significantly differed from each other. Furthermore, statistical significance was also shown in RPE. A significant main time effect was revealed ($F_{(4, 36)}$ = 95.947, p=0.001). *Post-hoc* analysis showed that as for blood lactate, all RPE scores significantly differed from each other. Finally, a significant main time effect was present for HR_{peak} ($F_{(2, 18)}$ = 21.954, p=0.001). The pairwise comparisons showed that HR_{peak} of the first interval significantly differed from the two others.

Statistical analysis also revealed a main condition effect on running pace ($F_{(1,9)}$ = 5.710, p=0.041). Runners were faster by ~6 s in minimalist compared to SHOD condition; and as displayed in Figure 4.2, although not significant, they were faster at each time point (first, fourth, and last interval). Indeed, the average run time for all 1000m intervals was lower during in the minimalist footwear compared to SHOD condition (3:25 ± 0:15 and 3:28 ± 0:17 min km^{-1}, respectively). Note that MAS was 18.0 ± 1.1 km hr^{-1} and that runners were required to perform intervals between 94 and 97% MAS during EIF, which corresponded to 16.9 ± 1.1 km hr^{-1} (3:26 ± 0:18 min km^{-1}) and 17.5 ± 1.1 km hr^{-1} (3:33 ± 0:17 min km^{-1}), respectively.

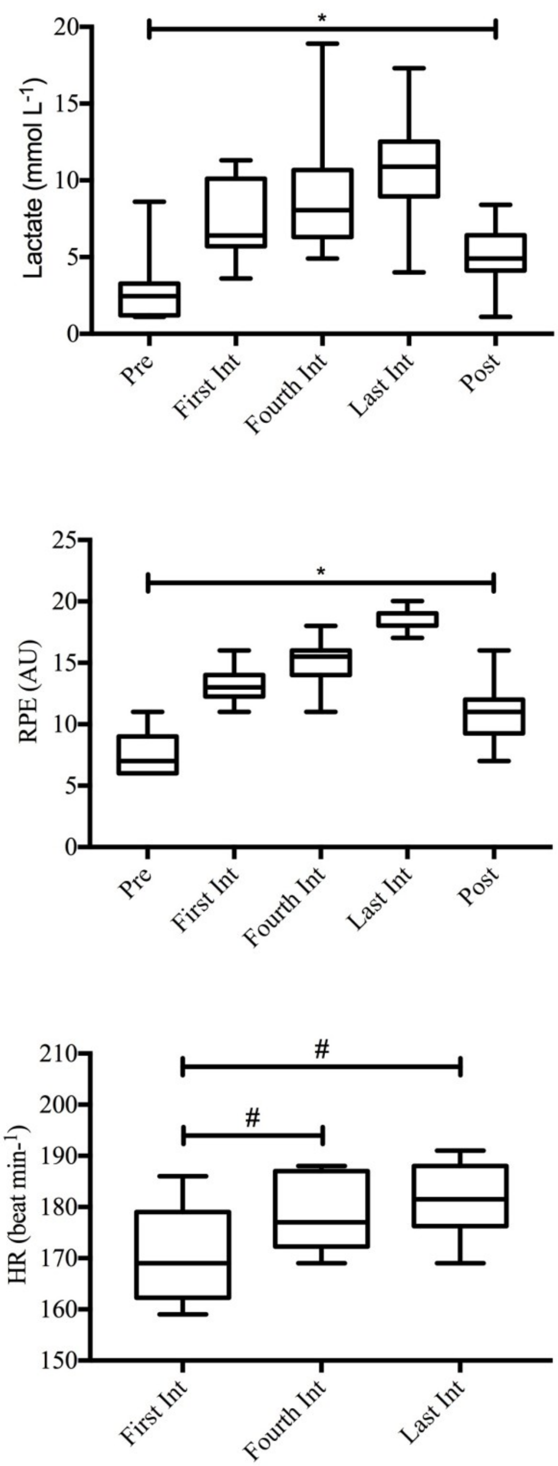

Figure 4.1: Lactate production, RPE score, and HR as a function of time during EIF. *significantly different from each other for lactate and RPE and #significantly different from the first exercise bout (First Int) for HR; $p<0.05$.

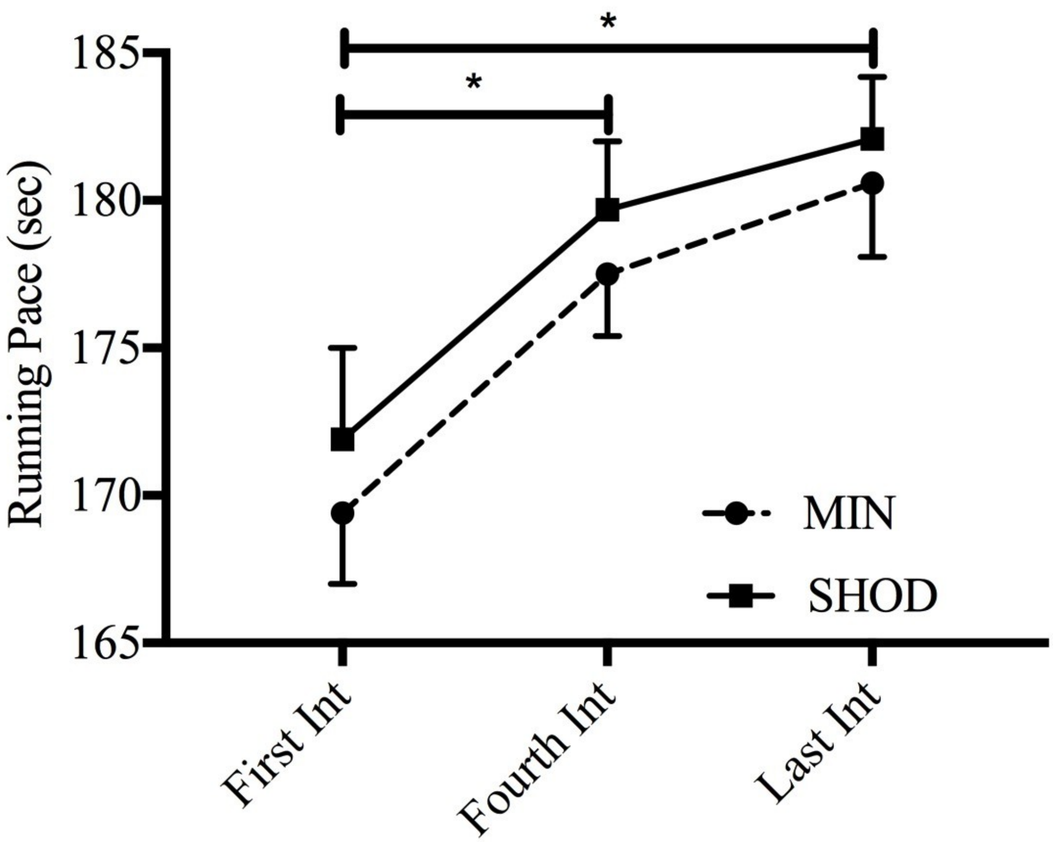

Figure 4.2: Running pace as a function of time during EIF. * significantly different from the first exercise bout (First Int); p<0.05.

4.4 Metabolic and cardiorespiratory parameters

As seen in Table 4.2, no significant effect of either condition or time was observed on metabolic parameters. Heart rate during the RE tests was significantly different between pre- and post-EIF ($F_{(1,8)}$ = 22.834, p=0.001) going from 148±35 to 158±31 bpm.

Table 4.2: Metabolic (Mean ± SD) responses across footwear and fatigue condition;
* significant time effect (pre-fatigue HR < post-fatigue HR).

	MINIMALIST SHOE (178 grams)			CONVENTIONAL SHOE (349 grams)		
VARIABLE	**PRE-FATIGUE**	**POST-FATIGUE**	**CHANGE**	**PRE-FATIGUE**	**POST-FATIGUE**	**CHANGE**
RE (mL kg^{-1} km^{-1})	206.7 (9.4)	204.2 (14.8)	-2.5 (16.3)	204.4 (7.3)	210.7 (10.2)	6.3 (6.6)
Energy Cost (kcal kg^{-1} km^{-1})	1.01 (0.04)	0.99 (0.09)	-0.02 (0.1)	1.00 (0.05)	1.03 (0.06)	0.03 (0.04)
VO_2 (ml min^{-1})	2932 (261)	2891 (278)	-41 (234)	2912 (245)	2972 (259)	60 (126)
HR (beats min^{-1})*	145 (10)	157 (11)	12 (5)	151 (13)	160 (12)	9 (10)
% Maximal HR	76 (6)	83 (63)	6 (2)	79 (7)	84 (7)	5 (5)
RER	0.89 (0.11)	0.85 (0.10)	-0.04 (0.03)	0.90 (0.14)	0.89 (0.10)	-0.01 (0.08)
VE (L min^{-1})	80.3 (10.0)	81.0 (11.3)	0.7 (3.6)	81.3 (12.1)	82.2 (12.2)	0.9 (4.9)

4.5 Kinematics

The descriptive statistics for kinematics are displayed in Table 4.3. There was no difference observed in foot strike pattern between SHOD and minimalist footwear conditions. The majority of participants adopted a rear-foot strike pattern that did not change substantially after fatigue. Similarly, there were no differences in either contact time or stride frequency between shoe conditions.

Table 4.3: Sagittal kinematic (Mean ± SD) responses across footwear and fatigue conditions.

	MINIMALIST SHOE (178 grams)			CONVENTIONAL SHOE (349 grams)		
Variable	**PRE-FATIGUE**	**POST-FATIGUE**	**CHANGE**	**PRE-FATIGUE**	**POST-FATIGUE**	**CHANGE**
Contact Time (ms)	534 (36)	531 (39)	-2 (14)	515 (40)	471 (9)	44 (182)
Stride Frequency (strides min^{-1})	81 (5)	82 (5)	1 (2)	81 (5)	82 (5)	1 (1)
Rear Foot Strike (%)	71 (33)	78 (32)	7(1)	77 (32)	75 (32)	2(0)

4.6 Electromyography

The statistical analyses revealed a condition effect on the medial *Gastrocnemius* for integrated EMG ($F_{(1, 8)} = 7.68$, p=0.024). As shown in Table 4.4 integrated EMG was higher in minimalist footwear compared to SHOD. No other significant effect was observed for the four other muscles (*Biceps Femoris*, *Tibialis Anterior*, *Vastus Lateralis*).

As shown in Table 4.5, a significant interaction has been revealed for the medial *Gastrocnemius* root-mean-square ($F_{(1,8)}$ = 7.32, p=0.027) and the *post-hoc* analysis showed that minimalist footwear condition (0.45±0.12) displayed higher root-mean-square values compared to SHOD (0.32±0.13) pre-EIF.

Table 4.4: Integrated EMG (Mean±SD) responses across footwear and fatigue conditions; # significant Condition effect, ns non-significant.

	MINIMALIST SHOE (178 grams)			**CONVENTIONAL SHOE (349 grams)**		
iEMG (%MVC)	**PRE-FATIGUE**	**POST-FATIGUE**	**Significance**	**PRE-FATIGUE**	**POST-FATIGUE**	**Significance**
Biceps Femoris	3.9 (2.0)	3.6 (19.4)	ns	3.9 (0.9)	5.0 (2.8)	ns
Medial Gastrocnemius	8.8 (2.5)	8.3 (3.1)	#	6.0 (2.8)	6.9 (2.7)	#
Gluteus Maximus	1.3 (10.3)	1.5 (1.0)	ns	2.0 (1.7)	1.5 (1.1)	ns
Tibialis Anterior	4.7 (2.4)	5.0 (3.6)	ns	5.0 (2.4)	5.0 (2.6)	ns
Vastus Lateralis	4.3 (0.9)	4.3 (1.6)	ns	4.4 (2.6)	4.9 (2.6)	ns

Table 4.5: Root-mean-square EMG (Mean ± SD) responses across footwear and fatigue conditions; † significant interaction effect, ns non-significant.

	MINIMALIST SHOE (178 grams)			**CONVENTIONAL SHOE (349 grams)**		
RMS (%MVC)	**PRE-FATIGUE**	**POST-FATIGUE**	**Significance**	**PRE-FATIGUE**	**POST-FATIGUE**	**Significance**
Biceps Femoris	18.8 (8.7)	16.9 (9.1)	ns	21.3 (10.5)	23.3 (12.4)	ns
Medial Gastrocnemius	42.3 (12.2)	39.7 (14.9)	ns	30.1 (11.7)	33.9 (12.7)	†
Gluteus Maximus	7.1 (5.0)	8.1 (4.9)	ns	9.8 (8.0)	8.3 (5.7)	ns
Tibialis Anterior	22.2 (13.7)	24.8 (20.1)	ns	23.3 (9.6)	23.8 (12.7)	ns
Vastus Lateralis	26.5 (6.9)	25.0 (8.8)	ns	26.2 (14.6)	27.6 (14.3)	ns

Chapter 5: Discussion

The purpose of this study was to examine the effects of footwear and fatigue on running economy and its relationship with lower limb muscle activation. As such, the study compared differences between standard and minimalist running shoes (MI= 30% and 70%, respectively) in well-trained male distance runners before and following exercise-induced fatigue. The findings of the study indicate that the footwear used, as well as fatigue status, had no effect on the metabolic and cardiovascular response (i.e. RE did not change) or muscle activation amplitude. Therefore, changes in RE, or lack thereof, were generally mirrored by changes in muscle activation in all conditions. This outcome may be a reflection of two methodological flaws within this study: the minimalist index of the minimalist footwear worn by participants and the time lapse between the final interval and post-fatigue RE test. However, an unexpected finding is that the minimalist footwear positively affects performance measures (running pace) during maximal bouts compared to traditional running shoes.

5.1 Characteristics and Training Status

It is important to note that comparisons of RE are only valid between a similar group of runners. Indeed, anthropometrics, training status and measures of fitness (such as MAS and $\dot{V}O_{2max}$) influence a runner's RE (Daniels, 1985; Morgan et al., 1990). As such, inter-individual comparisons are most valid when the said variables are well-controlled. As demonstrated in Table 4.1, the population in this study is homogeneous based on group characteristics and training status, respectively. Further, variation in the subjects' characteristics was low. For example, the coefficient of variance of mass, $\dot{V}O_{2max}$, and MAS is 6.7%, 11.9%, and 6.1%, respectively. Additionally, this group of participants was well trained with some variations in training load and 10k race performance of 6.7% and 10.7%, respectively. Therefore, variation in the participants' characteristics and training status was minimal and should not affect comparisons of the metabolic measures of this study. Furthermore, this homogeneity strengthens the validity of comparisons between both footwear and fatigue conditions.

5.2 Exercise-induced-fatigue

Results indicate that participants experienced fatigue as a result of the EIF trials. Blood lactate concentrations, HR_{peak}, and RPE are common measures used to monitor fatigue status during running trials (García Pinillos, Soto-Hermoso, & Latorre-Román, 2016; Latorre-Román, García Pinillos, Bujalance-Moreno, & Soto-Hermoso, 2017; Mann et al., 2015). As seen in Figure 4.1, fatigue occurrence is supported by significant increases in these variables, which are comparable to those reported in the studies above.

The second outcome and a key finding of the study is that the self-selected running speed during EIF was higher in minimalist footwear vs. SHOD. That is, participants completed the seven near-maximal (94-97% MAS) running bouts at a pace towards the higher bound of their prescribed pace while wearing minimalist footwear. This difference corresponds to an average of 6 ±7s between minimalist footwear to SHOD conditions. Although no other study directly comparing footwear condition and self-selected running speed was identified, this finding is supported by Kasmer and colleagues (2016) who reported faster runners were more likely to be wearing minimalist footwear during a 50 km trail race. Although no kinematic variables were measured during the EIF, there is evidence that suggests biomechanical adjustments made in response to the footwear, may benefit the runner at higher speeds and increasing distance covered.

Indeed, footwear is known to influence the biomechanics of running (García Pinillos et al., 2016; Latorre-Román et al., 2017; Mann et al., 2015) and some of these biomechanics parameters (e.g. contact time, stride length, and stride frequency) are used to regulate running speed (Kasmer et al., 2016). For example, the results of the current study have shown a positive linear relationship between running speed and contact time. Similarily, Paavolainen et al. (1999) reported that runners with faster 5- and 10-km race times had shorter mean contact time and Lussiana and colleagues (2013) reported decreased contact time while wearing minimalist footwear compared to SHOD. However, it is noted that the footwear in the former study had an MI=86%, whereas the footwear in the present study had an MI=70%.

Foot strike pattern is also manipulated with running speeds. As, Keller and colleagues (1996) reported a shift from a rear-foot strike to fore-foot strike with increasing near-maximal running speeds in predominately rear-foot strike runners. Furthermore, Ardigo and colleagues (1995) concluded that, due to anatomical constraints, a fore-foot strike is obligatory to attain higher speeds above submaximal intensities. In fact, they also demonstrated that contact time is shorter with a fore-foot strike compared to rear-foot strike. Therefore, in the current study a decrease in contact time and an anterior shift in foot strike pattern may have occurred during the minimalist footwear fatiguing trials, enabling participants to run faster during these trials. Given the absence of video data during these trials, this hypothesis cannot be confirmed.

Although the specific kinematics of runners during the EIF trials is unknown, one variable that can be definitively linked to performance during these trials has the mass of the shoes used. Therefore, the mass of the minimalist footwear most likely benefitted the runners during the maximal bouts and likely contributed to their faster running speed. Indeed, the mass of the SHOD footwear was almost double that of minimalist footwear (349 g and 178 g, respectively). This difference in mass throughout the EIF could have a cumulative and detrimental effect on the metabolic cost of running and thus on running speed. That is, the cost of running seven 1000 m intervals (7 km), regardless of speed, should be higher. In fact, an increased CR while carrying additional mass distally has been well established within the literature (Frederick, 1984; Myers & Steudel, 1985). Multiple other studies have also demonstrated that additional mass related to footwear worn by a runner increases CR thus reducing running efficiency (Burkett et al., 1985; Franz et al., 2012; Squadrone & Gallozzi, 2009). Further, Divert and colleagues (2008) reported that net efficiency (which has metabolic and mechanical components) is decreased in weighted SHOD conditions.

In summary, the aforementioned mass effect likely explains the significant difference in running pace between minimalist footwear and SHOD conditions during the EIF. It is also possible that changes to foot strike pattern and contact time while wearing the minimalist footwear had a positive impact on the high relative running speeds achieved during the maximal bouts.

5.3 Metabolic

A major finding of the study is that neither the footwear worn by the runners nor fatigue status resulted in a significant change in metabolic rate. In fact, across all conditions, RE increased on average 0.3% from minimalist to SHOD footwear. Typical intra-individual variations in RE are reported to be between 1.5 and 5% (Bonacci, Chapman, Blanch, & Vicenzino, 2009). Further, Saunders et al. (2004) suggested that the smallest worthwhile enhancement in RE of highly trained distance runners should be greater than 2.4%. Clearly, the small change in RE observed in the present study would not have had an impact on runners' performance.

Although there is debate within the literature about the influence of footwear on RE, this study found no influence of footwear and this is corroborated by other investigations (Cochrum, Connors, Coons, Fuller, & Morgan, 2017; Kahle et al., 2016). Additionally, no significant effect of footwear mass on RE was identified. Previous studies have reported a 1% increase in RE for every 100g of shoe mass

(Divert et al., 2008; Frederick, 1984; Squadrone & Gallozzi, 2009). Based on the studies mentioned above and the mass of each shoe, an approximate 3% increase related to footwear mass was expected (142g x 2 shoes).

Although this outcome contradicts reports within the literature, others have highlighted that other footwear characteristics account for changes in RE (Cheung & Ngai, 2016; Franz et al., 2012; Frederick et al., 1983). Differences in shoe sole characteristics (Tung et al., 2014) as well as individual comfort-ratings (Rao et al., 2015) have been found to influence metabolic rate. The combined effect of many shoe characteristics, including the potentially unknown effect of the heel-toe drop, may mask any shoe-mass effect on $\dot{V}O_2$ and hence RE. This point may be best explained by considering the level of minimalism of the footwear.

Studies by Paulson and Braun (2014), as well as, Squadrone and Galozzi (2009) compared barefoot to minimalist and conventional footwear conditions. Both studies showed that RE was better in both barefoot and minimalist footwear condition compared to conventional footwear conditions. Indeed, both studies concluded that RE improved with an MI >90% compared to conventional footwear. These results were corroborated by Perl and colleagues (2012) who also used the Vibram Fivefinger model as their minimalist footwear. However, studies by Sohbahni et al. (2014), and Kahle et al. (2016) reported no change in RE compared to the SHOD condition with a minimalist index of ~80% and 88%, respectively. Unfortunately, the minimalist index of the SHOD footwear for these studies was uncontrolled or undisclosed. Similarly, Cochrum et al. (2017) saw no change in RE from minimalist footwear to SHOD conditions, however, participants used their footwear in this study and therefore, the minimalist index of either condition is unknown. As such, it appears that a cut-off value of 90% on the minimalist index is needed for the footwear to sufficiently mimic the barefoot running condition and in turn, influence metabolic rates. Indeed, the minimalist footwear worn in our study had a MI=70% and, therefore, it is not surprising that no change in $\dot{V}O_2$ or RE was identified. This outcome is further supported by Willy and Davis (2014) who compared kinematic and kinetic variables using minimalist and conventional footwear similar to the current study (MI of minimalist and conventional footwear =70% and 30%, respectively). They concluded that the minimalist footwear used may not be enough to induce alterations similar to the barefoot condition.

As previously noted, fatigue had no significant impact on metabolic rate. A small and insignificant 0.8% increase in $\dot{V}O_2$ due to fatigue was identified. That is, there was no change in $\dot{V}O_2$ and RE from pre- to post-EIF. This result supports previous reports of no change in RE due to fatigue (Millet et al., 2000; Morgan et al., 1990). Similar to this study, Millet and colleagues (2000) compared $\dot{V}O_2$ pre- and post-high intensity exercise bouts. These authors reported a significant change in heart rate and ventilation in middle-level triathletes but not for elite triathletes. They also reported no significant change in CR (J Kg^{-1} m^{-1}). However, the cohort of this study was elite triathletes, and the fatiguing protocol consisted of cycling exercise. To induce fatigue, the participants first completed a progressive test to exhaustion to determine maximal aerobic power output, followed by continuous cycling at 80% maximal aerobic power until volitional fatigue. The authors also reported an increase in other physiological parameters, such as HR, in trained individuals compared to elite athletes. Similarly, Morgan et al., (1990) reported no change in $\dot{V}O_2$ from pre- to post-fatigue conditions, however, their protocol consisted of a 30-minute run at 85% MAS.

In contrast, experimental designs that have implemented prolonged, submaximal runs have shown increased $\dot{V}O_2$ and deteriorated RE (Brueckner et al., 1991; Guezennec et al., 1996; Hausswirth, Brisswalter, Vallier, Smith, & Lepers, 2000; Miura, Kitagawa, & Ishiko, 1999; Nicol et al., 1991). For example, Nicol (1991) reported a decreased RE pre- to post-marathon at three different speeds and Xu and Montgomery (1995) reported increased relative and absolute $\dot{V}O_2$ following a 90-min run at 65% and 80% $\dot{V}O_{2max}$ with increases in $\dot{V}O_2$ greater following the 80% compared to 65% bouts. Similarly, Miura and colleagues (1999) reported small increases in $\dot{V}O_2$ with time during a 75-min treadmill run at 60% MAS. This study separated participants into two groups based on race performance times. Both groups demonstrated an increase in $\dot{V}O_2$. However, a significant difference in $\dot{V}O_2$ between the two groups at each stage was noted. The authors concluded the difference between groups was related to better RE and thermoregulatory acclimations in the "superior" athletes. Brueckner and colleagues (1991) also demonstrated increased $\dot{V}O_2$ following a prolonged run. The authors reported a diminished increase with time as a habituation effect.

Like the current study, other studies have used HIIT to induce fatigue (Collins et al., 2000; Zavorsky et al., 1998). It is noteworthy that these two studies are based on the same group of participants and data set. Participants completed pre- and post-fatigue RE tests interspaced by HIIT consisting of 10 bouts of 400m (4km) at 100% $\dot{V}O_{2max}$ with varying recovery periods between interval bouts (60, 120, 180 s). In contrast, both studies reported small increases in $\dot{V}O_2$ and concluded that RE could be perturbed following HIIT regardless of the recovery period. Indeed, Zavorsky et al. (1998) reported a ~3-5% decrement in RE independent of recovery duration and Collins et al. (2000) reported ~2 and ~1 ml min^{-1} kg^{-1} increases in $\dot{V}O_2$ for RE tests at a speed of 3.33 m s^{-1} and 4.47 m s^{-1}, respectively. No differences in $\dot{V}O_2$ among recovery durations were reported. These results are in complete contrast with the current study. Three factors may account for the disparity in results: total running distance completed; duration of recovery from the final interval to post-fatigue RE test; and length of pre-testing fasting period.

Within the current study, participants covered a total calculated distance of 16.2 km compared to 10.6 km in the contrasting HIIT protocols (Collins et al., 2000; Zavorsky et al., 1998). These values are significant considering that Di Prampero and colleagues (1986) showed a distance effect. They highlight that increase in energy cost of running is more pronounced for a running distance greater than 15 km and that consequently no or small increases in the cost of running occurs following a fatiguing task using HIIT. More specifically, Brueckner et al. (1991) reported that cost of running was not significantly different after 15 km, but increased significantly after 32 and 42 km. Therefore, it is plausible the runners within the current study were not influenced by fatigue given the 16.2 km they ran was on the cusp of the 15km threshold reported by Di prampero et al. (1986).

Another critical difference between the HIIT protocol used in the current study and those of Collins and Zavorsky is the duration of recovery time from the final interval and the post-fatigue RE tests. Collins et al. had a 10-minute recovery period following their fatiguing task. Further, the authors suggested that if $\dot{V}O_2$ was measured immediately following the interval training session, a greater acute reduction in RE might have been observed. In contrast, the recovery period within our study was more than twice as long. Although every effort was made to minimize the time duration from the final interval and the post-fatigue RE test, a calculated 22:28 $\pm$ 5:24 min of elapsed time represents a considerable recovery time for runners of this fitness level. As such it is quite likely that any decrements to RE that may have been incurred as a result of the EIF trials were erased as a result of the relatively extended recovery period. This represents a possible extraneous variable within the current study.

Finally, it is important to note the participants in the current study were well-trained and that the fatiguing trial used consisted of a training method they commonly used. Therefore, considering this group is familiar with HIIT sessions, it is likely that previous experience and training efforts may have prepared them for both the psychological and physiological demands of the task. In turn, this may have impacted our results.

In summary, it appears that the footwear type (i.e., minimalist index) used in this study, as well as an extended recovery time following the HIIT, explain why no significant differences in metabolic variables were observed. Similarly, differences in fatiguing protocols, (prolonged vs. maximal exercise, recovery time) may account for the disparity in results with the current literature.

5.4 Kinematics during Submaximal Running Trials

In both minimalist and SHOD footwear conditions, most runners adopted a rear-foot strike (75 and 76%, respectively). These results are corroborated by other studies following distance runners throughout submaximal runs (Gazendam & Hof, 2007; Nummela et al., 2007; Paavolainen et al., 1999). The absence of differences in foot strike pattern is best explained by the relative low minimalist index (70%) of the minimalist footwear used. As previously noted, the degree of minimalism between footwear conditions was not enough to induce alterations in running patterns. As such, slight differences in foot-strike-patterns are expected.

5.5 Muscle Activation

The effect of footwear and/or fatigue on muscle activation was minimal in the current study as shown by increased muscle activation during submaximal trials in only one of five muscles. No other effects of footwear or fatigue on muscle activation were identified.

The results of this study add to the growing body of equivocal literature concerning minimalist footwear. Although other studies have demonstrated an increase in medial *Gastrocnemius* activity while wearing minimalist footwear (Rao et al., 2015), Kahle and colleagues (2016) as well as Khowailed et al. (2015) reported no change in either the *Gastrocnemius* or *Tibialis Anterior* between minimalist footwear and SHOD conditions. Previous studies have also demonstrated no effect of footwear on muscle activation in the other four muscles examined *(Biceps Femoris, Gluteus Maximus*, *Tibialis Anterior*, Vastus Lateralis) (Kasmer, Ketchum, et al., 2014; Rao et al., 2015). Many aspects of locomotion such as skeletal position, joint loading, and stability of the lower limb during stance alter muscle activation (Nigg & Wakeling, 2001). Previous discussions of muscle activation focused on the stance phase of running. As such, the medial *Gastrocnemius* has been shown to be active just before heel contact and throughout the stance phase (Gazendam & Hof, 2007). While wearing minimalist footwear, no effect of footwear on kinematics variables, except for a 1% increase in the incidence of fore-foot strike, were identified. Although it is difficult to determine which muscle activities are responsible for specific tasks from EMG (Khowailed et al., 2015; Nigg & Wakeling, 2001), the increased muscle activity of the medial *Gastrocnemius* may be a result of the differences in a heel-toe drop of the footwear. An altered foot position would result in an increased need for stability of the knee and ankle. For example, Willy and Davis

(2014) reported greater knee flexion and ankle dorsiflexion at foot contact in the minimalist footwear condition. The authors concluded that running in minimalist footwear appears to increase loading of the lower extremity compared to standard running shoes. These higher loading rates and reduced ground reaction forces are, in turn, suggested to alter muscle activity (Khowailed et al., 2015; Nigg & Wakeling, 2001). However, it should be noted that Willy and Davis (2014), who used footwear with the same minimalist index as this study, concluded that the minimalist footwear they used might not have been "minimalist" enough to induce alterations similar to barefoot running successfully. As such, it is likely that the lack off effect of footwear on muscle activation reported in this study is, also likely due to the low minimalist index of the minimalist footwear used in the study.

Alterations in muscle activity in response to fatigue have been reported in previous studies (Abe, Muraki, Yanagawa, Fukuoka, & Niihata, 2007). In contrast, the current study has not revealed any changes in muscle activity following EIF. Considering greater muscle activation reflects greater motor-unit recruitment or firing rate (Brooks, Fahey, & Baldwin, 2005), it appears that well-trained distance runners can maintain optimal motor recruitment with fatigue as demonstrated by no change in muscle activation amplitude, a small 3% shift towards a rear-foot strike, and no other changes in sagittal kinematics from pre- to post-EIF. As previously noted, the interval protocol used to induce fatigue represents a typical training session of an endurance runner. Chronic response to this type of training combined with the three-minute recovery period has allowed runners of this study to cope with high intensity running bouts. Further, similar to the metabolic data, it is likely that the extended recovery period between the EIF and post-fatigue RE testing was enough to allow the participants to complete the subsequent submaximal running bouts without significant changes to running mechanics. Therefore, as with other measures, the similarity in the minimalist index of footwear conditions and the extended recovery period following HIIT best explain why substantial, significant changes in EMG were not observed in this study.

5.6 Methodological Considerations

There are methodological considerations inherent to the current study:

First, the minimalist footwear in this study appear not to be “minimalist” enough to adequately contrast with the conventional footwear used. Despite a 171 g difference in shoe mass, the footwear was too similar to affect RE. This represents a substantial methodological flaw. The footwear was selected to satisfy recommended criteria such as heel-toe-drop, shoe mass and motion-control technologies (Esculier et al., 2015). However, it appears the minimalist index of this footwear (70%) was too low to mimic the barefoot condition adequately. In fact, a previous study using footwear with the same minimalist index also concluded the footwear are not minimalist enough to induce alterations similar to the barefoot condition (Willy & Davis, 2014) . Based on the previous works, it appears there is an minimalist index threshold upwards of 90% for the footwear to influence RE. Indeed, the only studies that report a significant improvement to RE while wearing minimalist footwear have used footwear with a minimalist index≥90% (Paulson & Braun, 2014; Squadrone & Gallozzi, 2009).

Adebayo (2017) has shown a shift towards lipid oxidation during a RE test after seven 3-minute running bouts. This outcome reflects glycogen depletion induced by high intensity exercise. The contribution of substrate oxidation to energy production has, therefore, shifted towards lipid oxidation to sustain the energy demand of running without impairing RE. however, the time lapse (>20-min) following HIIT and prior to the final RE test represents an extraneous variable and thus a second methodological consideration of this study. This extended recovery period is likely enough to help participants sufficiently recover from the fatiguing trial and, therefore, complete the subsequent submaximal running tests without experiencing perturbations in their RE.

Third, the sample size of ten participants may not be large enough to achieve statistical significance. Unfortunately, given the population of the local running community, recruitment of additional participants was impossible. This was especially true given the time constraints associated with completing this project in the time required for completion of a master's thesis.

Finally, a HIIT protocol was used for the fatiguing trial because of the runners' familiarity with interval training and to limit the duration of each session. Although fatigue induced by prolonged exercise is more representative of the ecological environment, HIIT completed by the participants successfully induced fatigue. Further, runners were not constrained to treadmill runs for long durations, but instead able to complete the demanding task on a track with the freedom to maintain preferred biomechanical characteristics.

5.7 Future Research

Future research regarding the effect of footwear on RE, muscle activation, and kinematic measures should be conducted using multiple footwear conditions with incremental increases in the minimalist index values. As such, a more in-depth investigation of the possible threshold to mimic barefoot running would help dispel any misconceptions about running in minimalist footwear. Researching the effect of varying recovery periods following fatigue on RE would also help clarify the conflicting results of this study and others within the literature (Collins et al., 2000; Zavorsky et al., 1998) following HIIT. Further, more research needs to be done to investigate the changes in RE following prolonged fatigue. More specifically, these studies should measure RE throughout a long-distance race event and compare it to prior laboratory-based RE tests. Doing so would help identify any entrainment effects of treadmill-based RE tests where runners perform multiple intervals of an imposed, rather than, self-selected submaximal running speed. Further studies observing muscle activation and RE are recommended to sample the entire gait cycle. This would add to current investigations that indicate pre-contact muscle activation of the lower limb has a functional influence on subsequent activation during ground contact (Chumanov, Wille, Michalski, & Heiderscheit, 2012; Kyröläinen, Avela, & Komi, 2005; Kyröläinen et al., 2001). Indeed there is evidence that muscle activation is altered by both step rate (Chumanov et al., 2012) and by preparation for ground contact (Kyröläinen et al., 2001). However, this study only measured muscle activation during the stance phase and, we noted no changes in *Biceps femoris*. Examining swing phase muscle activation in the current study may have identified a difference in muscle activation. This analysis is currently underway.

Chapter 6: Conclusions

6.1 Response to Hypotheses

The purpose of this study was to examine the effects of footwear and fatigue on RE and muscle activation and furthermore if there were any parallels between changes in RE and muscle activation. Our hypotheses were separated by two distinct independent variables: footwear and fatigue status. We hypothesized that footwear would not influence RE but only by the mass of the footwear; due to this mass effect, post-EIF RE in the minimalist footwear condition would not be reduced to the same extent as SHOD; and changes in muscle activation would mirror those of RE in all conditions. We found our hypotheses to be partly supported. Indeed, although there was no significant effect of footwear on RE, no "mass effect (i.e., 1% reduction In in RE per 100g of shoe mass) was present, and therefore, RE was not reduced at a higher magnitude in the SHOD compared to minimalist footwear condition. Further, our hypothesis that changes in muscle activation would mirror those of RE in all conditions was fully supported.

In general, neither footwear nor fatigue affected RE. Indeed, the metabolic rate following EIF was not altered in either footwear condition. Due to the lack of change in either muscle activation or RE it would appear that changes in muscle activation reflected changes in RE. However, to arrive at a more definitive conclusion concerning this hypothesis, changes in either RE or muscle activation would have had to occur.

6.2 Summary

Although the current study represents a comprehensive examination of the inter-relationship between RE, footwear, fatigue and muscle activation two methodological flaws (an MI that was too low in MIN and too long of a recovery period post-EIF), likely negatively impacted the results. As a result of these methodological flaws, this study is unable to confidently conclude the effect of minimalist footwear on both RE and muscle activation in the same study. The most novel finding of this study is that footwear with a minimalist index≤70% are not minimalist enough to differ from conventional footwear and induce alterations similar to running barefoot. Further, the lighter shoe mass in minimalist footwear condition appears to have a positive effect on performance measures during maximal bouts.

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Appendices

Appendix A: Training profile questionnaire

Participant code: ________________ Date: ________________

1. How old are you? ____________________ !
2. In the past 3 months, have you sustained a low-body injury (sprain, strain, tear, fracture, tendonitis, etc.)? ____________________
3. What is your dominant leg (which leg would you use to kick a ball)? ____________________
4. What is your running distance specialty (sprinting, middle- or long-distance)? ____________________
5. What are your 5K and 10K personal-best times?
   5K ____________________ 10K ____________________
   a. If you have never raced either of these distances, what are your personal-best races (time and distance)? ____________________
6. How many years have you been actively training (in a structured training program)? ____________________
7. How many training sessions do you undergo per week (including easy runs and high-intensity training sessions; but excluding weight training)? ____________________
8. How many training sessions per week consist of running at a steady pace of 3-4min/km (i.e., “tempo” / “threshold” runs)? ____________________
9. How many training sessions per week are interval-training (high-intensity work-bouts interspersed with brief rest/recovery interval; excluding “tempo”/”threshold” run)? ____________________
10. What is your average running distance per week (how many kilometres on average do you run per week?) ____________________
11. What is you longest running distance in a week (how many kilometres have you run in your highest running week ever)? ____________________
12. What is the longest distance you have run in a single session? ____________________
13. How many weight-training sessions do you do per week? ____________________
14. How many cross-training sessions do you do per week (e.g., cycling, swimming, elliptical, yoga, etc.)? ____________________
15. In which period of your annual training plan are you (i.e., general preparatory phase, specific preparatory phase, competition phase, taper or transition phase)? ____________________
16. At which level are you competing: provincial, national, international? ____________________
17. Do you wear minimalist or barefoot shoes? ____________________
    a. When did you start wearing this footwear? ____________________
    b. How often per week do you use this footwear? ____________________
    c. For what type of training do you use this footwear? ____________________
18. Do you run in minimalist or barefoot shoes? ____________________
    a. How far do you run in them? ____________________
    b. What is your average “barefoot” running distance per week? ____________________

Appendix B: Borg 6-20 Rate of perceived exertion (RPE) scale

Rating of Perceived Exertion
Borg RPE Scale

6		How you feel when lying in bed or sitting in a chair relaxed.
7	Very, very light	Little or no effort.
8		
9	Very light	
10		
11	Fairly light	
12		Target range: How you should feel with exercise or activity.
13	Somewhat hard	
14		
15	Hard	
16		
17	Very hard	How you felt with the hardest work you have ever done.
18		
19	Very, very hard	
20	Maximum exertion	Don't work this hard!