THE EFFECT OF CARBON-PLATED RUNNING SHOES ON PERFORMANCE

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ABSTRACT

Kyle M. Edgar: The Effect of Carbon-Plated Running Shoes on Performance
(Under the direction of Erik Hanson)

Differences in running economy (RE) in shoes with and without a carbon fiber plate were assessed. Nine participants who had previously run under 18-minutes in the 5km completed the study. Three shoe conditions were assessed at intensities slightly above and below the ventilatory threshold (VT), totaling six 5-minute RE bouts. In two otherwise identical Skechers running shoes, RE was unchanged with a carbon fiber plate running at intensities below ($p = 0.355$) and above VT ($p = 0.715$). The Nike Vaporfly 4% improved RE with respect to the Skechers Speed Elite carbon fiber shoe both below ($p = 0.005$) and above VT ($p = 0.019$). Changes in RE did not differ at intensities below and above VT ($p = 0.893$). The current interim findings suggest that a carbon fiber plate alone may not improve RE, but there may be a combined effect of midsole cushioning and a carbon fiber plate.

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LIST OF ABBREVIATIONS

ACSM – American College of Sports Medicine

BP – blood pressure

EORL – exercise oncology research lab

GCT – ground contact time

HR – heart rate

Km – kilometer

LBS – longitudinal bending stiffness

LT – lactate threshold

Min - minute

Mmol/L – millimole per liter

MTP – metarsophalangeal

PAR-Q – physical activity readiness questionnaire

R3 – Skechers Razor 3

RE – running economy

RER – respiratory exchange ratio

RPE – rating of perceived exertion

SE – Skechers Speed Elite Hyper

VCO_2 – carbon dioxide production

VO_2 – oxygen consumption

VO_{2max} – maximal oxygen consumption

VF – Nike Vaporfly 4%

VT – ventilatory threshold

CHAPTER 1: INTRODUCTION

The goal for runners of all levels is the same, to cover a given distance in as little time as possible. Historically, athletes have gone to great lengths to meet these goals by incorporating different training plans, fueling techniques for races, as well as using ergogenic aids (Bennett & Kehoe, 2008; Kenneally et al., 2017; Saunders et al., 2006; Schubert & Astorino, 2013). These aids include commonly used dietary supplements, USADA designated performance-enhancing drugs, and more recently footwear that contains carbon fiber plates and cutting-edge midsole cushioning compounds. While many performance-enhancers have been studied for years and are well established, the potential physiological and biomechanical benefits of these new "super shoes" are not entirely understood (Barnes & Kilding, 2019; Healey & Hoogkamer, 2021; Hébert-Losier et al., 2020; Hoogkamer et al., 2018; Hunter et al., 2019). This study will add to the growing body of work aiming to quantify the potential benefits of carbon fiber running shoes on running performance by examining running economy (RE).

Improvements in endurance running are often quantified using RE, a complex combination of physiological and biomechanical factors (Anderson, 1996; Barnes, Kyle R.; McGuigan, Michael R.; Kilding, 2014). RE is defined as the oxygen consumption (VO_2), as a measure of energy expenditure needed to maintain steady state at a given submaximal running speed (Barnes & Kilding, 2015a; Daniels, 1985). Thus, the ability to maintain a given running speed using lower absolute VO_2 results in improved RE. Alternatively, better RE also allows athletes to run faster at the same physiological intensity. Both scenarios lead to enhanced performance in endurance athletes.

Carbon fiber shoes have the potential to provide immediate improvements in RE. Simply switching to these carbon-plated shoes, increases in performance are similar to those observed following several weeks/months? of endurance training. Initial findings suggest a 4% improvement in RE while wearing the Nike Vaporfly (Hoogkamer et al., 2018). As this was the first data on a commercially available carbon fiber shoe, the Vaporfly has since become the “pseudo” Gold Standard for runners aiming to use footwear as a performance enhancer. Improvements in RE are hypothesized to be due primarily to a combination of the stiff carbon fiber plate and a compliant, yet resilient midsole in which the plate is embedded.

The incorporation of a carbon fiber plate results in an increased stiffness (longitudinal bending stiffness/LBS) that alters foot and ankle mechanics. This is of interest as runners naturally develop the most economical gait pattern, with a key part being ankle and knee joint stiffness (Hamill et al., 2014; Oh & Park, 2017). Energy loss while running is greatest at the metatarsophalangeal (MTP) joints, notably the great toe (Roy & Stefanyshyn, 2006; Stefanyshyn & Nigg, 1997). Therefore, the ability to conserve energy by either decreasing the work required (push-off during late stance phase) or energy lost (absorption during early stance phase) can result in performance improvements (see Chapter 2 Section 1.4.1). One method of doing so is through the addition of a carbon fiber plate. By increasing the stiffness of the foot, specifically at the MTP joint where net energy loss is significant, total energy expenditure decreases (Farina et al., 2019; Ortega et al., 2021). While knowledge of how carbon fiber plates affect running biomechanics and energetics is not new, the interplay of the stiff carbon plate with new midsole compounds that return more energy to the runner than ever before may be the difference.

In recent years, midsole compounds have been also been studied with findings both supporting (Tung et al., 2014; Worobets et al., 2014) and refuting (Aminaka et al., 2018; Hannigan & Pollard, 2020) their benefit on running performance. Newly formulated midsoles have been developed to be both compliant and resilient. Compression of the midsole foam during impact results in 65-87% of the energy being returned to the runner (Hoogkamer et al., 2018). Compliancy and resiliency allow for the shoe midsole to mitigate work done by muscles of the lower leg, specifically the triceps surae and Achilles tendon musculotendon system (Barnes & Kilding, 2015a; Cavagna et al., 1963). Thus, less muscular work is required, resulting in an overall decreased metabolic cost and improved RE.

Improvements in RE can be attributed to decreased energy expenditure, primarily resulting from the carbon plate and compliant midsole compound. However, there remains a limitation in the literature regarding which of these variables plays a more pivotal role in increasing RE. In an attempt to quantify the individual effect of the plate or midsole, groups have made modifications to shoes. Previous studies have added or removed midsole volume (Hannigan & Pollard, 2020) and made cuts into the carbon plate (Healey & Hoogkamer, 2021) to single out the effect that either variable has on changes in RE. Both studies reported that neither the carbon plate nor midsole individually account for the observed improvements in RE. However, the use of custom lab-made shoes likely altered the function of the carbon plate and midsole compounds, making the results inconclusive. To fill this gap in the literature the present study will utilize two commercially available shoes in which the sole difference is the presence or absence of a carbon fiber plate.

Therefore, the purpose of this study is to determine the effect of a carbon fiber plate on running economy in two, otherwise identical, commercially available running shoes. For this, oxygen consumption while running in the Skechers Speed Elite Hyper (carbon fiber plate) will be compared to the Skechers Razor 3. By doing so, the benefit of a single carbon fiber plate can be quantified.

Purpose

The purpose of this study is to determine the benefit of a carbon fiber plate on running economy in commercially available shoes of identical midsole composition.

Research Questions

1. Does a carbon fiber plate improve running economy in trained male runners?
2. Do improvements in running economy differ at speeds below and above the ventilatory threshold?

Study Aims

1. In trained runners, to compare running economy measures in two commercially available shoes in which the sole difference is the presence or absence of a carbon fiber plate.
2. To determine changes in running economy in trained runners while running at an intensity slightly above and below the ventilatory threshold.

Research Hypotheses

1. Running economy will be improved when running in a shoe containing a carbon fiber plate when all other shoe characteristics are the same.
2. Changes in running economy will not differ between running velocities.

Limitations

1. Participants are encouraged to replicate sleep and dietary patterns between visits, but otherwise, these factors are not controlled.
2. Participant 5k times are not verified aside from word of mouth.
3. Participants will not fatigue during visit 3 RE assessments.

CHAPTER II: REVIEW OF LITERATURE

This literature review is divided into six sections. The first section explains what running economy (RE) is and how it relates to performance. The second section reviews how carbon fiber plates in shoes can potentially improve RE. The third section provides a background on how characteristics of midsole cushioning may also improve RE. The fourth section describes the existing evidence for carbon fiber plated running shoes, and how these findings have changed the distance running world in such a short period. Section five explores biomechanical, spatiotemporal, and training variables that may explain the observed improvements in RE. The sixth and final section provides a justification of the methods in this research study.

Section 1: Running Economy

Running economy will be the primary variable of interest for this study and will be defined as the energy required to run at a given submaximal velocity.

Distance Running Triad

Improvements in distance running performance, from a physiological standpoint, can be primarily attributed to three factors. Runners who have a high VO2max, high lactate threshold, and high running economy are typically able to outperform their competitors (Joyner, 1991). VO2max is a representation of the body's ability to breathe in, transport, and supply oxygen to the working muscle. Oxygen demand increases with exercise intensity, so having a higher VO2max allows for individuals to run at a higher workload. The lactate threshold (LT) is the point at which lactate accumulation increases exponentially, signifying a shift from aerobic to anaerobic metabolism (Sjödin & Jacobs, 1981). LT is known to increase with endurance training, allowing runners to utilize aerobic pathways at higher intensities (Henritze et al., 1985). Thus, a high LT results in the ability to run at a given intensity for a longer period. Lastly, RE is a combination of various physiological and biomechanical factors that affect efficiency. These factors, which will be discussed in greater detail in the following sections, include energetics, biomechanics, neuromechanics, training status, and personal choices like footwear (Barnes, Kyle R.; McGuigan, Michael R.; Kilding, 2014; Barnes & Kilding, 2015a; Fletchern & MacIntosh, 2017). The ability to improve a runner's efficiency by optimizing any one of these variables results in an improved running economy.

What is Running Economy and how is it assessed?

Running economy is the energy required to run at a given submaximal velocity (D. L. Conley & Krahenbuhl, 1980). VO2 is commonly measured to quantify RE and compare results both within and between individuals (Daniels, 1985). It should be noted that individual variation is often due to various physiological and biomechanical differences between runners. Conclusions of economy from VO2 can be made because of the linear relationship between running velocity and VO2 at submaximal intensities (Henry & Demoor, 1956). This relationship suggests that a more economic runner will expend less energy, or have a lower VO2, at a given submaximal velocity. However, this relationship is not universally agreed upon and does not remain linear at near maximal intensities (Di Prampero et al., 2009; Fletcher et al., 2009; Shaw et al., 2014). As such, energy expenditure with respect to an individual's body mass is also commonly reported as kcal/kg/km (Cavagna et al., 1963; Shaw et al., 2014). Additionally, RE can only be accurately assessed when RER values are known to be < 1.0 (Barnes & Kilding, 2015a; D. L. Conley & Krahenbuhl, 1980). RE is closely related to improved endurance performance, making the accurate assessment of RE vital for endurance athletes.

Running Economy and Endurance Performance

Running economy is a key predictor of performance in endurance athletes (Joyner, 1991). How RE affects performance is not as straightforward because several different variables alter a runner's efficiency. However, it has been shown that a 100g increase in shoe mass increases VO2 by 1% (Frederick, 1984). The exact improvement or decrease in RE will depend on the runner's body mass and other factors but do not differ significantly from these findings. Knowledge of the effect of shoe mass on RE has since been used to determine the relationship between RE and performance (Hoogkamer et al., 2016). It was found that the addition of 100-300g (1-3% decrease in RE) decreased performance by 0.78% per 100g, on average. Extrapolating these findings to other factors enables predictions of performance improvement to be made based on laboratory RE measurements.

Factors That Affect Running Economy

Factors that affect RE are numerous and have varying degrees of influence on a runner's performance. Alterations to the factors discussed below, and others, can increase or decrease economy. By doing so the metabolic cost of running at a given velocity will also change.

Anthropometric

Body mass is a crucial determinant of RE as work performed by the muscle to move in a given direction will increase with greater mass. Supporting body mass is estimated to comprise 74% of the metabolic cost while running (Arellano & Kram, 2014). At nearly three-quarters of the metabolic cost, it is apparent that optimizing total body mass is important for endurance athletes. Aside from body mass, non-modifiable factors like Achilles' tendon and limb length may play a key role in running economy. The Achilles tendon moment arm is negatively correlated with RE (Barnes, Kyle R.; McGuigan, Michael R.; Kilding, 2014). The Achilles tendon stores elastic energy when it is stretched during the stance phase of running (phases of running in **Figure 1**). This energy is then utilized during the push-off phase and conserves energy by reducing the muscular work needed to move forward. Additionally, a shorter forefoot length has been found to improve RE (Fletcher & MacIntosh, 2015; Kunimasa et al., 2014). Thus, a smaller ratio of forefoot length to Achille tendon moment arm is believed to be an indicator of RE.

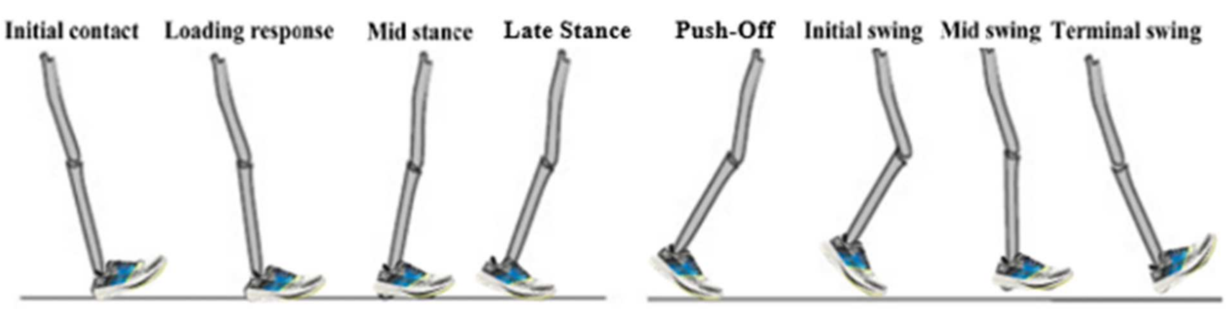


Figure 1: 8 Phases of a single gait cycle. Diagram adapted from Tao et al. 2012.

Cardiorespiratory

An increase in cardiorespiratory fitness results in increased RE. Lower heart rate (HR) and minute ventilation are both positively correlated with RE (Barnes & Kilding, 2015b). It is estimated that the mechanical work associated with ventilation accounts for 16-26% and 12-19% of oxygen consumption in women and men respectively (Barnes & Kilding, 2015a). Therefore, a trained individual, or someone with larger lungs and lower minute ventilation will require less energy, improving RE.

Biomechanical

Running biomechanics can vary greatly between runners and deviation from what is natural for a runner can negatively affect RE. Several studies have investigated how altering stride length affects RE by either shortening or lengthening each step (Barnes, Kyle R.; McGuigan, Michael R.; Kilding, 2014; Powers & K., 1982). These studies, among others, have reported that the natural stride length for an individual is almost always more economic. The other key biomechanical variable of interest is ground contact time (GCT), which can be related to stride frequency. Running speed is a function of stride frequency and stride length, so the more efficient an individual can be within these variables, the greater their RE. Mixed results regarding GCT have been published with some suggesting that longer GCT is more economic (Williams & Cavanagh, 1987) while others suggest shorter is more beneficial (Hunter et al., 2019; Nummela et al., 2007). However, studies that have found long GCT to be disadvantageous had participants running at near maximal velocities. This makes sense as sprinters often have very shorter GCTs in which power output is extremely high. Conversely, when participants are prescribed speeds representative of distance running, longer GCTs are more beneficial or show inconclusive results (Cavanagh et al., 1977; Williams et al., 1987). The mechanism by which RE is improved by changes in GCT is not completely understood and does seem to vary between individuals and based on footwear choice.

Neuromuscular

Neuromuscular implications for RE are directly related to muscular work performed and the rate at which this work is required. At slower running speeds GCT is greater. As a result, the contraction of muscles in the lower limbs occurs over a longer period. With slower contractions, lower levels of activation are required to propel the body forward (Fletchern & MacIntosh, 2017). As a result, the total energy required is decreased, increasing RE.

Several studies have investigated the efficacy of resistance and plyometric training on RE (Barnes et al., 2013; Li et al., 2021; Saunders et al., 2006). During the stance phase of the gait cycle muscles of the lower body contract eccentrically. RE and peak eccentric force were found to have a strong correlation at 12, 14, and 16 km/hr (R values: 0.686, 0.728, 0.761) suggesting that lower body strength may be an important factor when determining RE (Li et al., 2021). Plyometric training invokes neural adaptions that allow for greater activation, resulting in improved RE (Barnes et al., 2013; Saunders et al., 2006). Additionally, these quick explosive movements have been shown to increase muscle-tendon stiffness (Paavolainen et al., 1999). Increased stiffness is primarily observed at the Achilles tendon in runners following plyometric training. As a result, elastic energy that is stored when a tendon stretches is better utilized during contraction.

Training History

It is commonly agreed upon that runners naturally adapt the most economic running biomechanics (Moore et al., 2012). Subsequently, runners with more experience commonly have better RE than those who are less experienced. Additional training will also allow for the various physiological adaptations described above to occur, further enhancing RE in trained individuals.

Footwear

The impact that footwear has on RE varies greatly on different factors including shoe mass, midsole volume, and composition, presence of a carbon fiber plate, among others. Numerous studies have been conducted to determine the effect footwear has on RE (Frederick, 1984; Oh & Park, 2017; Tung et al., 2014; Worobets et al., 2014), but the field has grown rapidly with the introduction of running shoes with an embedded carbon fiber plate (Barnes & Kilding, 2019; Healey & Hoogkamer, 2021; Hébert-Losier et al., 2020; Hoogkamer et al., 2018). These studies and the variables of interest will be discussed in greater detail in the following sections to explore how these new "super shoes" may improve RE.

Section 2: Carbon Fiber Plates in Footwear

For years footwear has been designed to optimize performance for athletes, specifically runners. Companies and researchers alike have attempted to make runners more efficient by either decreasing the work necessary by muscle-tendon systems or decreasing energy lost during the gait cycle. During the initial stance phase of running, energy is absorbed at various joints to break and support an individual's body mass, but some of this energy is not returned during the subsequent push-off phase (Cavagna et al., 1963). Specifically, energy loss at the metatarsophalangeal (MTP) joints is significant (Stefanyshyn & Nigg, 1997). It was determined that the ankle and knee joints generate about the same amount of energy as they absorb while the MTP joint generates a minimal amount. The reason for this is believed to be that the MTP joints remain in a dorsiflexed position for most of the gait cycle. As a result, there is no "push-off" or return of elastic energy, so energy loss is considerable.

One way to potentially decrease energy loss at the MTP is through the addition of a stiff carbon fiber plate and increasing longitudinal bending stiffness (LBS). LBS is a measure of how stiff a shoe is, or how much force must be applied to cause a change in conformation. More force must be applied to a shoe with higher LBS to cause it to bend. When carbon plates with varying LBS were added as insoles a "stiff" (LBS: 38N*mm) plate was found to benefit RE more so than no plate (LBS: 18N*mm) or the "stiffest" (LBS: 45N*mm) condition (Roy & Stefanyshyn, 2006). Although ~1% improvements in RE were observed on average, negative work at the MTP did not change, leaving the mechanism by which optimal LBS improves RE unclear. These results counter previous findings that reported ~2% decrease in energetic cost while running due directly to decreased energy loss at the MTP (Stefanyshyn & Nigg, 2000). Additionally, results were not uniform across the sample of trained runners. A strong negative correlation ($R^2 = 0.602$) was found between body mass and improvements in RE suggesting that optimal LBS may differ between runners.

Several studies have attempted to identify what optimal bending stiffness is and what variables must be taken into account (Day & Hahn, 2020; Oh & Park, 2017; Roy & Stefanyshyn, 2006; Willwacher et al., 2013). The idea of a critical stiffness has been hypothesized for runners. Above this LBS there would be a detrimental effect on RE due to limitations of the natural MTP flexion (Oh & Park, 2017). A carbon plate must be stiff enough to decrease negative work at the MTP but not too stiff that it requires increased muscular work to push the runner forward. These results suggest that the optimal LBS likely differs between runners based on the natural range of motion of the MTP joints. The effect of carbon fiber plates is also speed-dependent. 78% of participants had better RE in a control shoe at 14km/hr while 40% had better RE in the "stiff" condition at 17km/hr (Day & Hahn, 2020). It should also be considered that adding a top-loaded carbon fiber plate does add additional mass to the shoe. It is plausible that the increased LBS has a greater effect on RE than is observed when being compared to a control shoe with no plate. Custom-made carbon plates range from 50-100g, and a 100g increase in shoe weight increases RE by 1% (Frederick, 1984).

The aforementioned studies all utilized custom top-loaded plates, which likely altered shoe comfort and properties that the manufacturer did not intend for. More recent studies have assessed commercially available carbon fiber shoes with the plate embedded in the midsole (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hoogkamer et al., 2018). Each of these three studies observed improvements in RE ranging from 2-4%. Alternatively, studies with top-loaded plates often saw changes of no more than 1% suggesting that plate location is crucial for increasing RE. Finally, while limited research is available, it appears that plate length and geometry may be important factors. A heavily curved plate was found to improve RE and decrease negative work at the MTP significantly more than a flat or removed plate (Farina et al., 2019). A curved plate allows for force to be applied close to the MTP joint while a flat plate extends the point more distally. As a result, the moment arm is extended and energy loss at the MTP is greater (Ortega et al., 2021). To date no published study found has assessed plates of varying length. The Nike Vaporfly 4% with a curved full-length plate is commonly used as the "gold standard" in recent RE footwear studies. Other studied carbon fiber shoes include Hoka RocketX, Saucony Endorphin Pro, Brooks Hyperion Elite2, New Balance RC Elite, and Asics Hyperspeed, all of which contain a full-length plate. However, the interaction of the plate, midsole, and foot of the runner may require different levels of compliance to optimize RE (Stefanyshyn & Nigg, 1997). In the following section the benefits of compliant and resilient midsoles will be discussed before exploring how these two variables may interact to improve RE further.

Section 3: Midsole Cushioning in Footwear

Running shoe midsoles are designed to be both compliant and resilient. The compliancy of a shoe describes how stiff or soft it is. Optimal compliance will provide a runner with cushioning during impact, and result in increased stiffness at the ankle and knee joints (Ferris et al., 1999). As stated previously, increased stiffness during running reduces the energetic cost of body weight support, improving RE. A softer, more compliant midsole improved RE by 1-1.2%, on average, in trained runners (Worobets et al., 2014). However, these results were not uniform as ~25% of participants had better RE while running in a "stiffer" midsole. Again, this suggests that RE responses are highly individualized and are the result of many different factors.

A more resilient shoe will store, and return, a greater percent of mechanical energy to the runner meaning that less energy is lost as heat (Hoogkamer et al., 2018). Mechanical testing suggests that resiliency varies greatly between shoes, with newly formulated compounds returning significantly more energy. The Nike Vaporfly 4% (87%) returned over 25% more energy to the runner than the Adidas Adios Boost 2 (75.9%) and Nike Zoom Streak 6 (65.5%). While substantial, the energy returned from midsoles (3.38-7.46J per step) is only a fraction of what is returned naturally from the Achilles tendon system (~35J per step) (Hoogkamer et al., 2018). These results suggest that optimal compliance is likely more important, and variable among runners, while resiliency can be seen as an added bonus.

The composition of the Vaporfly, and other newly developed shoe midsoles, allows for greater energy storage and return to the runner, resulting in improved RE. The chemical composition of midsoles is beyond the scope of this review, but it should be noted that newly developed running shoes are being designed to be more compliant, resilient, and lightweight than ever before. Maintaining a lightweight midsole is a balance of increasing total foam volume to make shoes compliant and resilient, while also minimizing shoe mass. "Maximal" shoe volume has been shown to decrease ground reaction and loading forces, which may contribute to improvements in RE, although limited research is available (Hannigan &

Pollard, 2020). Beyond the midsole composition itself, these newly formulated midsoles are being combined with the previously described carbon fiber plates, resulting in even greater improvements in RE.

Section 4: "Super Shoes"

The first commercially available running shoe with a carbon plate in the midsole was designed by Reebok in the 1980s (Jewell, 2019). Several others followed suit in years to come, but with no record-breaking performances to show, the design fell off. It was not until the release of the Nike Vaporfly 4% in 2018 that the new wave of footwear took off. The first study investigating the benefit of the Vaporfly as a prototype observed 4% decreases in oxygen consumption at 14, 16, and 18km/hr, hence the name of the show (Hoogkamer et al., 2018). Because mass was added to the Vaporfly to match the other shoes, the savings likely exceeded 4%. The Vaporfly, often referred to as the "gold standard" of the carbon shoes, was the first to incorporate a lightweight, curved plate with cutting-edge midsole foam that maximized energy return. Since this study was published two other groups conducted similar studies and found similar improvements in RE of 2.8% (Hunter et al., 2019) and 2.6% (Barnes & Kilding, 2019) when comparing the Vaporfly to a traditional marathon racing shoe. All three studies saw significant improvements in RE, but the mechanism by which these improvements occurred remains unclear. Ground contact time in the Vaporfly was reported to be unchanged (Hunter et al., 2019), shorter (Hoogkamer et al., 2018), or longer (Barnes & Kilding, 2019). Peak vertical ground reaction force also differed between these studies. Similar to ground contact time, ground reaction forces were observed to be unchanged (Hunter et al., 2019) and decreased (Hoogkamer et al., 2018) while wearing carbon fiber shoes. These findings are true for nearly all factors that affect RE discussed in Section 1 of this review. A plausible explanation is that many of these factors are optimized and result in minor improvements in RE, with the culmination being the observed 4% improvement. It should again be noted that there is a considerable interindividual variation with improvements in RE ranging from 1.3-7.5% within a single study (Hébert-Losier et al., 2020).

Few studies have experimented with carbon fiber footwear besides the Nike Vaporfly to date. Seven commercially available carbon fiber shoes were compared to a single traditional running shoe, and the Nike Alphafly Next% was found to be most beneficial on average (Joubert & Jones, 2021). Changes in oxygen uptake differed significantly across the shoes tested. Two of the five shoes (**Table 1**) did not significantly lower VO2, while the remaining five decreased VO2 by 1.37-3.03% on average. Individual variation again displayed that some runners respond more than others. 33% of participants improved RE by over 4% in the Nike Alphafly Next% while 25% improved by less than 2%. Additionally, by assessing several carbon fiber shoes by different manufacturers, it is difficult to conclude why improvements were greater in certain shoes. Characteristics of each shoe are provided in **Table 2**, including differences in stack height, midsole composition, plate geometry, and shoe mass. All of these factors can contribute to improvements, or lack thereof, in RE.

No study to date has been able to quantify the benefit of either a carbon fiber plate or midsole individually. The described studies assessed shoes in which both the plate and midsole differed, meaning that RE improvements cannot be accredited to one or the other. One study attempted to quantify the individual benefit of the carbon fiber plate in the Vaporfly by making horizontal cuts through it (Healey & Hoogkamer, 2021). The goal was to negate any effect of the plate by decreasing LBS, meaning that any observed changes in RE would be a result of the midsole. RE did not change when running with the cut plate compared to an intact shoe. These results suggest that the 4% improvements in RE observed were due solely to the midsole, counter previous studies that suggested an optimal plate could decrease oxygen consumption by up to 6% (Nigg et al., 2020). MTP range of motion and power were the only variables of interest that were affected by the horizontal cuts, suggesting that they may not play a pivotal role in improving RE. However, it is likely that the horizontal cuts made to the shoes did not negate the effect that the plate had while running. Cuts were only made in the mid and forefoot regions, so any benefit from the heel would still be expected. Because of these limitations, it is still unclear whether the carbon plate or midsole compound improves RE in the absence of the other. Knowledge of how these new "super shoes" improve RE is more important now than ever as international committees attempt to nail down regulations.

With large improvements in RE and subsequently performance, carbon fiber shoes have been the topic of discussion within the running economy in recent years. In 2018 Eliud Kipchoge broke the men's marathon world record by over one minute, and Brigid Kosgei broke the women's by nearly three minutes; both athletes wore variations of the Nike Vaporfly during their respective races. Furthermore, seven of the ten fastest marathon times in history have been run since 2018, when the Nike Vaporfly was first made available to the public. When Kipchoge famously broke the two-hour barrier, he was wearing a prototype that is now banned under World Athletics footwear regulations (World Athletics, 2020). Additional regulations include that no more than one plate may be embedded in the midsole and the shoe must be commercially available. These regulations come with the assumption that both the carbon fiber plate and midsole composition are crucial in the observed RE improvements. However, no study to date has investigated two identical shoes with and without a carbon fiber plate, so the true benefits remain unclear.

Table 1: Currently published studies that have investigated RE in carbon fiber plated shoes.

Study	Shoes	Population	Speeds	ΔRE
Hunter 2019	NK Vaporfly 4%, NK Zoom Streak, ADI Adios Boost	19 men, 10km <32min	16km/hr	2.80%
Healey 2021	NK Vaporfly 4%, NK Vaporfly 4% CUT	17 men, 5km <19min	14km/hr	0.5%
Joubert 2021	Hoka Rocket X, SCY Endorphin Pro, NK Alphafly Next%, Asics Metaspeed, NK Vaporfly Next% 2, NB Fuel Cell, Brooks Hyperion 2, Asics Hyperspeed	12 men, 5km <17:30min	16km/hr	3.03%
Hebert-Losier 2020	OWN, SCY Endorphin Racer 2, NK Vaporfly 4%	18 men, 5km x̄ 21:18min	60, 70, 80% VO_{2peak}	1.0, 1.2, 1.7%
Barnes 2019	NK Vaporfly 4%, NK Zoom Streak, ADI Adios Boost	12 men, 10km <30min 12 women, 10km <35:30min	M: 14, 16, 18km/hr W: 14, 15, 16km/hr	2.6±1.3%
Hoogkamer 2018	NK Vaporfly 4%, NK Zoom Streak, ADI Adios Boost	18 men, 10km <32min	14, 16, 18km/hr	4.01%

Blue indicates the shoe in which the best RE was observed. Red indicates the non-carbon fiber shoe used to determine ΔRE.

Abbreviations: NK, Nike; ADI, Adidas; SCY, Saucony; km, kilometer; km/hr, kilometer per hour; ΔRE, change in running economy

Table 2: Characteristics of shoes of interest to the current and former RE studies.

Shoe	Mass (oz)	Heel Stack (mm)	Forefoot Stack (mm)	Heel-Toe Drop (mm)	Midsole Composition	Plate Geometry
Nike Zoom Vaporfly 4%	6.9	39	29	10	ZoomX	Full-Length Curved
Skechers Speed Elite Hyper	5.7	28	24	4	Hyper Burst	Forefoot Winglet
Skechers Go Run Razor 3	5.4	28	24	4	Hyper Burst	None
Saucony Endorphin Pro	7.6	39	31	8	PWRRUN PB	Full-Length Curved
Nike Alphafly Next%	7.4	40	36	4	ZoomX	Full-Length Curved
Asics Metaspeed Sky	7.3	38	33	5	FlyteFoam	Full-Length
Nike Vaporfly Next% 2	6.9	40	32	8	ZoomX	Full-Length Curved
New Balance Fuel Cell RC Elite	7.8	34	24	10	FuelCell	Full-Length
Brooks Hyperion Elite 2	7.4	35	27	8	DNA Flash	Full-Length

The first three shoes listed will be assessed in the present study. Information was retrieved from runningwarehouse.com and based on a size 9 men's shoe.

Abbreviations: oz, ounce; mm, millimeter

Section 5: Potential Explanatory Variables

This section will postulate how several variables being analyzed may contribute to any changes in oxygen consumption based on prior studies.

Foot Strike Pattern & Plate Length

For the purposes of this study participants will be classified as a forefoot or rearfoot (heel) strikers. These terms reference the region of the foot that contacts the ground first during the initial stance phase of each step. In shoes with greater midsole volume and stack height it is more common for runners to heel strike. A non-significant difference in RE improvement (2.41 vs. 3.32%) was observed when forefoot and rearfoot strikers ran in the same two shoes (Perl et al., 2012). However, when comparing changes in RE across strike patterns in carbon fiber shoes, heel strikers benefited more (Hébert-Losier et al., 2020; Hoogkamer et al., 2018). Both of these studies used the Nike Vaporfly, but there is currently no agreed-upon mechanism to explain why heel strikers may benefit more than forefoot strikers. It may be that the full-length plate in the Vaporfly provides optimal LBS in the heel region that further benefits those runners. Alternatively, forefoot runners never contact the ground with their heel, so they would miss out on the additional improvement in RE.

Spatiotemporal Differences & Ground Reaction Forces

Spatiotemporal differences encompass changes in running mechanics such as GCT, stride length, and frequency, among others. GCT increases in shoes with greater midsole volume (Barnes & Kilding, 2019) and an increase in carbon fiber shoes (Hoogkamer et al., 2018). Results in carbon fiber shoes have been inconclusive and likely depend on other properties of the midsole and plate. It is hypothesized that an increase in GCT at the same running velocity decreases metabolic cost (Chapman et al., 2012). An increase in GCT allows muscle recruitment and contraction to occur over a greater period, decreasing the metabolic cost per unit weight of active muscle (Kram & Taylor, 1990). It is more costly from an energetics perspective to exert a large force over a short period than a small force for a slightly longer period. The onset of fatigue will occur earlier with larger ground reaction forces, decreasing RE significantly. Importantly, the magnitude of force application throughout the stance phase differs greatly between runners based on anatomical and biomechanical differences (Clark et al., 2017). As a result, some runners may display large changes while others show very little. Stride length will increase with GCT, while stride frequency will decrease slightly due to the natural relationship of the three variables at a set velocity.

Shoe Comfort Rating

Shoe comfort has been shown to significantly affect RE (Luo et al., 2009). When comparing two shoes rated as “most” and “least comfortable” oxygen consumption was up to 2% lower in the more comfortable shoe. Optimal LBS based on anatomical and biomechanical differences of the foot and ankle may explain why runners benefit more from a certain shoe (Day & Hahn, 2020). If the design of a shoe's midsole and plate are more optimal for runners with certain characteristics, they will likely perceive the shoe as more comfortable and experience greater benefits.

Table 3: Rationale for the method of collection for key variables of interest.

Outcome/Method	Options	Key Considerations	Selection	Rationale
Running Economy	Oxygen Cost - Direct calorimetry - Indirect calorimetry - Laboratory test - Field test Energetic Cost	- Valid & reliable - Participant burden - Ability to assess at the same time as spatiotemporal & GRF	Indirect calorimetry laboratory test	Section 6.1
Shoe Selection	All commercially available carbon fiber shoes (runningwarehouse.com)	- Cost/availability - Comparable non-carbon fiber shoe	Skechers Speed Elite Hyper & Skechers Go Run Razor 3	Section 6.2
Determination of running speeds	Fixed Speed Individualized Speed - VT - LT	- Validity/reliability - Participant burden - Translation to performance	Individualized speed based on VT	Section 6.3
Running bout duration	Theoretically, any duration could be performed.	- Time - Participant burden - Fatigue - Steady-state oxygen consumption	5-minutes with a 5-minute recovery in between each of the six trials	Section 6.4
Spatiotemporal variables	OptoGait Motion capture camera Wearable IMU device	- Validity/reliability - Cost/availability - Measure in tandem with RE - Subject burden/safety	OptoGait gait analysis system - RunScribe wearable IMU also collects spatiotemporal data	Section 6.5
Ground reaction force	Force treadmill Wearable IMU device	- Validity/reliability - Cost/availability - Measure in tandem with RE - Subject burden/safety	RunScribe wearable IMU device	Section 6.6

Abbreviations: GRF, ground reaction force; VT, ventilatory threshold; LT, lactate threshold; IMU, inertial mass unit; RE, running economy.

Fitness Level/Training Status

No substantial analysis on training status or fitness level has been conducted when assessing RE. This is likely because these variables are controlled to the best of the investigator's ability, and most studies use a homogenous sample. However, runners are likely at different phases of their respective training plans during a study, and individual training plans can vary significantly. An individual who is primarily doing "'base" training of long slow runs may not be prepared to run at the speeds required to receive the most benefit from a carbon fiber shoe.

Section 6: Justification of Methods

The following section and associated table provide the rationale for the study design.

Running Economy

RE is the energetic cost to run at a given submaximal velocity (D. Conley & Krahenbuhl, 1980). However, RE is commonly reported with respect to ventilatory data (i.e., VO2). The ability to report RE as a function of oxygen consumption is thus reliant on energetic and oxygen costs correlating to one another. It is well established that there is a linear relationship between running velocity and VO2 (Daniels, 1985), but this is not true for all intensities. It has been proposed that at intensities >80%Vo2max there is a deviation between oxygen and energetic cost of running (Shaw et al., 2014). At higher intensities, it would then be more accurate to quantify RE by calculating energetic cost via substrate utilization. For the present study, RE measures will be performed just above and just below VT. The trained, but not elite runners being recruited are expected to hit VT ~70-75%VO2max. If this assumption holds, runners should remain at or below 80%Vo2max. Thus, VO2 will be used to quantify RE. The use of direct calorimetry would not be appropriate for the given study because heat given off by the treadmill would confound results. Indirect calorimetry can be performed both in the laboratory and field settings, with VO2 assessments being valid and reliable across both methods (Meyer et al., 2003). However, the ability to control for temperature, pressure, and lack of wind resistance is vital when attempting to compare RE assessments between visits (Fletchern & MacIntosh, 2017). The availability of equipment was also a deciding factor because of cost and time restrictions. As a result, lab-based indirect calorimetry will be performed to assess RE. The Parvo Medics TrueMax® 2400 Metabolic system (Parvo Medics, Salt Lake City, UT, USA) will be used. Additionally, since VO2 will be assessed via a metabolic cart, RER values are obtained. This would allow the investigators to do a post-hoc analysis of energetic cost if deemed necessary.

Shoe Selection

The study of carbon fiber shoes and RE is a new field of interest for researchers, with the first study being published in 2018 (Hoogkamer et al., 2018). In the three years since several others have added to the body of literature, but few have expanded to other shoe models. One study assessed seven different carbon fiber shoes and one traditional (Joubert & Jones, 2021), while many others limited their analysis to the Nike Vaporfly (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hunter et al., 2019). In each of these, the shoes being compared differ in midsole volume, composition, and presence/absence of a carbon fiber plate. As a result, they were unable to determine which of these variables was the reason for improvements in RE, or if it is a result of the interaction between them. Runningwarehouse.com was used to search for carbon fiber shoes of interest at the study's inception in the fall of 2019. The Skechers' Speed Elite Hyper was chosen because of the nearly identical design to the traditional running shoe, Skechers Razor 3. Stack heights, heel-to-toe drop, and midsole composition are identical in both shoes. The sole difference being the carbon fiber plate in the Skechers Speed Elite Hyper, and subsequently an 8g increase in weight. Thus, the chosen shoes enable the researchers to quantify the benefit of the forefoot winglet plate in the Skechers Speed Elite Hyper. Additionally, no study known to the investigators has assessed the Skechers Speed Elite Hyper in a laboratory setting. Knowledge gained from the present study will allow runners to make a more educated decision regarding footwear.

Unfortunately, at the time of study inception, Skechers was not producing women's sizes in the chosen shoes. A follow-up study is being planned in which women's sizes will be assessed following the same protocol as the current study. As a result, the remaining funds were allocated to an additional shoe condition, the Nike Vaporfly 4%. Previous studies that tested the Vaporfly saw heel strikers benefit more than forefoot strikers (Hébert-Losier et al., 2020; Hoogkamer et al., 2018). This raises the question as to whether or not plate geometry and length may affect improvements in RE received. The current study plans to assess improvements in RE in the Vaporfly (full-length) and the Speed Elite (forefoot) with respect to foot strike pattern as an exploratory outcome.

Determination of Running Speeds

When assessing RE it is pivotal that measures are assessed at submaximal intensities. Previous studies used fixed speeds for all participants of 14, 16, and 18km/hr (Barnes & Kilding, 2019; Day & Hahn, 2020; Hoogkamer et al., 2018) while only one study attempted to individualize intensities (Hébert-Losier et al., 2020). By prescribing the same speed for all participants conclusions can be inferred as to how another runner may improve if running at the same speed. Additionally, this makes comparisons between runners simpler for statistical analyses. However, all participants would not be running at the same relative intensity. Distance running performance is correlated strongly with physiological parameters like lactate and ventilatory thresholds (Henritze et al., 1985) and should be considered when prescribing speeds for RE assessments. Determining the lactate threshold puts an additional burden on the participant with several blood samples being taken at various time points. Alternatively, the ventilatory threshold can be determined retrospectively through V-Slope analysis of the respiratory data (Albouaini et al., 2007). V-Slope is a reproducible and valid method of determining the ventilatory threshold. Finally, speeds 5-10% above and below will be prescribed for each participant. The below VT intensity is reflective of marathon and similar distance running (Costill, 1972). The above VT intensity is for exploratory purposes. If considerable improvements in RE occur with carbon fiber shoes, it is possible that a speed prescribed ~5% above VT will be below VT.

Running Bout Duration

Three main considerations were made when determining running bout duration and subsequent rest periods. First, when assessing RE it is crucial that steady state is achieved. It takes about three minutes for a runner to reach steady state at a submaximal intensity (Milani et al., 1998). By prescribing five-minute exercise bouts, two minutes of ventilatory data is obtained and averaged to determine RE. Second, adequate rest time needed to be provided to prevent the onset of fatigue during the six trials. Following pilot testing in the Exercise Oncology Research Lab and previous studies that used a similar group of athletes (Barnes & Kilding, 2019; Hoogkamer et al., 2018), it was determined that five minutes was appropriate. Finally, the time commitment of the participant and researchers was considered.

Although longer rest periods may be beneficial to ensure that fatigue is never a factor, even adding five minutes to each rest period will increase visit time by 30 minutes. Furthermore, recovery HR and subject RPE will be assessed throughout the visit to determine if there is an onset of fatigue.

Spatiotemporal Variables

Spatiotemporal variables including stride length and GCT are exploratory variables for the current study. As such, it is important that the collection does not interfere with the primary variable of interest, RE assessment via the metabolic cart. Several different systems have been used in running biomechanics studies. Motion capture cameras are commonly used for the analysis of joint angles as well as spatiotemporal variables (Hannigan & Pollard, 2020). However, joint angles are not of interest for the given study, so visual data was deemed unnecessary. The Optogait gait analysis system (Optogait, Microgait, Bolzano, Italy) is both valid and reliable for the assessment of running spatiotemporal variables (Lienhard et al., 2013). The portable LED bar design allows for the Optogait to be placed on the sides of the treadmill without interfering with the participant. Additionally, the RunScribe (Scribe Labs, Inc., Half Moon Bay, CA, USA) described below, gathers spatiotemporal variables and has been verified as valid and reliable (Koldenhoven & Hertel, 2018).

Ground Reaction Force

Ground reaction force is an exploratory variable for the current study. As such, it is important that the collection does not interfere with the primary variable of interest, RE assessment via the metabolic cart. Force treadmills are the optimal method of collecting ground reaction forces while running (Kram et al., 1998). Previous studies analyzing ground reaction forces have observed differences between carbon fiber shoes and traditional running shoes (Day & Hahn, 2020; Hoogkamer et al., 2018). Unfortunately, the current study does not have access to a treadmill equipped with force plates. However, wearable sensors have been developed to assess both spatiotemporal and kinetic variables. The RunScribe wearable IMU system is both valid and reliable (Koldenhoven & Hertel, 2018). The wearable pods strap seamlessly onto the laces of any shoe and cause no burden to the participant.

Study Design

The proposed study is using a randomized counterbalanced crossover design to determine changes in RE. Six trials will be performed by each participant. Speed (2) and shoe order (3) will be randomized to a total of six possible groups. Randomization ensures that there is no investigator bias towards the order of trials. Counterbalancing shoes and speeds increases internal validity by preventing order or sequence effects that could confound the results. Finally, a crossover design allows the researchers to analyze the difference in RE both within and between participants.

CHAPTER III: METHODOLOGY

Study Overview

This study used a randomized crossover design consisting of three separate visits in which participants visited the Exercise Oncology Research Lab (EORL) for exercise testing. Visit 1 served to familiarize participants with the metabolic cart while running on the treadmill. During Visit 2 all subjects completed a maximal aerobic capacity test to volitional exhaustion to determine ventilatory threshold (VT) and VO_{2max} values. During the final visit, subjects ran in each of the three shoe conditions at a speed eliciting a VO_2 5-10% below and 5-10% above VT. Each trial was five minutes long, with five minutes of recovery in between each effort.

Subjects

Subjects for this study were trained male runners aged 18-35. All participants had run an 18:00 5k or faster in the past year and were free of any musculoskeletal injury that limited their training in the past six months. Additionally, all subjects were considered low risk for participating in maximal exercise testing based on American College of Sports Medicine (ACSM) guidelines. Eligibility was determined via the completion of a medical history questionnaire and Physical Activity Readiness Questionnaire (PAR-Q). Participants were recruited from running groups and clubs in Chapel Hill and the surrounding communities. Subject eligibility was determined over the phone or via email by running performance and then confirmed following completion of the health history and PAR-Q questionnaires during the first visit. Once eligibility was confirmed, all participants were asked to provide written informed consent documents previously approved by the University of North Carolina Chapel Hill and Slippery Rock University of Pennsylvania IRBs.

Study Procedures

Height, weight, and resting vitals (HR and BP) were measured before each visit, and a questionnaire regarding fatigue, sleep, and diet was completed by the participant. Before visits 2 and 3, participants confirmed that all pre-assessment guidelines were followed accordingly. Urine specific gravity was measured before Visit 2 to ensure proper hydration levels for the maximal aerobic capacity test. Visits occurred 2-8 days from one another at a similar time of day to account for diurnal variations.

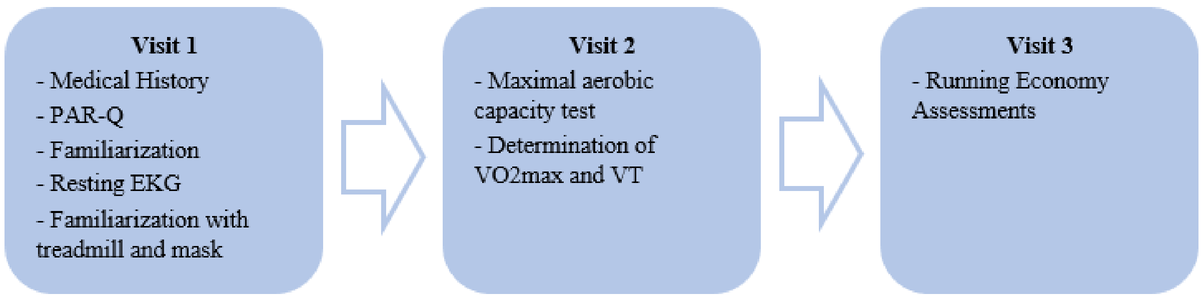


Figure 2: Study visit timeline.

Visit 1: Familiarization

During Visit 1, participants completed the PAR-Q and health history questionnaires to confirm that they were at low risk of adverse events during maximal testing and provided written informed consent. Heart rate, blood pressure, height, and weight were all measured within the EORL following completion of written documents. Prior to familiarization with the metabolic cart a resting ECG was performed. The ECG was sent to the study cardiologist for approval prior to the maximal test during visit 2.

Participants were then fitted with an appropriate facemask for the metabolic cart (Parvo Medics TrueMax® 2400 Metabolic System, Parvo Medics, Salt Lake City, UT, USA) and a heart rate monitor (Polar RS800CX, Polar, Kempele, Finland) was placed just below the sternum. All participants were instructed to bring their own training shoes and the brand, model, and size were recorded. The Rating of Perceived Exertion (RPE) scale was explained to each participant to ensure that subjective ratings accurately reflected the workload. After resting in a seated position for 2-3 minutes participants ran at a self-selected "warm-up" speed on the treadmill for 5-8 minutes. Heart rate and RPE were recorded every two minutes to simulate the following visits. Before leaving, participants were instructed on pre-assessment guidelines to be followed before the maximal test, which occurred 1-8 days following visit 1.

Visit 2: VO_{2max} Testing

Visit two occurred 1-8 days after visit 1. During visit two, all participants completed a VO_{2max} testing protocol. Forty-eight hours before the visit, participants were emailed and reminded of their visit and pre-assessment guidelines. Upon arrival, participants were asked to verify all pre-assessment guidelines again and report information regarding sleep, diet, and fatigue. A urine sample was then obtained, and specific gravity was assessed to ensure proper hydration. Participants with specific urine gravity values ≥1.01 were asked to drink a 16-ounce bottle of water, wait 15-30 minutes, and provide a second urine sample. The visit will proceed if adequate hydration status has been achieved. If a second specific urine gravity test again shows dehydration, the participant will be asked to reschedule the visit for a different day. (Moertl 2021) . Participants then sat down for 5-minutes and resting heart rate and blood pressure were measured, followed by height and body mass.

As performed in visit 1, participants were fitted with the appropriate face mask and heart rate monitor. While resting, participants were informed of the maximal testing protocol. A 5–8-minute warm-up was conducted at a self-selected pace and grade. The treadmill was set to 16 km/hr and the grade was increased 1% each minute until volitional exhaustion while running in their own shoes as performed previously ((Barnes & Kilding, 2019; Hoogkamer et al., 2018). A modification was made to the maximal test protocol after it was determined that the ramp protocol was too intense for some participants. Necessary IRB amendments were made and approved by the Slippery Rock University IRB to increase the grade 0.5% per minute. Speed remained at 16km/hr. Heart rate was acquired at the end of every 1-minute stage and RPE at the end of every other stage. When participants reached volitional fatigue, a final heart rate and RPE values were obtained. They were transitioned to a chair for recovery with their legs propped up. After 3 minutes, maximal blood lactate was measured using a handheld blood lactate analyzer (Nova Biomedical Lactate Plus, Waltham, MA). Standardized sampling methods, described below, were followed to measure blood lactate.

i) Participants were asked to sit with their palm up and if they preferred a certain finger to get stuck. In most cases, the ring finger was chosen.

ii) The desired finger was cleaned with an alcohol prep pad to remove impurities.

iii) The single-use lancet was pressed on the belly of the finger while holding the participants' finger with the other. The lancet was pressed, and the finger was squeezed before wiping away the first drop of blood.

iv) The second drop of blood was assessed by placing the lactate analyzer strip into the drop.

v) Participants were given a gauze pad to hold on to their finger until the bleeding stopped.

vi) After a reading was obtained and recorded, the needle, gauze pads, and gloves were disposed of.

The following five criteria were used following visit 2 to determine if the effort was a true maximal aerobic capacity test. To be considered a maximal test four of the five criteria must be met. If a test was not considered a maximal test, VT was still obtained, but it was instead considered a VO_{2peak}.

i) No change in VO_2 (< 2.0ml/kg/min) with an increase in grade

ii) Heart rate within 10 beats per minute of age-predicted maximum (220 – age)

iii) Blood lactate > 8.0mmol/L

iv) RER > 1.10

v) RPE > 18

The ventilatory threshold was determined using data from the VO_{2max} test using a modified V-Slope method (Albouaini et al., 2007). 1. Carbon Dioxide output (VCO2) is plotted against oxygen consumption (VO2) as measured per minute during exercise. 2. A line with a slope of 1 is drawn through the points on the graph during the early phase of exercise. 3. The point on the line where VCO2 departs drastically from VO2 (breakaway point) will be marked as the ventilatory threshold. The VO2 value at this point will be recorded and reported as a percentage of VO2max. VO_2 values 5-10% above and below VT were used for the prescription of speeds during visit 3. Trained runners likely run a marathon or similar distances slightly below VT, while shorter races such as a 5k will likely be performed at a physiological intensity slightly above VT.

Visit 3: Running Economy Assessments

Participants were randomized into one of six groups using an online random number generator to determine shoe and speed order. Identical pre-assessment guidelines were followed to visit 2, and participants were emailed twenty-four hours before their visit as a reminder. Prior to running economy assessments participants completed the same self-selected warm-up as in visit 2. Participants were handed the shoes to put on and tie themselves for comfort. Six separate five-minute trials were performed to assess running economy with two trials being completed in each of the three shoe conditions. Either the above VT or below VT condition was completed first for each shoe, dependent on group randomization. Both running speeds in each shoe were performed before changing shoes. In between RE trials, participants were able to sit or walk freely in the lab and drink water as needed.

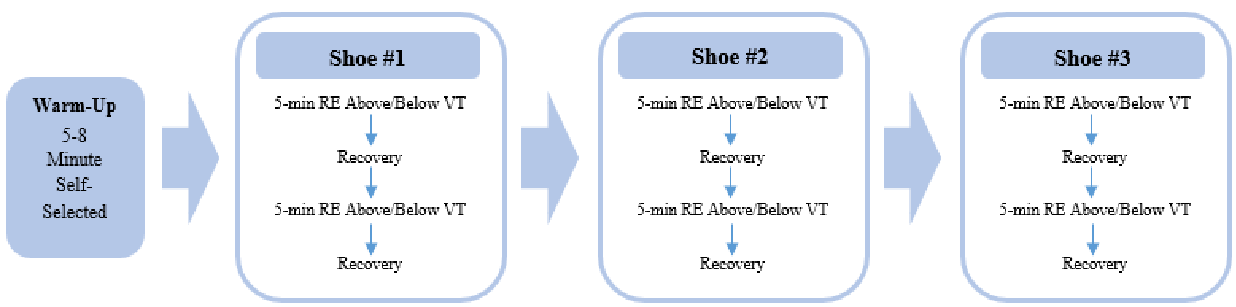


Figure 3: Description of the order of events during visit 3 Running Economy assessments.

Running Economy

Running economy was assessed within the six submaximal trials during visit 3. VO_2 data from the final 2-minutes of each 5-minute trial were averaged. Oxygen consumption was reported directly from the Parvo Medics metabolic cart as ml/kg/min for each shoe type both above and below VT. The respiratory exchange ratio (RER) was constantly monitored throughout each RE trial. RER must remain below 1.0 to meet the standards for RE assessment (D. Conley & Krahenbuhl, 1980).

Heart Rate & Rating of Perceived Exertion

Heart rate was recorded at the end of each minute during RE assessments using a Polar heart rate monitor (details). Rating of perceived exertion (RPE) on a 6-20 scale was assessed twice during each five-minute trial. Once during the third minute and once in the last minute to ensure that the trial did not "feel" more difficult as the participant progressed.

Power Analysis

A power analysis was performed a priori (G*Power 3.1 Universität Kiel, Germany). Several published research studies were referenced to determine that a significant and meaningful difference in oxygen consumption would be 2.2%. (Barnes & Kilding, 2015a). It was determined that a sample size of 24 was required to achieve an effect size of 0.35, matching previous literature (Hébert-Losier et al., 2020). Alpha and beta values were set a priori at 0.05 and 0.20 respectively. Two groups (shoe condition and running velocity) and three measures were used to determine the sample size.

Statistical Analyses

Data were analyzed using Jamovi Statistics Version 2.2.5 (Jamovi Project Computer Software, 2022). Differences in running economy between shoe conditions were determined using a linear mixed model. VO2 was the dependent variable, with shoe condition being the fixed factor. Subject ID was used as a cluster variable. Above and below VT running economy values were assessed separately for all statistical analyses. Non-significant interaction effects were moved from the model.

CHAPTER IV: RESULTS

Subjects

Nine trained male runners who had previously run a sub-18-minute 5k in the past year completed the study. Participants ranged from 18-28 years old, with anthropometric data and self-reported variables of interest listed in **Table 4** Participants also reported training phase (base n=5, strength n=2, speed n=1, taper or recovery n=1) and their typical training shoe. Individual shoe characteristics as well as characteristics of the three shoes assessed in the study are presented in **Table 5**.

Table 4: Participant Characteristics

Age (years)	Height (cm)	Weight (cm)	5k Run Time (min)	Weekly Training Volume (miles)
20.7 (2.9)	182.8 (5.1)	74.4 (8.4)	17.2 (0.8)	37.8 (18.2)

Abbreviations: cm, centimeter; kg, kilogram; min, minutes.
Data reported in mean (standard deviation).

VO_2max

Each participant completed a maximal aerobic capacity test during visit 2. Five participants completed the original protocol with a 1% grade increase each minute while running at 10mph. As most participants (n=4) were unable to run for the desired period (8-12 minutes), a modification was required. To date, four participants completed the revised protocol with grade increasing 0.5% per minute while running at 10mph. The average time to termination increased from 6.2 minutes before the change in protocol to 10.0 minutes.

Ventilatory variables from maximal aerobic capacity tests are listed in **Table 6**. Eight out of nine participants met at least three of the following five criteria for determining a maximal aerobic capacity test;

(i) Blood lactate >8.0mmol/L 3-minutes posttest termination; (ii) RER ≥ 1.10; (iii) HR within 10bpm of age-predicted maximum; (iv) No change in VO_2 (≤ 2ml/kg/min) with an increase in exercise intensity; (v) RPE ≥ 18. One test was deemed a VO2peak, but a valid ventilatory threshold could still be determined, so the participant remained enrolled.

Table 5: Shoe Characteristics

Shoe Model	Mass (oz)	Heel Stack Height (mm)	Forefoot Stack Height (mm)	Heel-Toe Drop (mm)	Midsole Composition	Plate Geometry
Skechers Speed Elite Hyper	5.7	28	24	4	Hyper Burst	Forefoot Winglet
Skechers Go Run Razor 3	5.4	28	24	4	Hyper Burst	None
Nike Zoom Vaporfly 4%	6.9	39	29	10	ZoomX	Full-Length Curved
Brooks Ghost	10	36	28	8	DNA Loft	None
Brooks Glycerin	10.2	31	21	10	DNA Loft	None
Asics GT 2000	10.6	22	14	8	LiteTruss	None
Altra Escalante	6.8	22	22	0	Altra EGO	None
Hoka Rincon 3	7.3	33	28	5	HOKA EVA	None
New Balance Tempo	6.5	24	18	6	Fresh Foam	None
Zoot Ultra TT Fade	7.3	23	20	3	ZVA	None
Adidas Energy Boost	11	31.5	21.5	10	Boost	None

Skechers Speed Elite Hyper, Skechers Go Run Razor 3, and Nike Zoom Vaporfly 4% were analyzed in the study. Participants regularly trained in one of the other six shoes described. No participants previously trained in the shoe conditions being assessed in the study.
Abbreviations: oz, ounce; mm, millimeter

Table 6: Maximal Aerobic Capacity Test

	VO2max (L/min)	VO2max (ml/kg/min)	VT (L/min)	VT (ml/kg/min)	VT (%VO2max)	Below VT Running Speed (mph)	Above VT Running Speed (mph)
Mean	5.0 (0.5)	67.9	3.7 (0.4)	50.1 (5.9)	73.9 (3.4)	7.7 (1.0)	9.6 (1.2)
Minimum	4.1	52.6	3.0	39.9	66.5	6.1	7.5
Maximum	5.4	73.8	4.2	56.8	77.8	8.9	11.0

Abbreviations: L/min, liters per minute; ml/kg/min, milliliters per kilogram per minute; mph, miles per hour. Data reported in mean (standard deviation).

Running Economy

The following two sections address RQ1: how RE differs across three shoe conditions at independent running intensities. Running speeds were prescribed 5-10% both above and below VT using ACSM metabolic equations, and the %VT measured during the trials is presented in **Table 7** We did not achieve this range for the below VT condition. On average participants' oxygen consumption was 14.6%, 15.3%, and 16.9% below VT for the SE, R3, and VF respectively with an average of 15.6% below VT across conditions. We did achieve this range for the above VT condition. On average participants' oxygen consumption was 7.9%, 8.1%, and 6.2% above VT for the SE, R3, and VF respectively, with an average of 7.4% above VT across conditions. Average running speeds across the sample size were 12.5kmh and 15.5kmh during the below and above VT trials respectively. Oxygen consumption while running at speeds above and below VT were analyzed separately.

Table 7: Running Economy Intensities

Shoe Condition	Above VT%	Below VT%
Speed Elite	107.9 (7.4)	85.4 (7.1)
Razor 3	108.1 (7.1)	84.7 (6.5)
Vaporfly	106.2 (6.3)	83.1 (5.8)

Abbreviations: VT, Ventilatory Threshold
Reported as mean (standard deviation)

Below Ventilatory Threshold

Oxygen consumption values while running at a speed 15.6% below ventilatory threshold are displayed in **Figure 4**. Relative to the SE, RE in the R3 was unchanged [MD = -0.35ml/kg/min; 95% CI (1.08, 0.372); p = 0.355; d = 0.05, **Figure 4A**). Relative to the SE, RE in the VF was decreased 1.3% [MD = -1.19ml/kg/min; 95% CI (-1.92, -0.47); p = 0.005; d =0.18).

Additionally, HR and rating of perceived exertion data while running at an intensity below VT are included in **Figure 4**. Relative to the SE, neither R3 HR [MD = 0.2; 95% CI (-1.9, 2.2); p = 0.875; d = 0.01, **Figure 4B**) or VF HR [MD = -2.2; 95% CI (-4.2, -0.1); p = 0.054; d = 0.14) were different. For

RPE, R3 [MD = 0.1; 95% CI (-0.4, 0.6); p = 0.660; d = 0.08, **Figure 4C**) and VF [MD = -0.4; 95% CI (-0.9, 0.1);   p = 0.136; d = 0.36) were not different than the SE.

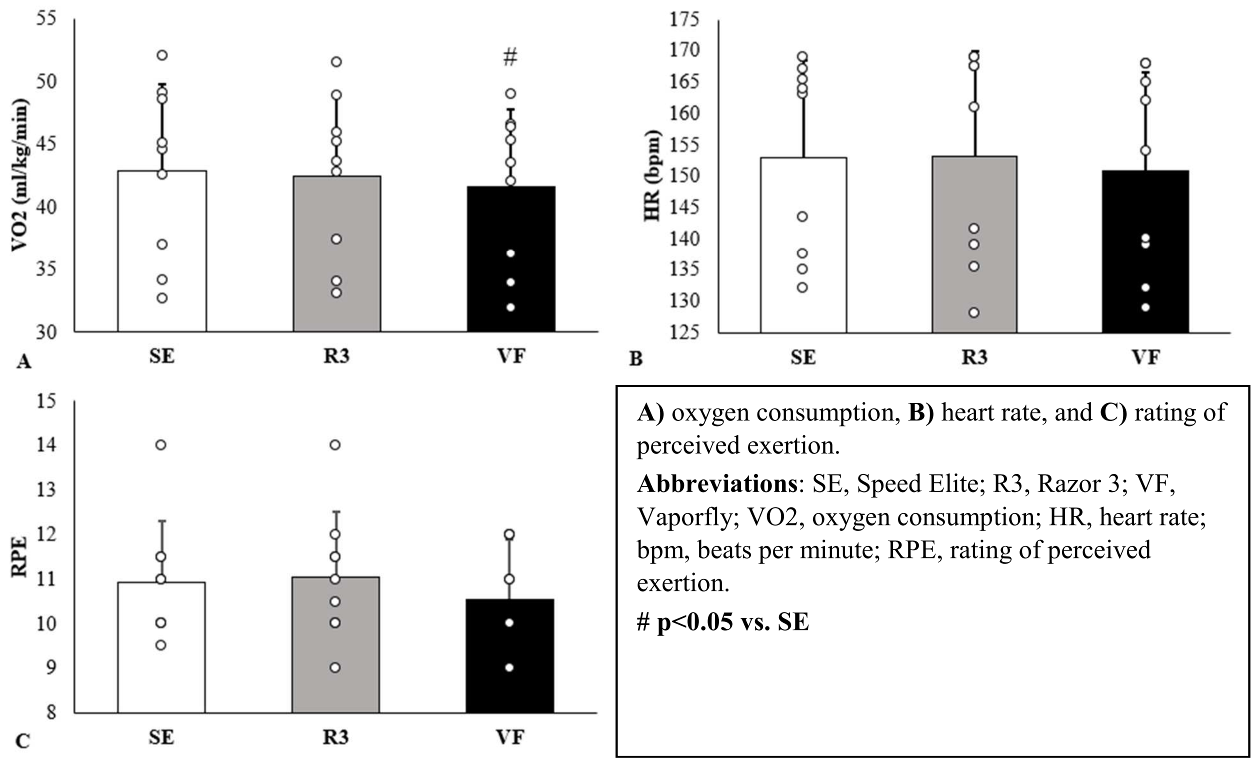
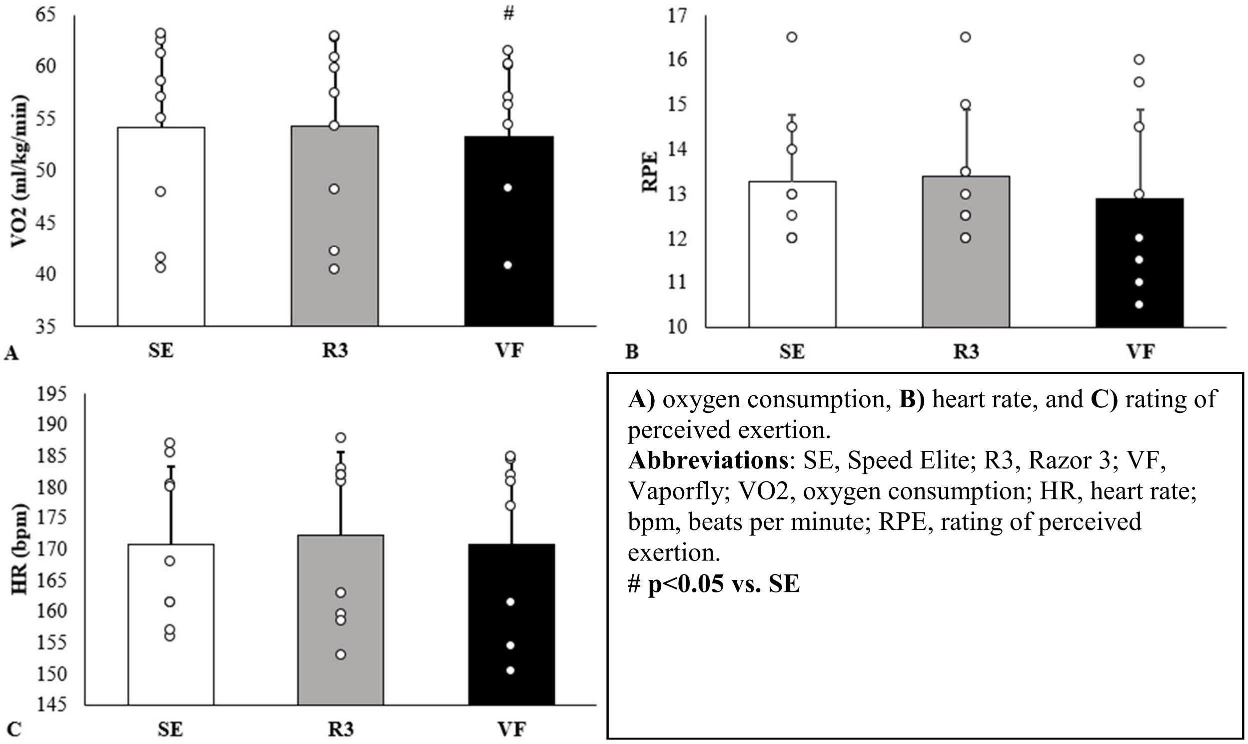


Figure 4: Mean and individual response while running at a speed prescribed 5-10% below ventilatory threshold

Above Ventilatory Threshold

Oxygen consumption values while running at a speed prescribed 5-10% above ventilatory threshold are displayed in **Table 5**. Relative to the SE, running economy in the R3 was unchanged [MD = 0.13; 95% CI (-0.55, 0.81); p = 0.715; d = 0.01, **Figure 5A**). Relative to the SE, RE in the VF was significantly decreased [MD = -0.90; 95% CI (-1.58, -0.23); p = 0.019; d =0.11). Individual responses to the three footwear conditions while running at an intensity above VT are displayed in **Figure 5**. Also included in **Figure 5** are cardiovascular (HR) and rating of perceived exertion data while running at an intensity above VT. Relative to the SE, neither R3 HR [MD = 1.4bpm; 95% CI (-1.5, 4.4); p = 0.346; d = 0.05, **Figure 5B**) or VF HR [MD = 0.1bpm; 95% CI (-2.9, 3.0); p = 0.971; d = 0.06) were different. For RPE, R3 [MD = 0.1; 95% CI (-0.8, 1.0); p = 0.805; d = 0.15, **Figure 5C**) and VF [MD = -0.4; 95% CI (-1.3, 0.5); p = 0.39; d = 0.36) were not different than the SE.



A) oxygen consumption, **B)** heart rate, and **C)** rating of perceived exertion.
Abbreviations: SE, Speed Elite; R3, Razor 3; VF, Vaporfly; VO2, oxygen consumption; HR, heart rate; bpm, beats per minute; RPE, rating of perceived exertion.
 # p<0.05 vs. SE

Figure 5: Mean and individual response while running at a speed prescribed 5-10% above ventilatory threshold

Changes in Running Economy Above and Below Ventilatory Threshold

To examine if RE changes different between the two running speeds, the condition x speed interaction was then examined. No interaction was found ($p = 0.893$) and this term was subsequently removed from the model. As expected, a main effect of running intensity (below vs. above VT) was observed for VO2 (MD 11.6ml/kg/min; 95% CI (10.8, 12.5); $p < 0.001$; $d = 1.6$, **Figure 6A**). Independent of running speed, a main effect of shoe condition is approaching significance ($p = 0.089$, **Figure 6**). Relative to the SE, running in the R3 was unchanged [MD = -0.11; 95% CI (-1.11, 0.89); $p = 0.827$; $d = 0.01$) independent of running speed. Alternatively, relative to the SE, RE in the VF was increased [MD = -1.1ml/kg/min; 95% CI (-2.1, -0.05); $p = 0.046$; $d = 0.14$). No shoe condition x speed interaction was observed for HR ($p = 0.323$) or RPE ($p = 0.125$). As expected, main effects of running intensity were observed for HR (MD = 19bpm; 95% CI (17.0, 21.0); $p < 0.001$; $d = 1.3$, **Figure 6B**) and RPE (MD = 2.3bpm; 95% CI (1.9, 2.7); $p <0.001$; $d = 1.6$, **Figure 6C**).

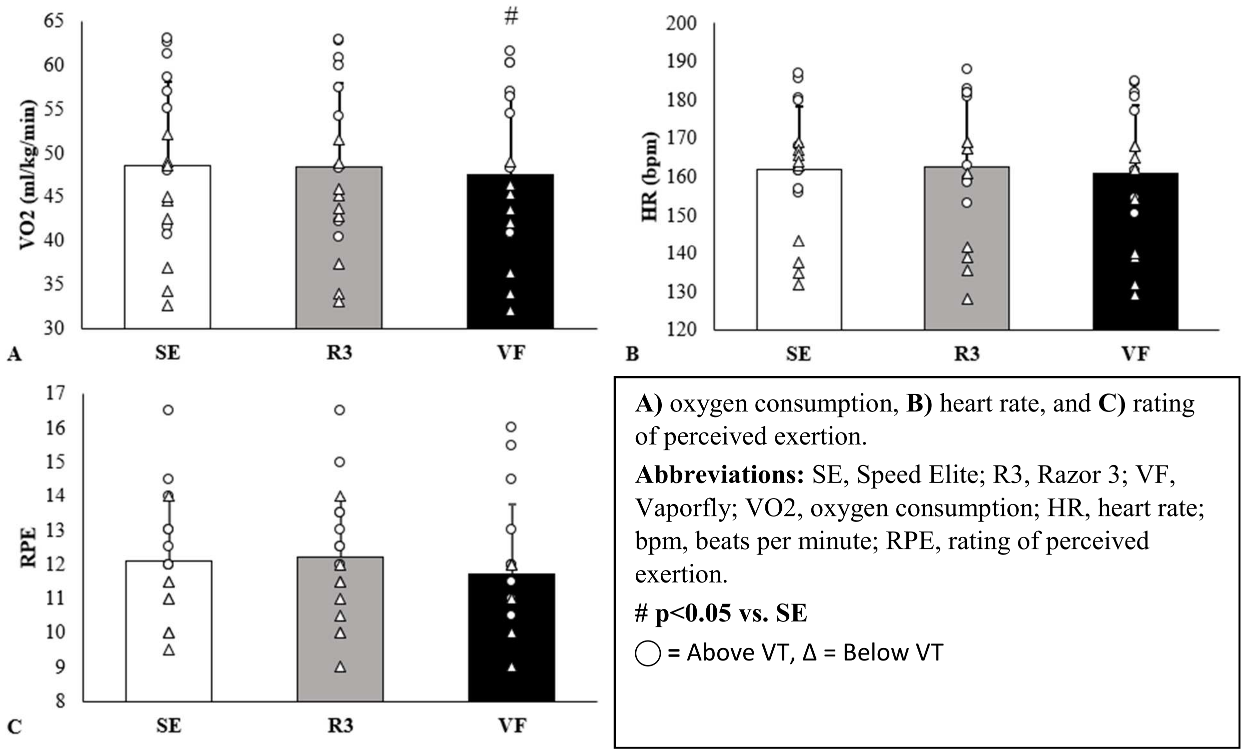


Figure 6: Combined mean and individual responses of running at intensities below and above ventilatory threshold.

CHAPTER V: DISCUSSION

With the goal of covering a given distance in as little time as possible, many runners opt to use various ergogenic aids to enhance performance. Carbon fiber shoes have been a popular choice in recent years, with evidence that these "super shoes" benefit most runners. However, it remains unclear whether this is a result of the carbon fiber plate, reliant and resilient midsoles, or a combination thereof. The present study is the first to assess the independent benefit of a carbon fiber plate by assessing RE in two nearly identical, commercially available, running shoes. Preliminary results suggest that a carbon fiber plate alone does not significantly improve RE when compared to an otherwise identical shoe. However, there is a trend towards significance for improvement RE while running in a shoe with both increased midsole volume and a carbon fiber plate that supports previous work. Initial results thus suggest that further research is warranted to determine which shoe characteristic is most important concerning RE improvements.

Limitations and strengths of the present study are presented initially to provide context for the interim findings. In this pre-planned interim analysis, we are currently underpowered ($\beta = 0.13$) due to the small sample size (n=9), and data collection remains ongoing. While these shoes were the top of the line at the time of the study's inception (early 2020), the current versions may be slightly outdated as new variations of both Skechers and Nike running shoes have since been released. Although differences in RE between shoe conditions may not be physiologically significant at this time it is important to determine if certain shoe characteristics (i.e., carbon fiber plate, midsole volume) are beneficial moving forward. Additionally, results from the current study cannot be extrapolated across sexes, as at the study’s inception Skechers had not yet released women’s sizes. Finally, despite being a trained population, there is some heterogeneity within our participants. All participants were trained runners, but differences in weekly training volume, training plans, and training phase were evident. There were also several triathletes within the group. However, all participants responded similarly across speeds and shoe conditions, so current findings may be appropriate for trained runners of various backgrounds.

The present study also had several strengths. Two commercially available running shoes were used, in which the sole difference is the presence of a carbon fiber plate. Moreover, participants were a well-trained population of competitive runners who are most likely to purchase and use this footwear. The inclusion of the Nike Vaporfly also allows for comparison to previous literature as the "gold standard" for RE studies. This is the first study to our knowledge that prescribed individualized running speeds in carbon fiber shoes, while also assessing intensities both above and below the ventilatory threshold. Furthermore, the crossover design performed in a single testing session reduced inter- and intra-subject variation. While not part of this thesis, additional analyses are ongoing that will allow us to identify if foot strike patterns or differences in the gait cycle result in improved or diminished RE.

The primary aim of this study was to determine the effect of a carbon fiber plate in two otherwise identical, commercially available running shoes. Preliminary results suggest that a carbon fiber plate alone may not improve RE while running at intensities above and below the VT. While running at an intensity above VT oxygen consumption was 0.23% lower in the SE compared to the R3. Interestingly, oxygen consumption was 0.82% higher in the SE compared to the R3 while running at any intensity below VT. While not statistically significant, this does suggest that the SE may be of greater benefit as running velocity continues to increase. Conversely, the SE could be detrimental to performance at slower running velocities. This aligns with previous literature that found a stiffer carbon fiber plate to be favorable at 17km/hr but not at 14km/hr (Day & Hahn, 2020). In the current study participants' average running speeds were 12.5km/hr and 15.5km/hr at the below and above VT intensities respectively. Of additional importance, the running speeds and fitness level of participants is similar to that of previous literature. Previous studies have attempted to isolate the carbon fiber plate as a variable of interest but made custom modifications to commercially available footwear. A top-loaded carbon fiber plate was found to have no effect on the energetic cost of running when compared to a similar control shoe (Beck et al., 2020; Flores et al., 2019), which is consistent with the current study. A similar study in which a carbon fiber plate was cut to reduce its' effect also found no benefit to increased LBS in an otherwise identical shoe. Our current results support these findings in previous work but provide the first results in non-modified commercially available shoes.

While not the primary focus of the study, RE was also assessed in the VF to provide a reference to previous literature. RE while running at an intensity above VT was 1.6% better in the VF compared to the SE. This difference was greater when running below VT, with the SE being 2.8% lower than the VF. These values align with previous studies that have reported improvements in RE ranging from 1.0-4.0% (Barnes & Kilding, 2019; Hébert-Losier et al., 2020; Hoogkamer et al., 2018; Hunter et al., 2019) when running in the VF compared to non-carbon fiber plated running shoe. Additional questions are raised based on the VF performing better independent of running speed in comparison to the SE. While most studies to date compared the VF to non-carbon fiber running shoes, a recent study (Joubert & Jones, 2021) assessed RE in seven different carbon fiber shoes. Running in the two shoes with the greatest midsole volume (Nike Alphafly Next% and Nike Vaporfly Next%2) provided the greatest improvement in RE. These results have been reproduced in the present study using different carbon fiber shoes, showing that shoes (e.g., VF) with greater midsole volume and a carbon fiber plate improve RE.

The current study assessed RE while running at intensities prescribed both below and above each participant's VT. This is a novel design as previous studies used a standardized running speed ranging from 14-18km/hr (Barnes & Kilding, 2019; Healey & Hoogkamer, 2021; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert & Jones, 2021). While not detailed in these studies, it is unlikely that each participant was running at the same relative intensity at a given velocity. Although we did not observe statistically significant differences in RE across running speeds, interim results offer that shoe selection may be meaningful for performance.

At present, the current study suggests that a carbon fiber plate alone may not account for improvements in RE while wearing different shoe models. As such, it remains unclear how exactly these "super shoes" result in significant improvements in RE. Thus, future studies should consider assessing RE in two nearly identical carbon fiber shoes with different midsole volumes, as our initial results suggest that inclusion of the carbon plate had little impact while controlling for the midsole. Furthermore, the findings presented in this study may be beneficial for runners who race at different distances. The VF (40mm stack heigh vs. 28mm in SE) and other high midsole volume running shoes are designed for marathon-like distances. During marathon running trained runners have been found to run at an intensity of 65-75% of VO2max for the majority of the race (Koivisto, 1986). In trained runners like those in the current study, these physiological intensities are typically just below the VT. The current results suggest that the VF would improve while the R3 would not change performance compared to the SE. would. For shorter races (i.e., 5km and 10km) shoe selection may differ. The VF remains significantly better than the SE, but improvements in RE are only 1.6% compared to 2.8% at slower speeds. It is important to consider the race day implications for small improvements in RE when determining how beneficial a given shoe may be. The ability to extrapolate improvements in RE at physiological intensities above VT is a novel aspect of the current study and may be a potentially important finding for a large number of runners training for shorter distance events.

Although current differences in oxygen consumption are not statistically significant, even a minor improvement in RE can substantially improve performance. A 1% improvement in RE has shown to result in a 0.78% improvement in performance (Hoogkamer et al., 2016). As a result, wearing the SE would improve performance by 0.18% (vs. the R3) at intensities 6% above VT and decrease performance by 0.64% at intensities 17% below VT, potentially suggesting that shoe selection needs to be race (distance) specific. Additionally, wearing the SE rather than the VF would decrease performance by 1.3% and 2.2% below and above VT respectively. For reference, a 1% improvement in performance for a runner who previously ran a three-hour marathon would result in a nearly two-minute personal best. For an 18-minute 5k runner, a 1% improvement would result in over a 10-second personal best by simply changing shoe conditions. Assuming that extrapolations to performance remain true, this could be important information as runners decide if running "X percent" faster is personally worth purchasing a pair of "super shoes."

In summary, this study adds to the growing body of literature regarding the effect of carbon fiber plated running shoes on RE and performance. The preliminary analyses conducted for the present study suggest that a carbon fiber plate alone may not significantly improve RE, but that changes in RE are consistent across physiological intensities. Going forward, additional analyses will be conducted in the future to assess the effect that gait cycle parameters, ground reaction forces, and foot strike patterns may have on changes in RE. Further research is necessary to determine what shoe characteristic is most important for manufacturers and runners alike when choosing footwear on race day. These may include but are not limited to foot strike pattern, midsole volume and composition, plate geometry, and gait mechanics.

REFERENCES

Albouaini, K., Egred, M., Alahmar, A., & Wright, D. J. (2007). Cardiopulmonary exercise testing and its application. *Heart*, *93*(10), 1285. https://doi.org/10.1136/HRT.2007.121558

Aminaka, N., Arthur, K., Porcari, J. P., Foster, C., Cress, M., & Hahn, C. (2018). No immediate effects of highly cushioned shoes on basic running biomechanics. *Kinesiology*, *50*(1), 124–130. https://doi.org/10.26582/k.50.1.10

Anderson, T. (1996). Biomechanics and Running Economy. *Sports Medicine*, *22*(2), 76–89. http://linkinghub.elsevier.com/retrieve/pii/S0065215608703880%5Cnhttp://www.journals.cambridge.org/abstract_S0884291412001641%5Cnhttp://dx.doi.org/10.1016/j.matdes.2012.10.046%5Cnhttp://www.sciencedirect.com/science/article/pii/S092401360000635X%5Cnhttp:/

Arellano, C. J., & Kram, R. (2014). Partitioning the metabolic cost of human running: A task-by-task approach. *Integrative and Comparative Biology*, *54*(6), 1084–1098. https://doi.org/10.1093/icb/icu033

Barnes, Kyle R.; McGuigan, Michael R.; Kilding, A. E. (2014). *Lower Body Determinant of Running Economy in Male and Female Distance Runners*. *28*(5), 1289–1297.

Barnes, K. R., Hopkins, W. G., Mcguigan, M. R., Northuis, M. E., & Kilding, A. E. (2013). Effects of resistance training on running economy and cross-country performance. *Medicine and Science in Sports and Exercise*, *45*(12), 2322–2331. https://doi.org/10.1249/MSS.0B013E31829AF603

Barnes, K. R., & Kilding, A. E. (2015a). Running economy: measurement, norms, and determining factors. *Sports Medicine - Open*, *1*(1), 1–15. https://doi.org/10.1186/s40798-015-0007-y

Barnes, K. R., & Kilding, A. E. (2015b). Strategies to Improve Running Economy. *Sports Medicine*, *45*(1), 37–56. https://doi.org/10.1007/s40279-014-0246-y

Barnes, K. R., & Kilding, A. E. (2019). A Randomized Crossover Study Investigating the Running Economy of Highly-Trained Male and Female Distance Runners in Marathon Racing Shoes versus Track Spikes. *Sports Medicine*, *49*(2), 331–342. https://doi.org/10.1007/s40279-018-1012-3

Beck, O. N., Golyski, P. R., & Sawicki, G. S. (2020). Adding carbon fiber to shoe soles may not improve running economy: a muscle-level explanation. *Scientific Reports*, *10*(1), 1–13. https://doi.org/10.1038/s41598-020-74097-7

Bennett, J. R., & Kehoe, M. P. (2008). Marathon fueling techniques: Physiologic understanding and a proposed intake schedule. *Strength and Conditioning Journal*, *30*(5), 56–65. https://doi.org/10.1519/SSC.0B013E318187F1B5

Cavagna, G. A., Saibene, F. P., & Margaria, R. (1963). Mechanical work in running. *Journal of Applied Physiology*, *2*, 249–256.

Cavanagh, P. R., Pollock, M. L., & Landa, J. (1977). a Biomechanical Comparison of Elite and Good Distance Runners. *Annals of the New York Academy of Sciences*, *301*(1), 328–345. https://doi.org/10.1111/j.1749-6632.1977.tb38211.x

Chapman, R. F., Laymon, A. S., Wilhite, D. P., McKenzie, J. M., Tanner, D. A., & Stager, J. M. (2012). Ground contact time as an indicator of metabolic cost in elite distance runners. *Medicine and Science in Sports and Exercise*, *44*(5), 917–925. https://doi.org/10.1249/MSS.0b013e3182400520

Clark, K. P., Ryan, L. J., & Weyand, P. G. (2017). A general relationship links gait mechanics and running ground reaction forces. *Journal of Experimental Biology*, *220*(2), 247–258. https://doi.org/10.1242/jeb.138057

Conley, D., & Krahenbuhl, G. (1980). *Running_economy_and_distance_running_performance.10.pdf* (pp. 357–360). Medicine & Science in Sports & Exercise.

Conley, D. L., & Krahenbuhl, G. S. (1980). Running economy and distance running performance of highly trained athletes. *Medicine & Science in Sports & Exercise*, *12*(5), 357–360. https://doi.org/10.1249/00005768-198012050-00010

Costill, D. L. (1972). Physiology of Marathon Running. *JAMA: The Journal of the American Medical Association*, *221*(9), 1024–1029. https://doi.org/10.1001/jama.1972.03200220058013

Daniels, J. T. (1985). *A physiologist's view of running economy* (Issue 17(3), pp. 332–338).

Day, E., & Hahn, M. (2020). Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent. *Footwear Science*, *12*(1), 3–13. https://doi.org/10.1080/19424280.2019.1696897

Di Prampero, P. E., Salvadego, D., Fusi, S., & Grassi, B. (2009). A simple method for assessing the energy cost of running during incremental tests. *Journal of Applied Physiology*, *107*(4), 1068–1075. https://doi.org/10.1152/japplphysiol.00063.2009

Farina, E. M., Haigh, D., & Luo, G. (2019). Creating footwear for performance running. *Footwear Science*, *11*(sup1), S134–S135. https://doi.org/10.1080/19424280.2019.1606119

Ferris, D. P., Liang, K., & Farley, C. T. (1999). Runners adjust leg stiffness for their first step on a new running surface. *Journal of Biomechanics*, *32*(8), 787–794. https://doi.org/10.1016/S0021-9290(99)00078-0

Fletcher, J. R., Esau, S. P., & MacIntosh, B. R. (2009). Economy of running: Beyond the measurement of oxygen uptake. *Journal of Applied Physiology*, *107*(6), 1918–1922. https://doi.org/10.1152/japplphysiol.00307.2009

Fletcher, J. R., & MacIntosh, B. R. (2015). Achilles tendon strain energy in distance running: Consider the muscle energy cost. *Journal of Applied Physiology*, *118*(2), 193–199. https://doi.org/10.1152/japplphysiol.00732.2014

Fletchern, J. R., & MacIntosh, B. R. (2017). Running economy from a muscle energetics perspective. *Frontiers in Physiology*, *8*(JUN), 1–15. https://doi.org/10.3389/fphys.2017.00433

Flores, N., Delattre, N., Berton, E., & Rao, G. (2019). Does an increase in energy return and/or longitudinal bending stiffness shoe features reduce the energetic cost of running? *European Journal of Applied Physiology*, *119*(2), 429–439. https://doi.org/10.1007/s00421-018-4038-1

Frederick, E. C. (1984). Physiological and ergonomics factors in running shoe design. *Applied Ergonomics*, *15*(4), 281–287. http://www.embase.com/search/results?subaction=viewrecord&from=export&id=L15160790%5Cn http://sfx.bibl.ulaval.ca:9003/sfx_local?sid=EMBASE&issn=00036870&id=doi:&atitle=Physiological+and+ergonomics+factors+in+running+shoe+design&stitle=APPL.+ERGON.&title=Ap

Hamill, J., Gruber, A. H., & Derrick, T. R. (2014). Lower extremity joint stiffness characteristics during running with different footfall patterns. *European Journal of Sport Science*, *14*(2), 130–136. https://doi.org/10.1080/17461391.2012.728249

Hannigan, J. J., & Pollard, C. D. (2020). Differences in running biomechanics between a maximal, traditional, and minimal running shoe. *Journal of Science and Medicine in Sport*, *23*(1), 15–19. https://doi.org/10.1016/j.jsams.2019.08.008

Healey, L. A., & Hoogkamer, W. (2021). *Longitudinal bending stiffness does not affect running economy in Nike Vaporfly shoes*. 1–24. https://doi.org/10.31236/osf.io/37uzr

Hébert-Losier, K., Finlayson, S., Driller, M., Dubois, B., Esculier, J., & Beaven, C. (2020). Metabolic and performance responses of male runners wearing 3 types of footwear: Nike Vaporfly 4%, Saucony Endorphin racing flats, and their own shoes. *Journal of Sport and Health Science*. https://doi.org/10.1016/J.JSHS.2020.11.012

Henritze, J., Weltman, A., Schurrer, R. L., & Barlow, K. (1985). Effects of training at and above the lactate threshold on the lactate threshold and maximal oxygen uptake. *European Journal of Applied Physiology and Occupational Physiology*, *54*(1), 84–88. https://doi.org/10.1007/BF00426304

Henry, F. M., & Demoor, J. C. (1956). Lactic and alactic oxygen consumption in moderate exercise of graded intensity. *Journal of Applied Physiology*, *8*(6), 608–614. https://doi.org/10.1152/jappl.1956.8.6.608

Hoogkamer, W., Kipp, S., Frank, J. H., Farina, E. M., Luo, G., & Kram, R. (2018). A Comparison of the Energetic Cost of Running in Marathon Racing Shoes. *Sports Medicine*, *48*(4), 1009–1019. https://doi.org/10.1007/s40279-017-0811-2

Hoogkamer, W., Kipp, S., Spiering, B. A., & Kram, R. (2016). Altered running economy directly translates to altered distance-running performance. *Medicine and Science in Sports and Exercise*, *48*(11), 2175–2180. https://doi.org/10.1249/MSS.0000000000001012

Hunter, I., McLeod, A., Valentine, D., Low, T., Ward, J., & Hager, R. (2019). Running economy, mechanics, and marathon racing shoes. *Journal of Sports Sciences*, *37*(20), 2367–2373. https://doi.org/10.1080/02640414.2019.1633837

Jewell, D. (2019). *The History Of Carbon Fiber in Running Shoes - Free Run Speed*. Free Run Speed. https://www.freerunspeed.com/the-history-of-carbon-fiber-in-running-shoes/

Joubert, D. P., & Jones, G. P. (2021). *A Comparison of Running Economy Across Seven Carbon-Plated A Comparison of Running Economy Across Seven Carbon-Plated Racing Shoes Racing Shoes Repository Citation Repository Citation RUNNING ECONOMY IN SEVEN CARBON-PLATED SHOES Title: A Comparison of Run*. https://scholarworks.sfasu.edu/kinesiology

Joyner, M. J. (1991). Modeling: Optimal marathon performance on the basis of physiological factors. *Journal of Applied Physiology*, *70*(2), 683–687. https://doi.org/10.1152/jappl.1991.70.2.683

Kenneally, M., Casado, A., & Santos-Concejero, J. (2017). “The Effect of Periodisation and Training Intensity Distribution on Middle-and Long-Distance Running Performance: A Systematic Review” by Article Title: The Effect of Periodisation and Training Intensity Distribution on Middle-and Long-Distance Running Performance: A Systematic Review. *International Journal of Sports Physiology and Performance (SPAIN). Journal: International Journal of Sports Physiology and Performance*. https://doi.org/10.1123/ijspp.2017-0327

Koivisto, V. A. (1986). The physiology of marathon running. *Science Progress (1933-)*, *70*(1 (277)), 109–127. http://www.jstor.org/stable/43420631

Koldenhoven, R. M., & Hertel, J. (2018). Validation of a Wearable Sensor for Measuring Running Biomechanics. *Digital Biomarkers*, *2*(2), 74–78. https://doi.org/10.1159/000491645

Kram, R., Griffin, T. M., Donelan, J. M., Chang, Y. H. U. I., Griffin, T. M., & Maxwell, J. (1998). Force treadmill for measuring vertical and horizontal groud reaction forces. *Journal of Applied Physiology*, 764–769.

Kram, R., & Taylor, C. R. (1990). Energetics of running: A new perspective. *Nature*, *346*(6281), 265–267. https://doi.org/10.1038/346265a0

Kunimasa, Y., Sano, K., Oda, T., Nicol, C., Komi, P. V., Locatelli, E., Ito, A., & Ishikawa, M. (2014). Specific muscle-tendon architecture in elite Kenyan distance runners. *Scandinavian Journal of Medicine and Science in Sports*, *24*(4), 269–274. https://doi.org/10.1111/sms.12161

Li, F., Newton, R. U., Shi, Y., Sutton, D., & Ding, H. (2021). Correlation of eccentric strength, reactive strength, and leg stiffness with running economy in well-trained distance runners. *Journal of Strength and Conditioning Research*, *35*(6), 1491–1499. https://doi.org/10.1519/JSC.0000000000003446

Lienhard, K., Schneider, D., & Maffiuletti, N. A. (2013). Validity of the Optogait photoelectric system for the assessment of spatiotemporal gait parameters. *Medical Engineering and Physics*, *35*(4), 500–504. https://doi.org/10.1016/j.medengphy.2012.06.015

Luo, G., Stergiou, P., Worobets, J., Nigg, B., & Stefanyshyn, D. (2009). Improved footwear comfort reduces oxygen consumption during running. *Footwear Science*, *1*(1), 25–29. https://doi.org/10.1080/19424280902993001

Meyer, T., Welter, J. P., Scharhag, J., & Kindermann, W. (2003). Maximal oxygen uptake during field running does not exceed that measured during treadmill exercise. *European Journal of Applied Physiology*, *88*(4–5), 387–389. https://doi.org/10.1007/s00421-002-0718-x

Milani, J., Fernhall, B., Gorman, P., & Donald, P. (1998). *Impact of Steady-State and Exercise Modality on Estimating Oxygen Consumption in Men With and Without Coronary Artery Disease* (pp. 129–138). Journal of Cardiopulmonary Rehabilitation.

Moore, I. S., Jones, A. M., & Dixon, S. J. (2012). Mechanisms for improved running economy in beginner runners. *Medicine and Science in Sports and Exercise*, *44*(9), 1756–1763. https://doi.org/10.1249/MSS.0b013e318255a727

Nigg, B. M., Cigoja, S., & Nigg, S. R. (2020). Effects of running shoe construction on performance in long distance running. *Footwear Science*, *12*(3), 133–138. https://doi.org/10.1080/19424280.2020.1778799

Nummela, A., Keränen, T., & Mikkelsson, L. O. (2007). Factors related to top running speed and economy. *International Journal of Sports Medicine*, *28*(8), 655–661. https://doi.org/10.1055/s-2007-964896

Oh, K., & Park, S. (2017). *The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion | Elsevier Enhanced Reader*. Biomechanics, Journal Of. https://reader.elsevier.com/reader/sd/pii/S0021929017300155?token=79A89F6237485496FDDB92B41BE1A7C6DC77C04C6B6762D27CCB2238E429E3456477CE0BD944311FEBBB20BFA2E815DF&originRegion=us-east-1&originCreation=20210810184303

Ortega, J. A., Healey, L. A., Swinnen, W., & Hoogkamer, W. (2021). Energetics and Biomechanics of Running Footwear with Increased Longitudinal Bending Stiffness: A Narrative Review. *Sports Medicine*, *51*(5), 873–894. https://doi.org/10.1007/s40279-020-01406-5

Paavolainen, L., Häkkinen, K., Hämäläinen, I., Nummela, A., & Rusko, H. (1999). Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology*, *86*(5), 1527–1533. https://doi.org/10.1152/jappl.1999.86.5.1527

Perl, D. P., Daoud, A. I., & Lieberman, D. E. (2012). Effects of footwear and strike type on running economy. *Medicine and Science in Sports and Exercise*, *44*(7), 1335–1343. https://doi.org/10.1249/MSS.0b013e318247989e

Powers, & K., S. (1982). Oxygen uptake and ventilatory responses to various stride lengths in trained women. *Amer. Corr. Ther. J.*, *36*, 5–8. http://ci.nii.ac.jp/naid/10025944495/en/

Roy, J. P. R., & Stefanyshyn, D. J. (2006). Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Medicine and Science in Sports and Exercise*, *38*(3), 562–569. https://doi.org/10.1249/01.mss.0000193562.22001.e8

Saunders, P. U., Telford, R. D., Pyne, D. B., Peltola, E. M., Cunningham, R. B., Gore, C. J., Hawley, J. A., Saunders, A., Telford, R. D., Pyne, D. B., Pel-Tola, E. M., Cunningham, R. B., Gore, C. J., & Hawley, J. A. (2006). SHORT-TERM PLYOMETRIC TRAINING IMPROVES RUNNING ECONOMY IN HIGHLY TRAINED MIDDLE AND LONG DISTANCE RUNNERS. *Journal of Strength and Conditioning Research*, *20*(4), 947–954.

Schubert, M. M., & Astorino, T. A. (2013). A systematic review of the efficacy of ergogenic aids for improving running performance. *Journal of Strength and Conditioning Research*, *27*(6), 1699–1707. https://doi.org/10.1519/JSC.0B013E31826CAD24

Shaw, A. J., Ingham, S. A., & Folland, J. P. (2014). The valid measurement of running economy in runners. *Medicine and Science in Sports and Exercise*, *46*(10), 1968–1973. https://doi.org/10.1249/MSS.0000000000000311

Sjödin, B., & Jacobs, I. (1981). Onset of Blood Lactate Accumulation and Marathon Running Performance. *Mt. J. Sports Medicine*, *2*, 23–26.

Stefanyshyn, D. J., & Nigg, B. M. (1997). Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. *Journal of Biomechanics*, *30*(11–12), 1081–1085. https://doi.org/10.1016/S0021-9290(97)00081-X

Stefanyshyn, D. J., & Nigg, B. M. (2000). Influence of midsole bending stiffness on joint energy and jump height performance. *Medicine and Science in Sports and Exercise*, *32*(2), 471–476. https://doi.org/10.1097/00005768-200002000-00032

Tung, K. D., Franz, J. R., & Kram, R. (2014). A test of the metabolic cost of cushioning hypothesis during unshod and shod running. *Medicine and Science in Sports and Exercise*, *46*(2), 324–329. https://doi.org/10.1249/MSS.0B013E3182A63B81

Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, *63*(3), 1236–1245. https://doi.org/10.1152/jappl.1987.63.3.1236

Williams, K. R., Cavanagh, P. R., & Ziff, J. L. (1987). Biomechanical studies of elite female distance runners. *International Journal of Sports Medicine*, *8*(SUPPL. 2), 107–118. https://doi.org/10.1055/s-2008-1025715

Willwacher, S., König, M., Potthast, W., & Brüggemann, G. (2013). *and Return at the Metatarsophalangeal Joint in Running ?* 583–592.

World Athletics. (2020). Technical Rules. *The FIE Rules for Competition*, *January*, 1–85. https://www.worldathletics.org/about-iaaf/documents/book-of-rules

Worobets, J., Wannop, J. W., Tomaras, E., & Stefanyshyn, D. (2014). Softer and more resilient running shoe cushioning properties enhance running economy Softer and more resilient running shoe cushioning properties enhance running economy. *Footwe*, *6*, 147–153. https://doi.org/10.1080/19424280.2014.918184