Effect of three different running shoes on running economy and 3-km time-trial performance in male recreational runners

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STEVEN JAMES FINLAYSON

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Abstract

Recreational running has gained immense popularity in recent years. Improving a race performance or time is a motivating factor for a number of recreational runners. It has been proposed that running economy (RE), $\dot{V}O_{2peak}$, fractional utilisation of $\dot{V}O_{2peak}$, lactate threshold, and footwear all contribute to running performance. Footwear manufacturing company Nike, Inc. has developed the Nike Vaporfly (VP4) running shoe, shown to improve running economy in elite athletes by ~3 to 4%. No research has explored the effect of VP4 on recreational runners. The aims of this Thesis were to: (1) review articles focusing on running economy, race and time-trial performance, footwear, footstrike, and perception (Chapter One); (2) investigate the energetic cost and time-trial performance in male recreational runners wearing VP4, lightweight racing flats (FLATS), and their own habitual running shoes (OWN) (Chapter Two); (3) summarises the findings of this Thesis, discuss its strengths and limitations, and addresses future research directions (Chapter Three).

In Chapter One, research on the relationship between RE, race and time-trial (TT) performance, footwear, footstrike, and perception in relation to running shoes was reviewed. Runners with a superior RE consume less oxygen and run faster than runners with an inferior RE. There is a positive correlation between $\dot{V}O_{2peak}$, fractional utilisation, lactate threshold, and average race or TT performance. Footwear midsole compliance, resilience, longitudinal bending stiffness, and mass are all key characteristics linked with RE and running performance. Research appears to indicate that rearfoot runners potentially benefit more from wearing VP4 than non-rearfoot runners. Running shoe comfort, brand name, advertising, price, and previous experience all play a role in runners' perception of running shoes.

In Chapter Two, 18 male recreational runners (age: 33.5 ± 11.9 y, $\dot{V}O_{2peak}$: 55.8 ± 4.4 mL·kg^{-1}·min^{-1}) completed three sessions to assess their RE and 3-km TT performance in VP4, FLAT, and OWN in a randomised manner. Participants completed 3 x 3-minute bouts at 60%, 70%, and 80% of their $\dot{V}O_{2peak}$ speed, followed by a 3-km TT after a 5-minute rest. Footwear significantly affected RE variables across intensities ($P < 0.002$). Oxygen consumption was lower in VP4 (3.6 to 4.5%, $P \leq 0.002$) and FLAT (2.4 to 4.0%, $P \leq 0.042$) versus OWN across intensities, with a non-significant difference between VP4 and FLAT (1.0 to 1.6%, $P \geq 0.325$). TT performance was superior in VP4 by 2.4% versus OWN ($P = 0.005$) and 1.8% versus FLAT ($P = 0.032$). Times between OWN and FLAT (0.5%, $P = 0.747$) were similar. Overall, VP4

improved lab-based RE measures in male recreational runners at relative speeds compared to OWN, but improvements in VP4 were not significant versus FLAT. More runners exhibited better treadmill TT performances in VP4 (61%) versus FLAT (22%) and OWN (17%). The variability in individual oxygen consumption (-3.1 to 12.1%) and TT (-3.8 to 8.2%) suggests individualised shoe responses.

Chapter Three summaries the findings from Chapter Two. Overall, this Thesis provides evidence that the commercially available VP4 can improve RE and 3- km TT in most male recreational runners using laboratory-based data particularly when compared to OWN. FLAT were also effective in improving RE and enhancing TT performance in some runners, albeit fewer. There was considerable variability between runners and intensities, which support individual rather than generalised benefit of VP4 in recreational runners seeking to improve running performance. Investigating the biomechanical adaptation to VP4, as well as responses to footwear based on footstrike patterns, could shed light on mechanisms that contribute to improved running performance in recreational runners.

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List of abbreviations

FFS – Forefoot strike

FLAT – Lightweight racing flats

MFS – Midfoot strike

OWN – Habitual shoes

RE – Running economy

RFS – Rearfoot strike

RPE – Rating of perceived exertion

TT – Time-trial

VAS – Visual analogue scale

$\dot{V}O_2$ – Oxygen uptake

$\dot{V}O_{2peak}$ – maximal aerobic power

VP4 – Nike Vaporfly 4%

$\upsilon\dot{V}O_{2peak}$ – speed found to elicit $\dot{V}O_{2peak}$

Thesis overview

The main aim of this Thesis was to compare running economy and 3-km time-trial performances of male recreational runners wearing three different footwear: the Nike Vaporfly 4%, Saucony Endorphin lightweight racing flats, and their habitual running shoes. This Thesis is comprised of three chapters (Figure 1). Chapter One presents a review of the literature on running economy, race and time-trial performance, footwear, footstrike, and perception. Chapter Two details an experimental study presented in an article format suitable for peer-review publication. Chapter Three summaries the key findings of the literature review and experimental study included in this Thesis, highlighting limitations, strengths, and suggestions for further research.

Chapter One – Literature review

Literature review on running economy, race and time-trial performance, footwear, footstrike, and perception

Chapter Two – Experimental study

Effect of three different running shoes on running economy and 3-km time-trial performance in male recreational runners

Chapter Three – Final chapter

Summary, limitations, strengths, and future directions

Figure 1 Flow diagram of the structure of this Thesis

Chapter One – Literature review

Introduction

According to legend, in 490 BC "Rejoice we conquer" were the words Pheidippides shouted at the walls of Athens, bringing news their army had defeated the Persians, in the famous battle at Marathon (Grogan, 1981; Martin & Gynn, 2000). Even though in all probability this legend is a myth, the first official marathon race was held at the inaugural 1896 Athens Olympic Games to commemorate Pheidippides' run (Martin & Gynn, 2000). The course followed the same path Pheidippides ran from the battlefield in Marathon, finishing at the Olympic Stadium in Athens. The total distance ran was 40 kilometres, with a winning time of 2:58.50 (Martin & Gynn, 2000). The current marathon distance of 42.1 kilometres (26.2 miles) was first ran at the 1908 Olympic Games in London (Martin & Gynn, 2000).

The Olympic motto "Citius-Altius-Fortius" and Olympic creed "The important thing in life is not the triumph, but the fight; the essential thing is not to have won, but to have fought well." (The International Olympic Committee, 2020) have inspired professional athletes to chase greater personal performances in their chosen sports. Attempts to realise these performances have led to pivotal sporting achievements (Weiss, Newman, Whitmore, & Weiss, 2016). When it comes to athletic endeavour, athletes continually show the "unattainable" is achievable. Similar to the 4-minute mile, it was long believed that a sub 2-hour marathon was physiologically impossible (Hoogkamer, Kram, & Arellano, 2017; Weiss et al., 2016).

In May 2017, wearing a pair of highly compliant, resilient, and lightweight shoes called the Nike Vaporfly Elite, Eluid Kipchoge ran an unofficial marathon record of 2:00.25 (Nike, 2019). This record was declared unofficial because the race excluded other competitors, included the use and rotation of pacesetters forming a shield to reduce wind resistance, and involved a pace car showing the ideal running course and current race time (Nike, 2019). Wearing the same shoes, Kipchoge went on to break the official marathon record, running 2:01.39 during the 2018 Berlin Marathon. Then in October 2019, and using similar tactics as May 2017, Kipchoge ran another unofficial marathon record of 1:59.40 wearing Nike's new concept shoe – the Nike Alphafly – becoming the first person to run a marathon distance in under two hours. That same weekend and allegedly wearing the Nike Vaporfly Next%, Brigid Kosgei broke the Women's World Record marathon time in Chicago in 2:14.04.

These recent monumental feats in running have sparked debate regarding the fairness of the Nike Vaporfly 4% (VP4) and associated shoe technological features (Burns & Tam, 2020). Due to this debate, the International Association of Athletics Federation (now World Athletics) clarified their shoe regulations in a manner that permitted runners to use VP4 and Nike Vaporfly Next% footwear in official races (World Athletics, 2020). Improving race times, international debate and controversy, and resulting World Athletics rule changes have catapulted the VP4 shoe and its successors into the consciousness of the running world. With millions more recreational runners than professional runners, Nike released the VP4 shoe for public purchase in North America stores and Worldwide online on the 20th July, 2017 (Nike, 2017).

In conjunction with RunRepeat, World Athletics analysed the results from 70,000 running events, determining that running has gained immense popularity in recent years (RunRepeat, 2020). Between 1986 and 2018, there has been a 57.8% increase in participants finishing running races (from 5 to 7.9 million). Over the same period, the average finishing times for all events surveyed by RunRepeat (2020) (5 km, 10 km, half marathons, and marathons) have become considerably slower, which reflects the increase in recreational runners (RunRepeat, 2020).

The health benefits of physical activity and running have been extensively studied, and include a reduction in several types of cancer, diabetes, hypertension, obesity, and coronary and cerebrovascular diseases (Blair, Sallis, Hutber, & Archer, 2012; Knight, 2012; Lee et al., 2014; Taylor, 2014; Williams, 2012). The top five risk factors for mortality are smoking, high blood pressure, high blood glucose levels, physical inactivity, and obesity (World Health Organization, 2010). Blair et al. (2012) contend that three of these factors are linked to physical inactivity: high blood pressure, high blood glucose, and obesity. Lee et al. (2014) and Pedisic et al. (2019) found that runners had a 27 to 30% lower all-cause mortality, 30 to 45% lower cardiovascular mortality, and 23% lower cancer mortality with an increase in life expectancy of 3 years compared to non-runners. Even low levels of running reduce the risk of all-cause mortality compared to no running, with no further benefits in life expectancy with increased levels of running (Lee et al., 2014; Pedisic et al., 2019). In summary, mass participation in recreational running has many health enhancing benefits.

From a performance perspective, running performance has been linked to a series of physiological factors, including running economy, maximum oxygen consumption, and lactate threshold (Barnes & Kilding, 2015; Hausswirth & Lehénaff, 2001; Swinnen, Kipp, & Kram, 2018). Running economy (RE) defines the rate of oxygen consumption when running at a given submaximal speed. Maximum oxygen consumption, also known as aerobic power or peak oxygen uptake ($\dot{V}O_{2peak}$), is the volume of oxygen consumed and used during a maximal effort (Bassett & Howley, 2000; McArdle, Katch, & Katch, 2015). The juncture where energy supplied to the muscle via aerobic metabolism is exceeded and lactate begins to accumulate in the blood is referred to as the lactate threshold (Bassett & Howley, 2000; McArdle et al., 2015). It has long been understood that the top competitor amongst athletes with comparable $\dot{V}O_{2peak}$ values is usually the one who can maintain aerobic energy production at the greatest percentage of their $\dot{V}O_{2peak}$, without accumulating substantial amounts of lactate in their blood and muscles (i.e., estimate of fractional utilisation) (Costill, Thomason, & Roberts, 1973).

A direct link between RE and running performance has been established (Hoogkamer, Kipp, Spiering, & Kram, 2016; Kipp, Kram, & Hoogkamer, 2019; Maughan & Leiper, 1983). This relationship has led to active research into the effects of acute changes in footwear on RE and running performances (Hoogkamer et al., 2018; Hunter et al., 2019). Amongst other factors, research into the modifications in running shoe technology has focused on foam-cushioned midsole, longitudinal bending stiffness, and shoe mass. Softer resilient midsoles that are able to store and return more energy from an external load have been shown to improve RE in most runners (Frederick, Howley, & Powers, 1986). Increasing longitudinal bending stiffness by inserting a carbon fibre plate has been shown to improve RE by ~1% (Roy & Stefanyshyn, 2006). However, this improvement in RE may be dependent on running speed, as well as the location and thickness of the carbon fibre plate (Flores, Delattre, Berton, & Rao, 2019; Flores, Rao, Berton, & Delattre, 2019). Shoe mass has been consistently linked with meaningful improvements in RE and time-trial (TT) performance (Franz, Wierzbinski, & Kram, 2012; Fuller, Bellenger, Thewlis, Tsiros, & Buckley, 2015; Hoogkamer et al., 2016). The VP4 shoe combines all three of these aspects and has been shown to decrease oxygen consumption and energetic cost on average by ~3 to 4% in well-trained runners, and by as much as 7.15% in some of these athletes (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019).

Running footstrike classifications generally use three categories: rearfoot (RFS), midfoot (MFS), and forefoot (FFS) strike. Depending on the level, ethnicity, and speed of runners, research has shown that 54 to 95% of runners are RFS, with MFS ranging from 3.5 to 44%, and FFS representing 0.2 to 6% (Cheung et al., 2017; de Almeida, Saragiotto, Yamato, & Lopes, 2015; Hanley, Bissas, Merlino, & Gruber, 2019; Larson et al., 2011; Patoz, Lussiana, Gindre, & Hébert-Losier, 2019; Perl, Daoud, & Lieberman, 2012). Hoogkamer et al. (2018) observed a tendency for greater improvements in RE in terms of energetic cost in RFS than non-RFS when running in VP4 compared to other marathon racing shoes. de Almeida et al. (2015) and Larson et al. (2011) noted that ~95% of recreational and sub-elite runners are RFS. With such a large proportion of recreational runners being RFS, the likelihood of a positive effect on RE (and therefore running performance) from wearing the VP4 in this group of runners, based on their typical footstrike pattern, is high.

Motivation to meet self-set goals can have both a positive and negative impact on self-satisfaction. The sense of fulfilment that individuals feel when reaching their goals and disappointment when goals are unmet can act as a motivating or demotivating factor depending on the individual's perception that the goal was attainable (Bandura & Cervone, 1983; Bandura & Jourden, 1991; Bueno, Weinberg, Fernández-Castro, & Capdevila, 2008). When goals are realised, athletes typically set new goals and/or challenges to raise performance (Bandura & Cervone, 1983; Bandura & Jourden, 1991; Bueno et al., 2008). In conjunction with The New York Times, Quealy and Katz (2019) used public race records to corroborate marathon and half-marathon race improvements in both faster and slower runners wearing the now commercially-available VP4. Their analyses indicated that runners wearing VP4 or Nike Next% in half-marathon and marathon races ran ~4 to 5% faster and had an ~72 to 73% chance of setting a personal best compared to wearing other popular running shoes (i.e., their habitual footwear) (Quealy & Katz, 2019). This information could lead to recreational runners believing the VP4 will aid them in achieving their race-goal time, or improving their potential finishing position in a race. To date, there has been no laboratory-based study undertaken that looks at the impact of VP4 on RE and running performance in recreational runners.

Intra-individual variation in performance measures needs to be considered when assessing the effectiveness of an intervention (Barnes & Kilding, 2015). Several components may affect reliability in running-related performance outcomes between testing sessions, including testing

environment and equipment, treadmill familiarity, training, nutrition, time of day, footwear, and individual variability (Morgan, Martin, Krahenbuhl, & Baldini, 1991; Pereira & Freedson, 1997; Saunders, Pyne, Telford, & Hawley, 2004a). Previous studies using moderately-trained athletes report intra-individual variations in RE between 2 to 3% running at speeds of ~9.5 to 14 km·h^{-1} (Pereira & Freedson, 1997; Williams, Krahenbuhl, & Morgan, 1991). The intra-individual variability in running time from time-trials conducted on a motorised and non-motorised treadmill is also low and reported to range from 1 to 3% when performed ~1 week apart (Driller, Brophy-Williams, & Walker, 2017; Stevens et al., 2015). These values indicate that RE and time-trial outcomes between sessions are relatively stable and can be useful in determining the magnitude of effects associated with a given intervention.

Prior to the experimental component of this Thesis, the aim of this literature review chapter is to summarise literature focused on RE, race and TT performance, footwear, footstrike, and perception. Addressing these elements will aid in understanding and interpreting the results from the experimental chapter of this Thesis, which is important given that research on recreational runners wearing VP4 is not available.

Running economy

As mentioned above, RE defines the rate of oxygen consumption when running at a given submaximal speed and is a key measure linked with running performance (Barnes & Kilding, 2015; Hausswirth & Lehénaff, 2001; Swinnen et al., 2018). There is considerable inter-individual difference in RE between athletes of similar performance abilities (Billat, Sirvent, Lepretre, & Koralsztein, 2004; Foster & Lucia, 2007; Morgan et al., 1995; Scrimgeour, Noakes, Adams, & Myburgh, 1986). These differences may be related more too anatomical and physiological variables than training status and competition history (Foster & Lucia, 2007; Morgan et al., 1995; Pate, Macera, Bailey, Bartoli, & Powell, 1992). Fitter runners have a superior RE in comparison to less fit runners (Morgan et al., 1995; Pollock, 1977) and there is a *U*-shaped curvilinear association between speed and RE (Black, Handsaker, Allen, Forrester, & Folland, 2018). A superior RE means that if two athletes are running at the same speed and all other factors are equal, the more economical runner will consume less oxygen.(McLaughlin, Howley, Bassett, Thompson, & Fitzhugh, 2010). Therefore, at the same oxygen consumption, the more economical runner should run faster than the less economical runner.

RE is typically measured running on a treadmill at a range of speeds, while measuring oxygen consumption using a metabolic cart. The measurement time must be long enough to elicit a steady state of oxygen consumption. Studies have revealed that intervals of 3 to 15 minutes are long enough to elicit a steady state response, as long as intensities are below lactate threshold (Barnes & Kilding, 2015; Whipp & Wasserman, 1972). To estimate whether an effect or intervention is meaningful, the smallest worthwhile change in RE should be established for a given cohort of runners (Saunders et al., 2004b). Even though the measurement of RE might appear straightforward, it results from a complex interaction of several systems with metabolic, cardiopulmonary, neuromuscular, and biomechanical factors contributing to RE (Barnes & Kilding, 2015).

Lowering the energetic cost of running means aerobic energy production pathways are spared, leading to a reduced energetic cost of running at a given velocity or an increased velocity within the runner's current physiological capacity (Hoogkamer et al., 2016; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999). Kipp, Byrnes, and Kram (2018) predicted that a 1% improvement in RE would lead to a 1.17% faster marathon time for a recreational runner, given that improvements in RE in slower runners improve running velocities to a greater extent than in faster runners. Accordingly, acute changes in RE via footwear interventions has become an active area of research. Variations in midsole compliance and resilience, shoe mass, and longitudinal bending stiffness have all been shown to affect energetic cost and RE to various extents (Franz et al., 2012; Hoogkamer et al., 2016; Kerdok, Biewener, McMahon, Weyand, & Herr, 2002; Roy & Stefanyshyn, 2006; Tung, Franz, & Kram, 2014; Worobets, Wannop, Tomaras, & Stefanyshyn, 2014).

VP4 are compliant, resilient, lightweight, and stiff. Previous laboratory-based studies conducted in high-calibre runners show improved RE in runners wearing VP4 (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Hunter et al. (2019) reported 2.8% RE improvements in high-calibre runners wearing VP4 at 16 km·h^{-1} compared to the Adidas Adios Boost. Both Barnes and Kilding (2019) and Hoogkamer et al. (2018) reported an ~3 to 4% improvement in RE and energetic cost of running in high-calibre runners wearing VP4 at absolute speeds ranging from 14 to 18 km·h^{-1} after adding lead weights to equalise shoe mass.

These results indicate that when wearing VP4, these runners had an improved RE, although generalisation of findings to recreational runners has not yet been confirmed.

For every 100 g of added shoe mass, oxygen consumption increases ~0.7 to 1% (Franz et al., 2012; Hoogkamer et al., 2016; Tung et al., 2014; Worobets et al., 2014). Running at 12.6 km·h^{-1}, energetic cost of high-calibre runners was shown to increase by 0.61% when 100 g was added to each shoe, and by 3.51% when 300 g was added (Hoogkamer et al., 2016). Linear regression analysis predicted a 1.11% increase in metabolic rate at 12.6 km·h^{-1} for each 100 g of added shoe mass (Hoogkamer et al., 2016). In the same study, adding 100 g and 300 g to each shoe increased the average 3-km TT time by 0.65% and by 2.37%, respectively. Thus, linear regression analysis predicted a 0.78% increase in 3-km time-trial (TT) time per 100 g of added shoe mass (Hoogkamer et al., 2016).

Race and time-trial performance

There are four main physiological variables that impact running performance: $\dot{V}O_{2peak}$, RE, fractional utilisation, and lactate threshold (Scrimgeour et al., 1986). Athletes who perform well in endurance sports generally have a superior capacity for aerobic energy transfer (McArdle et al., 2015). Attaining a high $\dot{V}O_{2peak}$ requires high levels of interaction between pulmonary ventilation, and cardiovascular and neuromuscular systems (Marieb, 2009; McArdle et al., 2015). Factors that influence a muscle's capacity to sustain high levels of aerobic output and elicit a high $\dot{V}O_{2peak}$ include capillary density, mitochondrial size and number, enzyme activity, and muscle fibre type and strength (Marieb, 2009; McArdle et al., 2015).

The velocity an athlete is able to sustain during a race or TT is a combination of $\dot{V}O_{2peak}$ and RE (McLaughlin et al., 2010). The link between $\dot{V}O_{2peak}$ and adenosine triphosphate (ATP) production means the percentage of $\dot{V}O_{2peak}$ (fractional utilisation) used to maintain race velocity is important (Bassett & Howley, 2000; Billat et al., 2004; Faude, Kindermann, & Meyer, 2009; Midgley, McNaughton, & Wilkinson, 2006). Fractional utilisation is the percentage of $\dot{V}O_{2peak}$ an athlete uses when running hard for an extended period. Fractional utilisation is positively correlated to average race velocity and is a determinant of running race or TT performance (Bassett & Howley, 2000; Billat et al., 2004). It has long been considered

that fractional utilisation and concentrations of blood lactate are closely linked; therefore, blood lactate tests are commonly used to identify fractional utilisation (Costill et al., 1973; Farrel, Wilmor, Coyl, Billin, & Costil, 1993). When running a marathon, recreational athletes are able to maintain aerobic exercise intensities equivalent to running at ~83 to 85% of $\dot{V}O_{2peak}$ (Gordon et al., 2017).

TT conducted on a treadmill completed ~1 week apart have demonstrated excellent reliability, with coefficients of variations ranging from 1 to 3% and intra-class correlation coefficients ranging from 0.80 to 0.99 (Driller et al., 2017; Stevens et al., 2015). Control of environmental conditions along with blinding of time and distance are important in providing an accurate comparison of results when conducting testing (Driller et al., 2017). Testing treadmill deck compliance also provides an indication of comparability to the harder surfaces involved in outdoor running (Colino et al., 2020; Gidley, Lankford, & Bailey, 2020). Running TT conducted in a laboratory has been shown to be closely related to running field-based TT (Laursen, Francis, Abbiss, Newton, & Nosaka, 2007); and thus, provide a valid proxy of running performance.

Footwear

In relation to running shoes, midsole compliance and resilience are complimentary attributes. Compliant foams are softer and compress more under a given external load. Resilience represents the capacity of a structure to return to its original shape. The resilience of a midsole reflects the proportion of the stored energy that is returned from the compliance of the midsole (Hoogkamer et al., 2018). In mechanical testing of three different running shoes, Hoogkamer et al. (2018) tested a highly compliant and resilient prototype Nike shoe (i.e., a VP4 prototype) against two other marathon racing shoes. The Nike prototype shoe returned up to 33% more stored energy than the other shoes. Hoogkamer et al. (2018) commented that the increased energy returned from the Nike prototype shoe was due to the significantly larger compliance, rather than the greater resilience, of the midsole than the other running shoes tested. The additional compliance and resilience of these Nike prototype shoes could lead to lesser muscular effort at a specific velocity (Hoogkamer et al., 2018).

There does appear to be a trade-off between the thickness of midsoles and surfaces, and potential enhancements in RE, where thicker soles and surfaces do not necessarily lead to further reductions in energy cost (Kerdok et al., 2002; Tung et al., 2014). However, overall, studies have shown that shoes with more compliant and resilient midsoles improve RE. In comparing more compliant to conventional running shoes, Frederick et al. (1986) found that all participants improved their RE in the more compliant shoes by $2.4 \pm 1.8\%$ running at their average (or estimated average) marathon pace. Similarly, Worobets et al. (2014) demonstrated that 9 out of 12 runners improved their RE running on a treadmill (mean change 1%, $p = 0.044$), and 10 out of 12 participants improved their RE on the road (mean change 1.2%, $p = 0.028$) wearing shoes with more compliant and resilient midsoles. Using a treadmill with gradually softer surfaces, Kerdok et al. (2002) showed a 29% increase in leg stiffness and 12% improvement in RE as the treadmill surface became more compliant.

Midsole longitudinal bending stiffness of running shoes can also affect the energy cost of running. Increasing the longitudinal bending stiffness of midsoles is postulated to reduce the energy dissipation at the metatarsophalangeal joint, thereby improving RE (Roy & Stefanyshyn, 2006). When longitudinal bending stiffness is increased in a running shoe, the application of force is more anterior than a conventional running shoe; the kinetics and kinematics of the metatarsophalangeal joint are altered; and there is less negative work at the metatarsophalangeal joint during the push-off phase (Willwacher, Koňig, Potthast, & Bruğgemann, 2013). During the terminal phase of push-off, the metatarsophalangeal joint produces a large amount of positive work (Willwacher et al., 2013). Roy and Stefanyshyn (2006) speculated that the improved RE with increased midsole longitudinal bending stiffness could be due to the greater dorsiflexion and angular velocity of the ankle plantar flexors leading to greater peak force generation. Roy and Stefanyshyn (2006) observed that a shoe with a bending stiffness of 38 N·mm compared to 18 N·mm (control) improved RE by 1%; however, increasing the stiffness to 45 N·mm showed no marked improvements in RE compared to the control shoe. Improvements in RE due to longitudinal bending stiffness likely depend on a number of factor, including running speed, body mass, location, thickness, and amount of bending stiffness (Flores, Delattre, et al., 2019; Flores, Rao, et al., 2019; Roy & Stefanyshyn, 2006)

Shoe mass is a key footwear characteristic that has been linked with RE and race performance. Lighter shoes can reduce oxygen consumption and energetic cost of running (Franz et al., 2012; Hoogkamer et al., 2016). For each 100 g of additional mass per shoe, the energetic cost of running increases by ~1% (Franz et al., 2012; Hoogkamer et al., 2016; Tung et al., 2014). In other words, runners wearing lighter shoes carry less distal mass, which reduces the energetic cost of running, improves RE, and can potentially enhance racing performance (Franz et al., 2012; Fuller, Thewlis, Tsiros, Brown, & Buckley, 2017; Hoogkamer et al., 2016). Hoogkamer et al. (2016) attached 100 g and 300 g lead pellets to each running shoe. Regression analysis indicated that each 100 g of added mass increased oxygen cost by 1.11% when running on a treadmill at 12.6 km·h^{-1}, and worsened 3-km TT performance by 0.78%.

Since running barefoot involves zero shoe-mass, barefoot running may seem ideal for reducing mass at the foot and improving running performance; however, this is not necessarily the case due to the effort the muscles of the lower limbs and feet exert to cushion the impact of each footfall (Frederick, Clarke, Larsen, & Cooper, 1983; Tung et al., 2014). Franz et al. (2012) suggested that a shoe weight of 129 g is the lightest mass where a running shoe would provide a metabolic advantage over running barefoot. To remove the influence of shoe mass on RE when running, Tung et al. (2014) attached 10-mm and 20-mm foam material similar to running shoe midsole cushioning to a treadmill. In support of other research, running barefoot on the 10-mm foam treadmill compared to running barefoot on a conventional treadmill surface required 1.63 ± 0.67% less metabolic energy, but no significant difference existed between the conventional treadmill surface and the 20-mm cushioned surface. These findings suggest that improvements in RE could be influenced by the thickness of running shoe midsole materials, wherein some cushioning is beneficial to RE, but that more cushioning is not necessarily better.

In 2015, a consensus definition and rating scale for minimal shoes, called the Minimalist Index, was established. The consensus definition reached was the following: "Footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel-to-toe drop, weight and stack height, and the absence of motion control and stability devices" (Esculier, Dubois, Dionne, Leblond, & Roy, 2015). Alongside the definition, a rating scale based on five shoe characteristics (weight, stack height, heel-to-toe drop, the presence/absence of motion control and stability technologies, and longitudinal and torsional flexibility) was devised and validated (Esculier et al., 2015). The Minimal Index is a continuum, rating shoes

between 0 to 100%, with 100% representing the highest degree of minimalism in shoes (Esculier et al., 2015). The Minimal Index score resulting from rating these five show characteristics (intra-class correlation coefficient = 0.84 to 0.99), and the weight, stack height, heel-to-toe drop, and flexibility subscales (Gwet's AC1 indices with quadratic weighting = 0.82 to 0.99) demonstrate high intra- and inter-rater reliability, and good inter-rater reliability for the presence/absence of technology subscale (Gwet's AC1 indices with quadratic weighting = 0.73) (Esculier et al., 2015). The Minimalist Index has subsequently been used to help researchers and clinicians interpret the effects of footwear on running biomechanics and running-related injuries (Cudejko, Gardiner, Akpan, & D'Août, 2020; Hannigan & Pollard, 2020; Ramsey, Lamb, & Ribeiro, 2020; Sinclair, Taylor, & Liles, 2020; Yang et al., 2019).

As mentioned, Nike Inc. developed the Nike Vaporfly Elite in an attempt to break the 2-hour marathon barrier (Nike, 2019). These prototype shoes were lighter than equivalent marathon racing shoes; had a midsole composed of compliant and resilient ZoomX foam made from polyether block amide (PEBA); a 31 mm heel height; a 10 mm heel-to-toe drop; and a carbon fibre panel embedded in the midsole (Barnes & Kilding, 2019; Hoogkamer et al., 2018). Compared to other popular brands of marathon shoes and track spikes, the commercially available equivalent of the Nike Vaporfly Elite (i.e., the VP4) was shown to improve RE and energetic cost on average by ~3 to 4% (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). To date, however, no research that compares VP4 to a runner's habitual shoes or minimalist racing shoes in recreational runners has been undertaken.

The considerable improvements in race results in athletes wearing VP4 have sparked debate in the running community regarding fairness and potential for technology doping of athletes (i.e., ergogenic aid via technology) using prototype and technology-enhanced shoes like the VP4 (Burns & Tam, 2020). World Athletics Rule 143 Clothing, Shoes and Athlete Bibs, subsection Shoes 5.2 states "They [footwear] must not give athletes any unfair assistance or advantage" (World Athletics, 2019). Substantiating the controversy, in the last few months of 2019, public race records collected from Strava mobile application show ~41% of marathons that were run under 3 hours were run by athletes wearing VP4, running 4 to 5% faster than a runner in another shoe (Quealy & Katz, 2019). Athletes were ~72 to 73% more likely to set a personal best when swapping from their usual racing shoes to VP4 based on this dataset (Quealy & Katz, 2019). In January 2020, World Athletics brought modifications to their rules regarding footwear. The

new rules included a maximum heel height, a limit on the number of embedded plates, and a clause that shoes needed to be available to the public for several months prior to athletes racing in them (World Athletics, 2020) in response to the growing controversy regarding the VP4 and its successors. The ruling ensured that the current version of the VP4 and Nike Next% were race legal.

Footstrike

As stated in the introduction section of this Chapter, running footstrike classifications generally use three categories: rearfoot (RFS), midfoot (MFS), and forefoot (FFS) strike. RFS is characterised by initial ground contact by the heel or rear third part of the foot, greater ankle dorsiflexion, and larger impact peaks than MFS or FFS (Breine, Malcolm, Frederick, & De Clercq, 2014; Larson et al., 2011). MFS is characterised by initial ground contact of the heel and metatarsals of the foot almost simultaneously (Breine et al., 2014; Larson et al., 2011). FFS is characterised by an initial ground contact made with the front half of the foot, with no heel contact, or heel contact shortly after the ball of the foot contacts the ground (Breine et al., 2014; Larson et al., 2011). The raised heel and cushioned heel and midsole of modern day running shoes promote RFS landings in shod runners (Lieberman et al., 2010; Perl et al., 2012).

Depending on the level, ethnicity, and speed of runners, research findings have indicated that 54 to 95% of runners are RFS, with MFS ranging from 3.5 to 44%, and FFS representing 0.2 to 6% (Cheung et al., 2017; de Almeida et al., 2015; Hanley et al., 2019; Larson et al., 2011; Patoz et al., 2019; Perl et al., 2012). Larson et al. (2011) observed no significant relationship between footstrike patterns and marathon race times in recreational and sub-elite runners. In contrast, Patoz et al. (2019) noted an increase in the number of MFS and RFS as race marathon times increased, while noting FFS runners were found throughout the race field, from the faster to the slower runners. Footstrike patterns change in relation to running speed and fatigue, with the proportion of RFS to MFS and FFS increasing as speed decreases and fatigue increases (Cheung et al., 2017; Larson et al., 2011). In general, the proportion of non-RFS is greater in elite athletes (Hanley et al., 2019), as well as when running barefoot or in lightweight, minimalist shoes (Cheung & Ngai, 2016; Lieberman et al., 2010).

When running, the moment the foot strikes the ground, ground reaction forces reach 1.5 to 3.0 times bodyweight (Lieberman et al., 2010). Most FFS and some MFS do not produce the same level of initial load as RFS. When running barefoot, RFS produce 7 times more average load than FFS, and about half the impact force when comparing barefoot FFS to shod RFS (Lieberman et al., 2010). The interaction between footstrike pattern and footwear may be a key reason why differences in loading rates between MFS and RFS are not clearly established, with some research showing 25% to 39% decreases in loading rates, and some research showing no change in loading rate based on footstrike pattern (Chan, Zhang, Ferber, Shum, & Cheung, 2020; Chen et al., 2016; Giandolini et al., 2013). When running in shoes, some research findings suggest no statistical difference in peak vertical ground reaction forces between MFS and RFS (Almeida, Davis, & Lopes, 2015).

Some runners will attempt to transition from shod to minimalist shoes in the belief that it will enhance performance (Cheung & Ngai, 2016). Running in minimalist shoes that are lighter promotes FFS (Cheung et al., 2017). The shift towards a FFS can result in a reduction in stride length and increased cadence, as well as an increased load on the Achilles tendon and activation of the gastrocnemius and soleus muscles (Almeida et al., 2015; Fuller, Thewlis, Tsiros, Brown, & Buckley, 2016; Yong et al., 2020). It has been postulated that the greater vertical leg compliance and reduced ground contact time of FFS lead to reduced vertical loading rates (Lieberman et al., 2010), with the load absorbed via the greater ankle plantarflexion and knee flexion at footstrike (Almeida et al., 2015; Lieberman et al., 2010).

MFS loads tend to be more variable due to the variability in the moment the foot strikes the ground (Daoud et al., 2012). Much like FFS, the load at initial ground contact for MFS depends on the compliance of the knee joint and ankle stiffness (Daoud et al., 2012). The alignment of the ankle and knee joints creates a "flatter foot" during the swing phase (De Wit, De Clercq, & Aerts, 2000). MFS reduces the amount of load at the heel at ground contact, spreading the load through the entire foot (De Wit et al., 2000; Giandolini et al., 2013). MFS results in lower stride length, reduced ground contact time, greater plantarflexion and activation of gastrocnemius and soleus muscles, and lesser activation of the tibialis anterior than RFS (De Wit et al., 2000; Giandolini et al., 2013).

The highly compliant, resilient, and stiff midsole of the VP4 has led to improved RE compared to other shoes (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Previous research appears to indicate that RFS runners potentially benefit more from wearing VP4 than MFS or FFS. Hoogkamer et al. (2018) proposed that due to an interaction between footstrike and VP4, RFS may improve their RE more than MFS or FFS. These greater benefits for RFS may be due to midsole properties at the heel region, leading to greater compression (and energy restitution) for RFS runners (Sun, Yang, Wang, Zhang, & Fu, 2018), although there is insufficient data at present to support these speculations.

Perception

Individuals differ greatly in terms of their tolerance, preference, and perception of exercise intensity (Ekkekakis, Thome, Petruzzello, & Hall, 2008). There is an inverse relationship between exercise intensity and adherence. As exercise intensity increases, there is a decrease in exercise enjoyment, especially at intensities above lactate or ventilatory thresholds (Ekkekakis et al., 2008; Perri et al., 2002). Similar to intensity, perception of running shoe comfort is very individual (Bishop, Buckley, Esterman, & Arnold, 2020) and an important factor athletes consider when purchasing shoes (Chan, Au, et al., 2020; Lindorfer, Kröll, & Schwameder, 2019). Research indicates that the most important shoe characteristics to runners are cushioning in the heel and forefoot, shoe stability, and forefoot flexibility (Bishop et al., 2020). To assess changes in perception, it is important to use a scale that is sensitive to any negative or positive change.

Borg (1982) proposed that the single best indicator of physical strain is perceived exertion. Perceived exertion is linked to the intensity of the afferent signal sent to the central nervous system from the working muscles, tendons, and ligaments, as well as the effort from the cardiovascular and respiratory systems (Borg, 1982). Sustainable levels of muscle glycogen and body temperature have also been linked to perceived exertion (Tucker, 2009). The Borg rating of perceived exertion (RPE) 6 – 20 scale is a rating scale used to measure fatigue in a number of sports that shows a strong correlation between exercise intensity and general fatigue (Grant et al., 1999). The Borg RPE scale is used alongside physiological markers to aid in exercise prescription and interpretation of individual effort. The perceived exertion rating on

the Borg RPE scale has been correlated to heart rate, $\dot{V}O_{2peak}$, and lactate threshold from a graded exercise test, such as during a $\dot{V}O_{2peak}$ test (Faulkner, Parfitt, & Eston, 2007).

Preferred exercise intensity is defined as "predisposition to select a particular level of exercise intensity when given the opportunity" (Ekkekakis et al., 2008). The exercise intensity that individuals can tolerate is defined as "a trait that influences one's ability to continue exercising at an imposed level of intensity beyond the point at which the activity becomes uncomfortable or unpleasant" (Ekkekakis et al., 2008). Exercise preference and tolerance are not the lone factors of intensity preference or tolerance. Some of the variables that influence the individual differences in the intensity preference or tolerance of exercise are: Age, health status, current fitness levels, psychological traits, life experience, cultural influences, situational appraisals, and experiential factors (Ekkekakis et al., 2008). To minimise the metabolic cost of running, adjusting the intensity to match the running distance impacts the chosen running intensity (McNeill, 2002). Lussiana and Gindre (2015) described a running pattern classification model wherein self-selected running styles and speeds were linked with feelings of pleasure or displeasure. Such findings suggest that individual perceptions might be linked with running sensations and performance.

Nigg, Baltich, Hoerzer, and Enders (2015) hypothesised that when purchasing a pair of shoes, runners apply their individual "comfort filter" based on their own perception of comfort. Enhanced perception of running shoe comfort can lead to reduced injury potential and improved RE (Luo, Stergiou, Worobets, Nigg, & Stefanyshyn, 2009). Shoe comfort is dependent on several variables, including past experiences, normal movement path of lower limbs, anthropometrics (alignment of bones in the foot), tactile sensitivity, and comfort of inserts such as orthotics (Lindorfer et al., 2019; Mündermann, Nigg, Stefanyshyn, & Humble, 2002; Nigg et al., 2015; Slade, Greenya, Kliethermes, & Senchina, 2014). Shoe mass may have less impact on perceived comfort. Slade et al. (2014) noted that a difference of ~140 g per shoe was needed before runners perceived shoe mass differences.

When an athlete is looking to purchase running shoes, there may be a bias towards perceptions of comfort and brand names (Hennig & Schulz, 2011). In an experimental study, individuals rated six running shoes in a blinded and un-blinded situation. Only the less well-known shoe was rated more positively under the blinded condition, demonstrating that brand knowledge

can influence how a shoe is perceived (Hennig & Schulz, 2011). Chan, Au, et al. (2020) found that despite having identical shoes, participants rated shoes as more comfortable when associated with a greater amount of marketing information and dearer price. Advertising may mislead individuals to believe that they are purchasing a superior brand of running shoes compared to other brands (Robbins & Waked, 1997). These factors would suggest that aspects other than shoe design and materials play a role in runners' perception of footwear comfort, and supports shoe blinding to eliminate bias when comparing running shoes of different brands.

Visual analogue scale (VAS) is a rating scale that is extensively used to evaluate a range of subjective feelings, correlates well with mood states, and is valid, reliable, and reproducible (Leung, Chan, Lee, & Lam, 2004; Lindorfer et al., 2019). Answers to VAS are easy to acquire and involve little instruction. Although several factors can affect the sensitivity and reliability of VAS; overall, these scales have been shown to provide valid and reliable results in relation to footwear perceptions (Lindorfer et al., 2019; Mündermann et al., 2002).

Conclusion

This literature review focused on RE, race and TT performance, footwear, footstrike, and perception. There is a positive correlation between $\dot{V}O_{2peak}$, RE, and 3km-TT measures; and a negative correlation between shoe mass and these measures. Running shoes with greater midsole compliance and resilience, reduced mass, and greater longitudinal bending stiffness have been shown to improve RE and running performance. The VP4 is lighter than equivalent marathon racing shoes; has a midsole composed of compliant and resilient foam; and has a carbon fibre plate embedded in the midsole. All these components are proposed to contribute a beneficial effect from VP4 in high-calibre runners (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019).

Previous research has shown VP4 improves RE by ~3 to 4% in high-calibre runners (sub 32:00 men and 35:30 women 10 km) running at absolute velocities compared to marathon shoes and track spikes. There is some evidence to suggest that RFS may benefit more from the VP4 than MFS/FFS (Hoogkamer et al., 2018). Given that up to 95% of recreational runners are RFS (de Almeida et al., 2015; Larson et al., 2011), it is reasonable to expect that a large proportion of recreational runners would respond favourably to wearing the VP4.

To date, no studies have investigated the energetic cost or TT performance of VP4 at relative speeds in male recreational runners wearing the commercially available VP4, or sought to compare these measures to lightweight racing flats or runners' habitual running shoes. In addition, since previous studies have not blinded participants to footwear, it is unsure whether any 'placebo effect' is contributing to the reported benefits of the VP4 (Hunter et al., 2019; Quealy & Katz, 2019). Hence, the aims of Chapter Two were to compare RE at relative running speeds and 3-km TT performances of male recreational runners wearing the commercially available VP4, compared to racing flats and runners' habitual running shoes.

Chapter Two – Experimental study

Effect of three different running shoes on running economy and 3-km time-trial performance in male recreational runners

Abstract

Objective: To compare running economy (RE) and 3-km time-trial (TT) variables of runners wearing Nike Vaporfly 4% (VP4), Saucony Endorphin lightweight racing flats (FLAT), and their habitual running (OWN) footwear. *Methods:* Eighteen male recreational runners (age: 33.5 ± 11.9 y, $\dot{V}O_{2peak}$: 55.8 ± 4.4 mL·kg^{-1}·min^{-1}) attended 4 sessions ~7 days apart. The first session consisted of a $\dot{V}O_{2peak}$ test to inform subsequent RE speeds set at 60, 70, and 80% of the speed eliciting $\dot{V}O_{2peak}$. In subsequent sessions, treadmill RE and 3-km TT were assessed in the three footwear in a randomised, counterbalanced crossover design. *Results:* Oxygen consumption (mL·kg^{-1}·min^{-1}) was lower in VP4 (3.6 to 4.5%, $P \leq 0.002$) and FLAT (2.4 to 4.0%, $P \leq 0.042$) versus OWN across intensities, with a non-significant difference between VP4 and FLAT (1.0 to 1.6%, $P \geq 0.325$). Findings relating to energy cost (W·kg^{-1}) were comparable. VP4 3-km TT (11:07.6 ± 0:56.6 mm:ss) was enhanced to OWN by 16.6-seconds (2.4%, $P = 0.005$) and FLAT by 13.0-seconds (1.8%, $P = 0.032$). Times between OWN and FLAT (0.5%, $P = 0.747$) were similar. Only five runners were more economical across intensities *and* faster in VP4. *Conclusions:* Overall, VP4 improved lab-based RE measures in male recreational runners at relative speeds compared to OWN, but improvements in VP4 were not significant versus FLAT. More runners exhibited better treadmill TT performances in VP4 (61%) versus FLAT (22%) and OWN (17%). The variability in individual oxygen consumption (-3.1 to 12.1%) and TT (-3.8 to 8.2%) shoe-responses suggests individual responses to footwear.

Keywords: footwear, individual responses, minimalist, physiology, running.

Introduction

Running economy (RE) defines the rate of oxygen consumption at a given submaximal running speed and is a key measure linked with distance running performance (Barnes & Kilding, 2015). Although maximal aerobic power ($\dot{V}O_{2peak}$) and $\dot{V}O_{2peak}$ fractional utilisation are also key factors in distance running performance (Foster & Lucia, 2007), runners with superior RE at a similar $\dot{V}O_{2peak}$ and lactate threshold generally outperform their peers (Foster & Lucia, 2007). Given the direct link between RE and running performance (Hoogkamer et al., 2016), acute changes in RE via footwear interventions has become an active area of research (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Kipp et al., 2019).

Until recently, shoe mass was one of few footwear characteristics consistently linked with improvements in RE and running performance (Franz et al., 2012; Fuller et al., 2015; Hoogkamer et al., 2016). The energetic cost of running has been shown to increase ~0.7 to 1.1% for each 100 g of added mass per shoe (Franz et al., 2012; Hoogkamer et al., 2016), explaining why most elite runners race in lightweight racing flats. However, the 2017 Breaking2 event introduced the Nike Vaporfly Elite shoes that were lighter than comparable marathon racing shoes; had a foam midsole constructed from Pebax (ZoomX) with considerable energy return characteristics; and an embedded carbon fibre plate to increase longitudinal bending stiffness (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Eliud Kipchoge subsequently ran a 2:01.39 World Record marathon in Berlin wearing Nike Vaporfly Next%, and was successful in running the marathon distance under two hours during the INEOS 1:59 Challenge in 2019 wearing unreleased Nike Alphafly prototype shoes. Although there are several factors involved in racing performance to consider, these achievements sparked debate in the running community regarding whether the use of novel technologically-advanced running shoes constitutes technology doping (Burns & Tam, 2020).

Research has reported RE improvements under laboratory conditions in high-calibre runners (sub-32:00 men and sub-35:30 women over 10 km) wearing Nike Vaporfly (VP4) shoes (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019), mechanistically driven by the elastic properties and energy return from midsole compression (Hoogkamer, Kipp, & Kram, 2019). Mobile application (Strava) data released by the New York Times corroborate

laboratory work, indicating that runners wearing VP4 or Next% run 4 to 5% faster in marathons and half-marathons and have a ~72 to 73% chance of setting a personal best compared to wearing their habitual running footwear (Quealy & Katz, 2019). While it is debatable whether such a comparison is fair given that most recreational runners wear relatively heavy running shoes, the analysis feeds into the fairness debate of the Vaporfly (Burns & Tam, 2020) effects at both the elite and recreational level. In addition, Hunter et al. (2019) noted that "a placebo effect cannot be ruled out". Since previous studies on the VP4 did not attempt to blind participants to footwear, it is unsure whether any 'placebo effect' contributed to the reported VP4 benefits (Hoogkamer et al., 2016; Hunter et al., 2019; Quealy & Katz, 2019).

It has also been suggested that recreational runners might reap greater percentage benefits than elite from wearing VP4 shoes, as modelling predicts greater percent improvements at running velocities slower than ~11 km·h^{-1} (Kipp et al., 2019), although laboratory-based data from recreational runners are not available. Depending on the level, ethnicity, and speed of runners, 54 to 95% of runners are RFS, 3.5 to 44% MFS, and FFS 0.2 to 6% (Cheung et al., 2017; de Almeida et al., 2015; Hanley et al., 2019; Larson et al., 2011; Patoz et al., 2019; Perl et al., 2012). The proportion of RFS is greater in non-elite athletes (Hanley et al., 2019). Previous research has also demonstrated that changes in laboratory-based RE variables translate to similar changes in distance running performances as assessed using a 3-km time-trial (Hoogkamer et al., 2016).

Our aims were to compare running economy variables at speeds relative to $\dot{V}O_{2peak}$ and 3-km time-trial performances of male recreational runners wearing the commercially available Nike Vaporfly 4%, Saucony Endorphin Racer 2 lightweight racing flats, and their own habitual running shoes. We hypothesised that wearing Nike Vaporfly 4% would result in improved running economy and running performance variables overall. We were also interested in exploring individual responses.

Materials and methods

Participants
Sample size calculations based on RE (Barnes & Kilding, 2019) and time-trial (TT) (Driller et al., 2017) data indicated that 18 runners were required to detect a moderate effect size between

conditions with β = 0.20 and α = 0.05. Accordingly, 18 male recreational runners (mean ± standard deviation age: 33.5 ± 11.9 y, height: 1.79 ± 5.4 m, mass: 76.5 ± 8.4 kg, body mass index: 23.4 ± 2.4 kg·m^{-2}, $\dot{V}O_{2peak}$: 55.8 ± 4.4 ml·kg^{-1}·min^{-1}, and recent 5-km time 21:18.61 ± 1:58.22) completed the experimental protocol. Participants typically ran 3 times a week and 24 km per week (interquartile range: 2 to 4 times and 14.5 to 40 km, respectively). Two researchers characterised participants' footstrike patterns (Hasegawa, Yamauchi, & Kraemer, 2007) as rearfoot ($n = 14$) or non-rearfoot (mid/forefoot, $n = 4$) from 2D video recordings (50 Hz) at 70% of the speed found to elicit $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$). Runners were recruited through personal contacts, running clubs, social media, and word-of-mouth. Inclusion criteria were male runners with a 5-km run time of ~20-25 minutes within the past 3 months. Runners with current or recent (< 3 months) injuries were excluded. All participants provided written informed consent, and were informed of the potential injury risks. The experiment was approved by our institution's Human Research Ethics Committee [HREC(Health)2018#81] and abided to the ethical standards of the Declaration of Helsinki (Appendix A).

Design and methodology

The effect of footwear on RE and TT treadmill performance was assessed using a randomised crossover study that required participants to attend four laboratory sessions (Figure 2). The first session collected baseline measures, established $\dot{V}O_{2peak}$, ensured proper shoe fit, and familiarised runners to the VP4 and Saucony Endorphin Racer 2 lightweight racing flats (FLAT) footwear. Given that knowledge of shoe brand can affect perceived shoe comfort (Hennig & Schulz, 2011) and can potentially affect performance measures (Hoogkamer et al., 2016; Hunter et al., 2019), we spray-painted the VP4 and FLAT shoes black to blind the participants to the brand and model details (Figure 2).

In the second, third, and fourth sessions, RE at 60, 70, and 80% of $v\dot{V}O_{2peak}$ and 3-km TT performance were assessed in each footwear condition in a randomised counterbalanced manner. Four to seven days (6.6 ± 0.9 days) separated each session with a maximum of 14 days separating the first from last RE and 3-km TT trials. Reliability of measures from RE (Saunders et al., 2004b) and TT (Driller et al., 2017) treadmill-based tests completed one-week apart has been shown elsewhere. Participants were tested at the same time of day and asked to replicate their nutrition, sleep, and training patterns prior to each session, which was confirmed using a

self-reported log. All tests were performed in a temperature-controlled laboratory (temperature: 18-20 °C, humidity: 55-60%).

The surface stiffness of the motorised treadmill (Steelflex PT10 Fitness, Steelflex Fitness, Taipei, Taiwan) used for data collection was quantified using similar methods to those described elsewhere (Hardin, van den Bogert, & Hamill, 2004; Kerdok et al., 2002). Weights (~25 kg each measured using a force plate) were sequentially positioned over the centre of the treadmill running area up to 300 kg. The displacement of the treadmill surface was tracked for each 25-kg increment twice using a 3D motion capture system and 6 retro-reflective markers positioned on the treadmill bed. The average readings generated from 75 to 225 kg (up to 3 x body mass of participants) was 365 $kN \cdot m^{-1}$. This stiffness value is similar to stiffness readings from an HP Cosmo (303 $kN \cdot m^{-1}$) (Smith, McKerrow, & Kohn, 2017) and reflective of the *hard* treadmill surface condition (350 $kN \cdot m^{-1}$) examined by Hardin et al. (2004).

VISIT 1
Baseline measures
$\dot{V}O_{2peak}$ (OWN)
Shoe familiarisation (NIKE ↔ FLAT)
Shoe VAS (immediate) comfort
Shoe VAS experience

4 – 7 days

VISIT 2 – VISIT 3 – VISIT 4
(NIKE ↔ FLAT ↔ OWN)
RE 3 min at 60, 70, and 80% $v\dot{V}O_{2peak}$
Shoe VAS (RE) comfort
3-km TT
Shoe VAS performance

4 – 7 days between visits

NIKE   NIKE

FLAT   FLAT
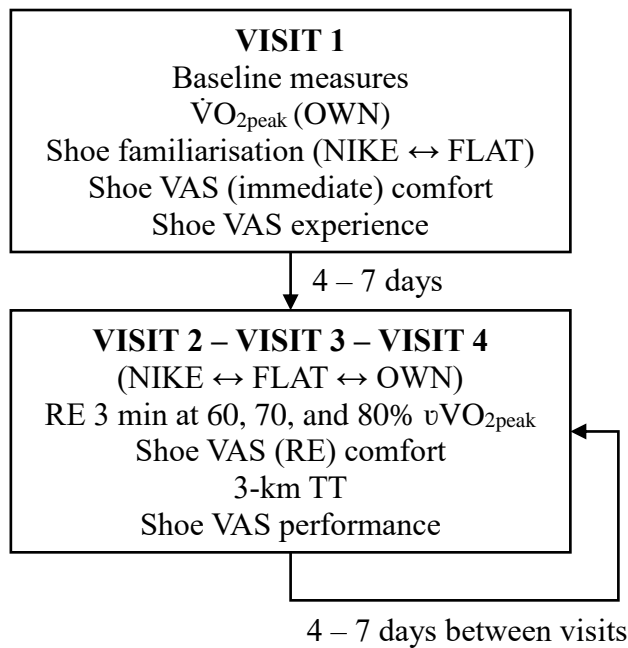
Figure 2 Experimental study design (top) and experimental footwear (bottom) pre and post being spray-painted black. ↔, randomised; FLAT, Saucony Endorphin Racer 2 racing flats; NIKE, Nike Vaporfly; OWN, habitual shoes; RE, running economy; TT, time-trial; VAS, visual analogue scale; $v\dot{V}O_{2peak}$, speed that elicited $\dot{V}O_{2peak}$.

Visit 1

Baseline information, anthropometric characteristics, and the mass, make, and model of participants' habitual running shoes (OWN) were recorded in Visit 1. OWN shoes were self-selected by each participant in the knowledge that they were being asked to perform a $\dot{V}O_{2peak}$, RE, and 3-km time-trial on a treadmill. Participants then trialled the two experimental footwear to ensure proper fit, jogging around the laboratory. Immediate shoe comfort and experience in VP4, FLAT, and OWN were recorded using a visual analogue scale (VAS) based on work by Lindorfer et al. (2019). The corresponding anchor points for these scales were '0 = Not comfortable at all – 10 = Maximal comfort' and '0 = No experience at all (beginner) – 10 = Extensive experience (expert)' (Appendix C). The minimalist index is a valid and reliable tool

used to determine the level of minimalism of shoes and assesses several footwear characteristics without the need for specialised equipment (Esculier et al., 2015). Together with footwear mass, heel height, and heel-to-toe drop, the minimal index permitted characterisation of participants' OWN shoes relative to the FLAT and VP4. Shoe-related characteristics are presented in Table 1.

Table 1 Shoe characteristics, comfort, and experience. Data are mean (standard deviation)

Characteristics	OWN	NIKE	FLAT
Mass (g)	313 (44) [N,F]	211 (12) [O,F]	153 (8) [O,N]
Stack height (mm)	26.0 (7.9) [F]	31.0 (0) [F]	13 (0) [O, N]
Heel-to-toe drop (mm)	9.4 (6.7) [F]	7.0 (0) [F]	1.0 (0) [O, N]
Minimalist index (%)	35 (16) [F]	48 (0) [F]	88 (0) [O, N]
VAS comfort (0 – 100)	79 (12) [F]	65 (30)	48 (28) [O]
VAS experience (0 – 100)	87 (13) [N,F]	29 (34) [O]	25 (28) [O]

Notes. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. VAS, visual analogue scale. Data from right shoes only (size: US 8.5 to 12). [F, N, O] Significant difference during post-hoc comparisons ($p < 0.05$) vs FLAT, NIKE, and OWN, respectively.

Participants subsequently completed a 4-minute warm-up at 10 km·h^{-1} running with their own shoes on a motorised treadmill (Steelflex PT10 Fitness, Steelflex Fitness, Taipei, Taiwan) prior to completing a $\dot{V}O_{2peak}$ ramp test using an incremental speed protocol and 1% incline to assess maximal aerobic power. The test started at 10 km·h^{-1} and increased 1 km·h^{-1} per minute until volitional exhaustion. The mean $v\dot{V}O_{2peak}$ was 18.4 ± 1.0 km·h^{-1}. After a 10-minute rest, participants ran 2 x 3-minutes at a self-selected speed on the treadmill once in VP4 and once in FLAT for shoe familiarisation.

Visits 2, 3, and 4
RE and 3-km TT performance in VP4, FLAT, and OWN were assessed in Visits 2, 3, and 4 using a 1% incline. Participants ran 2-minutes at a self-selected speed as warm-up in their allocated shoe condition and completed 3 x 3-minute bouts: 60% [11.0 ± 0.6 km·h^{-1}], 70% [12.9 ± 0.7 km·h^{-1}], and 80% [14.7 ± 0.8 km·hr^{-1}] of $v\dot{V}O_{2peak}$. Running durations between 3 to 15-minutes are typically used in RE tests (Barnes & Kilding, 2015), with 3-minute bouts shown to provide a valid running economy measures (Shaw, Ingham, & Folland, 2014). After each 3-minute bout, participants rested 1-minute during which time ratings of perceived exertion (RPE) using a 6-20 Borg scale and blood lactate concentration levels from capillary fingertip samples using a Lactate-Pro 2 analyser (Arkray Inc., Kyoto, Japan) were collected (Appendix B). Throughout the 3-minute bouts, heart rate (HR, Polar RS800CX, Kempele,

Finland) was recorded at 15-second intervals and expired gases were continuously measured using a calibrated metabolic cart (True One 2400, Parvo Medics, Salt Lake City, Utah, USA) to determine oxygen uptake ($\dot{V}O_2$) and respiratory exchange ratio (RER). Attainment of steady state for each participant was confirmed through manual graphical inspection of the $\dot{V}O_2$ output (Gidley et al., 2020). The highest 30-second mean $\dot{V}O_2$ registered in the last minute of each bout was used to determine oxygen consumption ($mL \cdot kg^{-1} \cdot min^{-1}$) and energy cost ($W \cdot kg^{-1}$) using the Péronnet and Masicotte equation (Péronnet & Massicotte, 1991). Following the last bout, participants rated their perceived shoe comfort on the comfort VAS and rested 5-minutes (Appendix D).

The starting speed for the blinded 3-km TT was set at 90% of $v\dot{V}O_{2peak}$ (16.4 ± 0.9 $km \cdot h^{-1}$). Participants were reminded to run the 3-km TT as fast as they could and provide a maximal effort. Given that the reproducibility of this test can be enhanced subsequent familiarisation (Driller et al., 2017), participants were familiarised with the starting speed, speed increases, and speed decreases used during the TT (± 0.5 $km \cdot h^{-1}$) for 1 minute before the TT. Participants rested 1 minute following familiarisation and then started the TT.

During the TT, runners were blinded to their elapsed time and speed. Participants verbally communicated 'up' or 'down' when they wanted 0.5 $km \cdot h^{-1}$ changes in speed. The researcher verbally communicated the covered distance to participants in 400-metre increments up to 2400-metres, and in 100-metre increments during the last 400-metres. The researcher provided no other verbal encouragement. At TT completion, RPE was collected and a perceived shoe performance VAS was obtained to examine whether participants perceived the shoes had aided their performance. The corresponding anchor points were '0 = No help in performance – 10 = Maximal help in performance' (Appendix D). At the end of all experimental sessions, participants were asked whether they knew what shoes they had been tested in. Only one runner correctly identified the VP4, with no runner identifying the make or model of the FLAT.

Statistical analysis

Descriptive statistics are reported as mean $\pm$ standard deviation unless stated otherwise. Data were analysed using repeated measures analyses of variance (RM ANOVA) and covariance (RM ANCOVA). Identity was the between-subject error term and footwear (VP4, FLAT, OWN) was the repeated-measure term in all analyses. Shoe mass and Visit (2, 3, 4) were added

in the analyses of the main RE (oxygen consumption and energy cost) and TT (time) variables as covariates to evaluate any potential effect of shoe mass or test order on outcomes. When not significant, covariates were removed. Tukey's honest significant difference was used in post-hoc pairwise comparisons to determine which shoe-by-shoe comparisons significantly differed. Statistical significance was set at $P \leq 0.05$ in all analyses.

To interpret practical meaningfulness, standardized effects were calculated using Cohen's d and the pooled between-subject standard deviations from the three footwear conditions. Cohen's d magnitudes were interpreted using thresholds of 0.2, 0.5, and 0.8 for *small*, *moderate*, and *large* (Cohen, 1988). Smallest worthwhile changes were set at 0.2 times the pooled between-subject standard deviation for each metric to provide an indirect estimation of the smallest worthwhile change in our particular cohort (Saunders et al., 2004b), with smaller effects considered *trivial*. The calculated smallest worthwhile change at 60%, 70%, and 80% of $v\dot{V}O_{2peak}$ was 1.9% across intensities for oxygen consumption; and 2.0, 1.9, and 1.9% for energy cost. This estimate was 1.7% for 3-km TT time. The effect was deemed unclear if Cohen's d 95% confidence interval [lower, upper] overlapped the thresholds for small positive and negative effects (i.e., $d \pm 0.2$). The data from one RE test in VP4 failed to save; hence, RE data from VP4 derive from $n = 17$.

Results

Running economy

Shoe mass ($P \geq 0.208$) and Visit ($P \geq 0.200$) had no significant effect on the main RE variables and were removed as covariates. Footwear significantly affected RE variables across intensities ($P < 0.002$, Figure 3). Oxygen consumption improvements of 4.4 [1.3, 7.5], 4.5 [2.2, 6.7], and 3.6 [1.4, 5.8]% in VP4 ($P \leq 0.002$) and of 4.0 [1.6, 6.4], 3.0 [0.9, 5.1], and 2.4 [0.8, 3.9]% in FLAT ($P \leq 0.042$) versus OWN were significant and of *small* magnitude (Table 2) at the intensities of 60, 70, and 80% of $v\dot{V}O_{2peak}$. The 1.0 [-1.3, 3.4], 1.6 [-1.0, 4.2], 1.5 [-0.9, 3.9]% oxygen consumption differences between VP4 and FLAT ($P \geq 0.325$) at these intensities were *trivial*. Similarly, energy cost was significantly improved by 4.5 [1.3, 7.8], 4.8 [2.4, 7.1], and 4.0 [1.7, 6.4]% in VP4 ($P \leq 0.001$) and by 4.3 [2.1, 6.6], 3.2 [1.3, 5.1], and 2.7 [1.2, 4.3]% in FLAT ($P \leq 0.042$) versus OWN at intensities of 60, 70, and 80% of $v\dot{V}O_{2peak}$. The 0.9 [-1.5,

3.2], 1.7 [-0.6, 4.1], 1.6 [-0.9, 4.1]% difference between VP4 and FLAT ($P \geq 0.208$) were not significant.

For individual runners, the change in oxygen consumption (energy cost) across all intensities ranged from -8.6 to 13.3% (-10.3 to 13.1%) in VP4 versus OWN; -9.6 to 9.7% (-9.7 to 9.2%) in VP4 versus FLAT; and -5.5 to 14.2% (-4.6 to 14.6%) in FLAT versus OWN, where a positive percent change indicates improved RE. Of the seventeen runners with complete dataset; eight (47%) were most economical in VP4, two (12%) in FLAT, and seven (41%) demonstrated inconsistency across intensities. One of the four non-rearfoot strikers (25%) was most economical in VP4, and the other three (75%) in different footwear across intensities.

Other statistically significant findings from the RE tests (Table 2 and Table 3) were lower lactate levels in VP4 at 70% $\upsilon\dot{V}O_{2peak}$, and VP4 and FLAT at 80% $\upsilon\dot{V}O_{2peak}$ versus OWN of *moderate* and *small* magnitudes; and lower RPE in VP4 versus OWN and FLAT at 80% $\upsilon\dot{V}O_{2peak}$ of *moderate* magnitudes. Runners perceived their OWN footwear as more comfortable than VP4 and FLAT during the RE test.
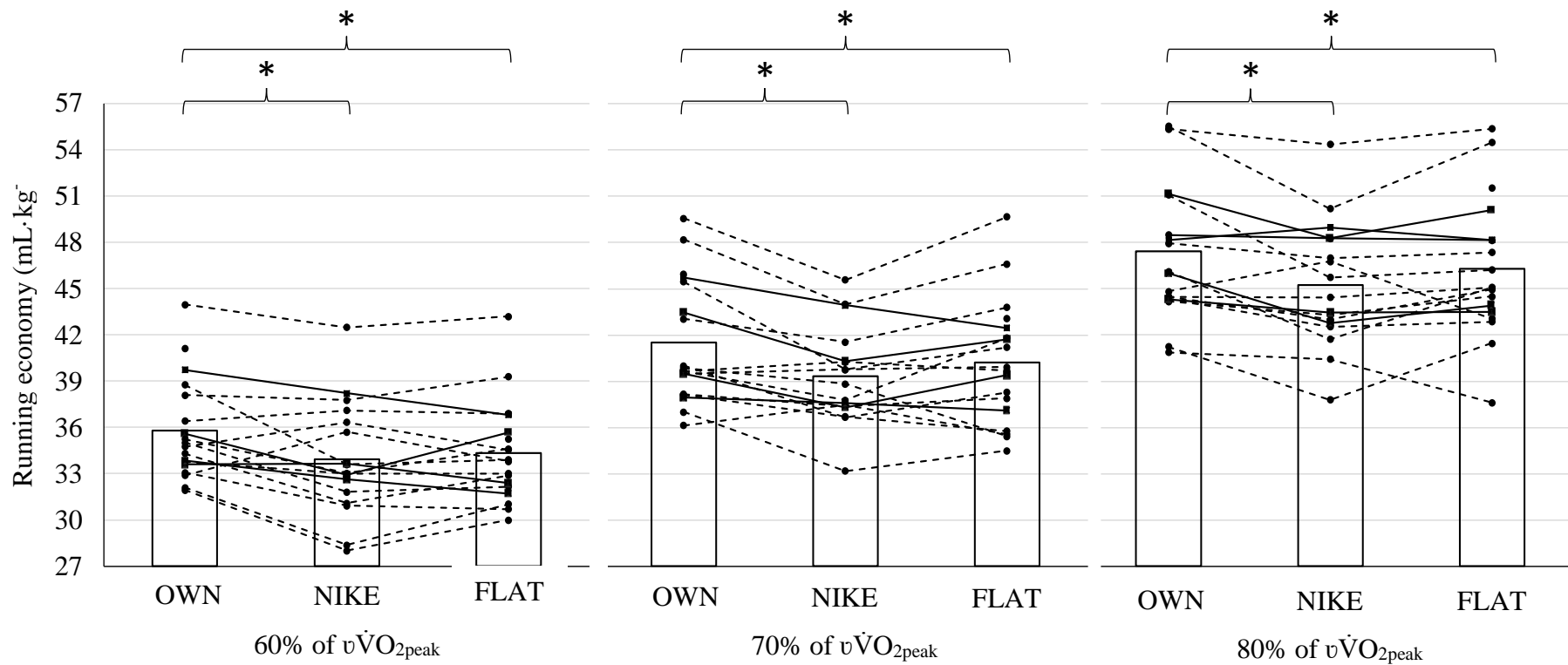
Figure 3 Running economy ($mL \cdot kg^{-1} \cdot min^{-1}$) at 60%, 70%, and 80% of the speed that elicited $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$). Bar graphs represent mean values, circles joined by dashed lines represent rearfoot runners, and squares joined by black lines represent non-rearfoot runners. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. *$p \leq 0.05$ during post-hoc comparisons when main effect of footwear significant. NB: For NIKE condition, $n = 17$

Table 2 Comparison of all physiological, perceptual, and performance variables from the running economy test (mean [95% CI] and Cohen's d effect size [95% CI]) between footwear conditions from 18 male runners[†].

Variable	Intensity	OWN – NIKE Cohen's d	FLAT – NIKE Cohen's d	OWN – FLAT Cohen's d
Running economy (mL·kg^{-1}·min^{-1})	60%	1.6 [0.5, 2.6] * 0.43 [0.13, 0.73], *Small*	0.4 [-0.4, 1.1] 0.10 [-0.12, 0.31], *Trivial*	1.5 [0.5, 2.4] * 0.41 [0.15, 0.66], *Small*
	70%	1.9 [1.0, 2.9] * 0.49 [0.24, 0.74], *Small*	0.8 [-0.3, 1.8] 0.19 [-0.08, 0.46], *Trivial*	1.3 [0.4, 2.2] * 0.32 [0.10, 0.55], *Small*
	80%	1.7 [0.7, 2.8]* 0.38 [0.14, 0.61], *Small*	0.8 [-0.3, 1.8] 0.16 [-0.07, 0.39], *Trivial*	1.1 [0.4, 1.9]* 0.25 [0.08, 0.52], *Small*
Lactate (mmol·L)	60%	-0.1 [-0.6, 0.5] -0.10 [-0.78, 0.57], *Unclear*	-0.3 [-0.7, 0.1] -0.38 [-0.91, 0.16], *Small*	0.2 [-0.2, 0.7] 0.27 [-0.28, 0.83], *Unclear*
	70%	0.4 [0.1, 0.7] * 0.58 [0.15, 1.01], *Moderate*	0.2 [-0.1, 0.4] 0.25 [-0.14, 0.65], *Small*	0.2 [-0.1, 0.5] 0.33 [-0.17, 0.82], *Small*
	80%	0.7 [0.3, 1.2] * 0.62 [0.22, 1.02], *Moderate*	0.2 [-0.2, 0.6] 0.16 [-0.15, 0.47], *Trivial*	0.6 [-0.1, 1.2] * 0.46 [-0.05, 0.98], *Small*
Heart rate (bpm)	60%	3.8 [-3.3, 10.9] 0.26 [-0.23, 0.75], *Unclear*	4.6 [-2.2, 11.5] 0.32 [-0.15, 0.79], *Small*	0.5 [-6.0, 7.0] 0.03 [-0.41, 0.48], *Unclear*
	70%	4.7 [-0.9, 10.3] 0.34 [-0.06, 0.75], *Small*	2.0 [-2.2, 6.2] 0.14 [-0.16, 0.45], *Trivial*	3.3 [-0.4, 7.0] 0.24 [-0.03, 0.51], *Small*
	80%	1.1 [-2.5, 4.7] 0.08 [-0.18, 0.33], *Trivial*	-0.1 [-2.5, 2.4] -0.01 [-0.18, 0.17], *Trivial*	2.2 [-1.9, 6.2] 0.15 [-0.13, 0.44], *Trivial*
RPE (6 – 20)	60%	0.5 [-0.2, 1.2] 0.32 [-0.11, 0.74], *Small*	0.3 [-0.4, 1.0] 0.18 [-0.27, 0.62], *Unclear*	0.2 [-0.3, 0.7] 0.14 [-0.19, 0.47], *Trivial*
	70%	0.6 [0.04, 1.2] 0.47 [0.03, 0.91], *Small*	0.3 [-0.2, 0.8] 0.26 [-0.14, 0.65], *Small*	0.3 [-0.2, 0.8] 0.21 [-0.15, 0.58], *Small*
	80%	0.8 [0.3, 1.2] * 0.55 [0.22, 0.89], *Moderate*	1.0 [0.4, 1.6] * 0.71 [0.29, 1.13], Moderate	-0.2 [-0.8, 0.4] -0.16 [-0.59, 0.27], *Unclear*
VAS comfort (0 – 100)	NA	15.0 [5.9, 24.2] * 0.75 [0.29, 1.22], *Moderate*	-6.2 [-20.5, 8.2] -0.31 [-1.03, 0.41], *Unclear*	21.2 [12.3, 30.1] * 1.06 [0.62, 1.51], *Large*

Notes. [†] For NIKE condition, *n* = 17. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. bpm, beats per minute; CI, confidence interval, NA, not applicable; RPE, rating of perceived exertion. VAS, visual analogue scale. *$p \leq 0.05$ during post-hoc comparisons when main effect of footwear significant. Cohen's d interpreted using thresholds of 0.2, 0.5, and 0.8 for *small*, *moderate*, and *large*, and *trivial* < 0.2.(Cohen, 1988) Effect deemed unclear if its 95% CI overlapped the thresholds for small positive (+0.2) and negative (-0.2) effects.

Table 3 Running economy variables [mean (SD)] from 18 male runners[†].

Variable	Intensity	OWN	NIKE	FLAT	RM ANOVA Footwear (p-value)
Lactate (mmol·L)	60%	2.1 (0.9)	2.2 (0.7)	1.9 (0.6)	0.392
	70%	2.3 (0.8) [N]	2.0 (0.5) [O]	2.1 (0.6)	0.031
	80%	3.7 (1.3) [N, F]	2.9 (0.8) [O]	3.1 (1.2) [O]	0.006
Heart rate (bpm)	60%	132.5 (13.3)	129.4 (14.1)	132.4 (13.8)	0.356
	70%	150.0 (12.4)	145.6 (13.7)	147.1 (12.9)	0.080
	80%	163.8 (12.0)	161.7 (13.9)	161.4 (13.6)	0.312
RPE (6 – 20)	60%	10.3 (1.2)	9.8 (1.6)	10.1 (1.6)	0.264
	70%	12.3 (1.1)	11.7 (1.2)	12.1 (1.4)	0.059
	80%	14.2 (1.0) [N]	13.4 (1.3) [O, F]	14.4 (1.6) [N]	0.002
VAS comfort (0 – 100)	NA	75 (15) [N, F]	60 (22) [O]	54 (20) [O]	< 0.001

Notes. [†] For NIKE condition, $n = 17$. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. bpm, beats per minute; RM ANOVA, repeated measures analysis of variance; RPE, rating of perceived exertion. VAS, visual analogue scale. [F, N, O] Significant difference ($p \leq 0.05$) vs FLAT, NIKE, and OWN during post-hoc comparisons when main effect of footwear significant, respectively.

Time-trial

Shoe mass had no significant effect on any of the TT variables ($P \geq 0.190$) and was removed as a covariate. Footwear significantly affected TT performance ($P = 0.005$, Figure 4). Runners ran their 3-km TT with an average speed of 16.3 ± 1.3 km·h^{-1} wearing VP4, 16.0 ± 1.3 km·h^{-1} wearing FLAT, and 15.9 ± 1.3 km·h^{-1} wearing OWN. The superior TT performance in VP4 of 2.4 [0.6, 4.1]% versus OWN ($P = 0.005$) and of 1.8 [0.3, 3.4]% versus FLAT ($P = 0.032$) were significant and of *small* magnitudes (Table 4). Performances were similar between OWN and FLAT (0.5 [-0.3, 1.4]%, $P = 0.747$).

For individual runners, changes in TT performance in VP4 versus OWN ranged from -3.8 to 8.2%, and from -4.7 to 9.3% versus FLAT. Of the eighteen runners, eleven (61%) produced their fastest performance in VP4, four (22%) in FLAT, and three (17%) in OWN. Two of the four non-rearfoot strikers (50%) performed their best TT in FLAT, with one in VP4 (25%) and one in OWN (25%). There was no significant difference in RPE measures between footwear, and no perceived difference regarding the effect of shoe on performance (Table 5).

Of the seventeen runners that presented with complete RE and TT data, five (29%) exhibited their best RE measures across intensities *and* TT performance in VP4. The remaining twelve (71%) performed their best RE across intensities and TT performances in different shoes, including the four non-rearfoot strikers.

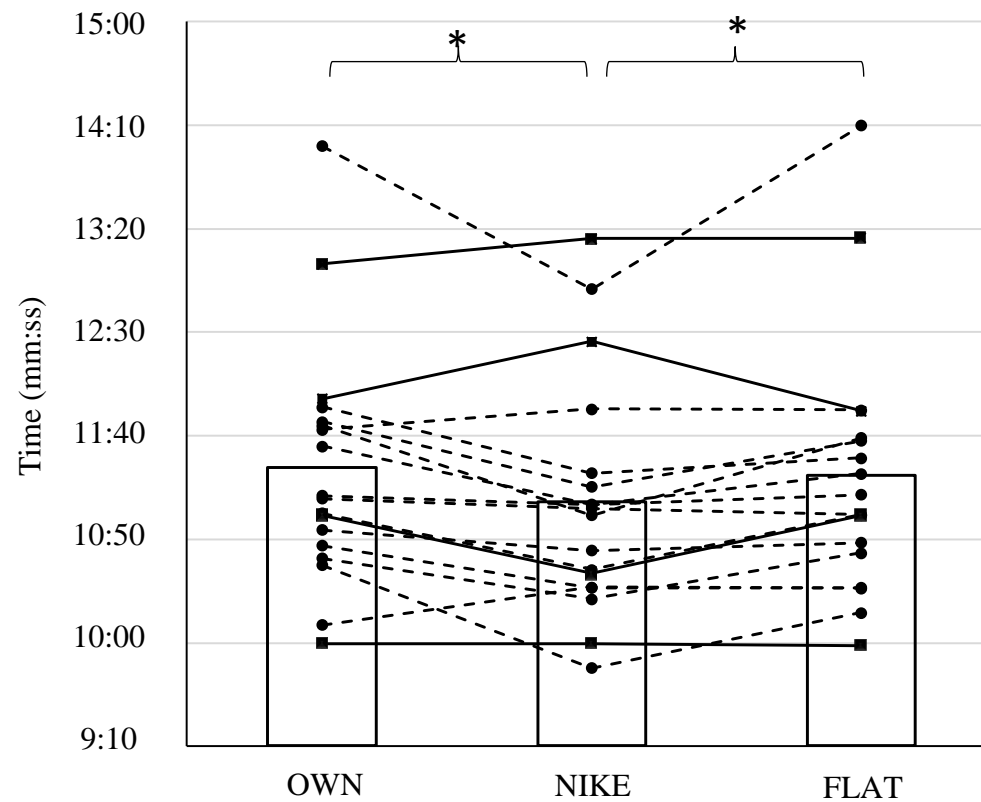**Figure 4** 3-km time-trial time (mm:ss). Bar graphs represent mean values, circles joined by dashed lines represent rearfoot runners, and squares joined by black lines represent non-rearfoot runners. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. * Significant difference ($p \leq 0.05$) during post-hoc comparisons when main effect of footwear significant.

Table 4 Comparison of all physiological, perceptual, and performance variables from the 3-km time-trial (mean (SD) and Cohen's d effect size) [†].

Variable	OWN – NIKE Cohen's d	FLAT – NIKE Cohen's d	OWN – FLAT Cohen's d
Time (s)	16.6 [4.2, 29.1]* 0.27 [0.07, 0.47], *Small*	13.0 [1.5, 24.6]* 0.21 [0.02, 0.40], *Small*	3.6 [-2.3, 9.5] 0.06 [-0.04, 0.15], *Trivial*
RPE (6 – 20)	0.5 [-0.1, 1.1] 0.36 [-0.05, 0.77], *Small*	-0.1 [-0.6, 0.5] -0.04 [-.46, 0.38], *Unclear*	0.6 [0.01, 1.1] 0.40 [0.01, 0.79], *Small*
VAS performance (0 – 100)	3.8 [-9.2, 16.8] 0.16 [-0.40, 0.72], *Unclear*	-6.9 [-26.0, 12.1] -0.30 [-1.12, 0.52], *Unclear*	10.7 [-3.3, 24.8] 0.46 [-0.14, 1.07], *Small*

Notes. [†] For NIKE condition, $n = 17$. FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. CI, confidence interval, RPE, rating of perceived exertion. VAS, visual analogue scale. *$p \leq 0.05$ during post-hoc comparisons when main effect of footwear significant. Cohen's d interpreted using thresholds of 0.2, 0.5, and 0.8 for *small*, *moderate*, and *large*, and *trivial* < 0.2.(Cohen, 1988) Effect deemed unclear if its 95% CI overlapped the thresholds for small positive (+0.2) and negative (-0.2) effects [95% CI]) between footwear conditions from 18 male runners[†]

Table 5 3-km time-trial variables [mean (SD)] from 18 male runners [†].

Variable	OWN	NIKE	FLAT	RM ANOVA Footwear (p-value)
RPE (6 – 20)	18.8 (0.9)	18.3 (1.5)	18.3 (1.5)	0.088
VAS performance (0 – 100)	62 (18)	58 (26)	51 (22)	0.345

Notes. [†] FLAT, Saucony Endorphin Racer 2 road racing flat. NIKE, Nike Vaporfly 4%. OWN, runners own habitual running shoes. RM ANOVA, repeated measures analysis of variance; VAS, visual analogue scale. [N, F, O] Significant difference ($p < 0.05$) vs NIKE, FLAT, and OWN when main effect of footwear significant, respectively.

Discussion

Our study adds to the body of knowledge on the VP4 from an independent laboratory, and is the first to observe that VP4 can benefit laboratory-based RE measures in recreational runners compared to their habitual footwear and at relative rather than absolute speeds. Despite individual variability, VP4 benefited oxygen consumption in recreational runners compared to OWN on average by 4.2%, which was clearly superior to the established smallest worthwhile change of 1.9%. In contrast, the average 1.4% difference in RE between VP4 and FLAT was not significant. VP4 enhanced 3-km TT performance compared to the other two footwear. The 2.4% and 1.8% TT improvement in VP4 versus OWN and FLAT were also greater than the established worthwhile change of 1.7%. Eleven (61%) of runners ran their fastest TT in VP4, and five (29%) ran more economically *and* faster in VP4. Responses to footwear did not appear driven by runners' perceptions based on VAS ratings.

Our RE findings align with previous laboratory-based studies conducted in high-calibre runners insofar that RE variables improved in VP4 at a group level (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Hunter et al. (2019) reported 2.8% oxygen consumption improvements in high-calibre runners wearing VP4 at 16 km·h^{-1} compared to the Adidas Adios Boost. Hoogkamer et al. (2018) and Barnes and Kilding (2019) reported ~3 to 4% improvements in oxygen consumption and energy costs in VP4 at absolute speeds ranging from 14 to 18 km·h^{-1} after equalising shoe mass. The variation in RE gains from VP4 between studies likely relate to running speed differences (Kipp et al., 2019); type of runners and footwear examined (Quealy & Katz, 2019); variations in treadmill properties (Hardin et al., 2004); and individual responses to footwear and cushioning (Colino et al., 2020; Hardin et al., 2004). The placebo effect has also been cited as a potential reason for changes in performance with footwear (Hoogkamer et al., 2016; Hunter et al., 2019). At the completion of our experimental trials, only one runner correctly identified the VP4, confirming that the potential for placebo or expectation was minimised. Our perceptual analyses relating to shoe experience, shoe comfort, and TT performance enhancement suggest no clear relationship between physiological or actual performance, with participants being most comfortable wearing their own running shoes.

VP4 has been shown to return 87% of the mechanical energy stored (7.46 J energy return per step) (Hoogkamer et al., 2018) when tested under conditions similar to running at 18 km·h^{-1}. Although the amount of energy returned is relatively small compared to that from musculoskeletal structures (Fletcher & MacIntosh, 2015; Ker, Bennett, Bibby, Kester, & Alexander, 1987), it is sufficient to decrease the energetic cost of running. Our data demonstrated that, at 70 and 80% of $v\dot{V}O_{2peak}$, lactate concentration levels were lower in VP4 than OWN. A rightward shift in the lactate-velocity curve is indicative of a decreased metabolic disruption at a given speed (Gladden, 2011), thus enhancing endurance performance (McArdle et al., 2015). Lactate concentrations were also lower in FLAT than OWN at the greatest intensity.

For every 100 g of added shoe mass, the energy cost of running increases ~0.7 to 1.0% (Franz et al., 2012; Hoogkamer et al., 2016). In our study, the mean mass of VP4 was 209 g, FLAT was 156 g, and OWN was 313 g. Considering these shoe mass values and the average change in energy cost we observed, these values suggest an ~2.2% increase in energy cost for each 100 g of added mass per shoe when comparing FLAT to OWN, and ~4.3% increase comparing VP4 to OWN. Thus, the mass–energy relationship does not fully explain the overall RE advantages observed in the current study, and highlights the positive effects of the VP4 construction on the metabolic cost of running; further evidenced by the observation of a non-significant effect of shoe mass in our analyses.

Frederick et al. (1983) were among the first researchers to address the 'cost of cushioning' after noting no difference in RE measures between barefoot and well-cushioned shoes. Subsequent research confirmed that 10 mm cushioning reduces metabolic cost, but that the detrimental effects of shoe mass on energy expenditure counteract any benefits of cushioning when comparing barefoot to shod treadmill running (Tung et al., 2014). When matched for mass and controlling for other footwear features, shoes with a more compliant (i.e., more cushioned) and resilient (i.e., less energy loss) midsole can reduce oxygen cost by ~1% (Worobets et al., 2014). Similarly, inserting carbon fibre plates to midsoles to increase the longitudinal bending stiffness of footwear has also been shown to improve RE ~1%, (Roy & Stefanyshyn, 2006) although the location of the plate (Flores, Rao, et al., 2019), running speed (Flores, Delattre, et al., 2019), and induced changes in running biomechanics (Cigoja et al., 2019; Flores, Rao, et al., 2019) can influence this relationship. The 'cost of cushioning' concept and energy return

from the VP4 midsole – alongside the lighter shoe mass and stiffer midsole – likely underpin the 3.6 to 4.5% improvement in oxygen consumption compared to OWN across running intensities.

Runners in this study also performed better during the 3-km TT in VP4 by 16.6 and 13.0-seconds compared to OWN and FLAT. These laboratory-based observations support the New York Times reported marathon and half-marathon race improvements from Strava mobile application data (Quealy & Katz, 2019). Hoogkamer et al. (2016) found that 3-km TT performance degraded in a predictable fashion based on shoe mass, whereby adding 100 g per shoe negatively affected performance by 0.78%. Accordingly, TT performance should have been 1.2% and 0.8% better in FLAT and VP4 compared to OWN based on shoe mass alone, rather than the 0.5% and 2.4% differences observed. The lack of agreement between studies may reflect the different calibre of runners (Hoogkamer et al., 2016) (10:26.1 ± 0:55.6 mm:ss in control footwear; our runners 11:24.3 ± 0:58.4 mm:ss in OWN footwear), technological benefits of VP4 (Hoogkamer et al., 2018), differences in footstrike patterns of cohorts, and more substantial difference between our runners' OWN and FLAT footwear compared to VP4 (Table 1). By design, our study did not seek to equalise shoe mass by adding lead pellets to footwear (Barnes & Kilding, 2019; Hoogkamer et al., 2018) to maintain the ecological validity of findings and reflect how runners would wear running shoes in real-life.

VP4 significantly improved 3-km TT performance compared to FLAT, whereas RE measures were similar between these footwear. Typically, improvements in RE lead to improved TT performances in a predictable manner (Hoogkamer et al., 2016). It is possible that the greater difference in shoe characteristics (Table 1) between FLAT and OWN compared to VP4 and OWN was more challenging for runners to adapt to at a sustained maximal effort. It is also possible that 3-km TT performance would have improved in FLAT versus OWN had a period of habituation or training in FLAT been provided; however, a similar beneficial effect of habituation to the VP4 shoes could be speculated.

Although our findings overall indicate that VP4 can benefit RE and long-distance racing performance in male recreational runners, the non-rearfoot strikers in our study appeared to respond less favourably to VP4, as also observed Hoogkamer et al. (2019). Based on our 3-km TT results, 21 runners per group would be needed to detect a significant difference in response

to footwear between non-rearfoot and rearfoot strikers with 80% power. The potential for greater benefits of VP4 in rearfoot strikers might be due to the greater compression of the midsole at the heel region (Sun et al., 2018). Research specifically examining responses to VP4 footwear based on footstrike pattern is warranted to elucidate the interaction between footstrike characteristics and performance enhancing effects of footwear.

Although reliable with a typical error of measurement of 1.0% following familiarisation (Driller et al., 2017), conducting a treadmill TT has limitations. The TT difference between VP4 and OWN equates to approximately one speed increment difference for the duration of the trial, with non-treadmill TT performances potentially more ecologically valid. We only recruited male runners because of shoe cost considerations; however, we speculate that recreational female runners would respond similarly given the findings of similar VP4 responses from elite (Barnes & Kilding, 2019) and Strava (Quealy & Katz, 2019) cohorts. Even though the spray-painting of the shoes minimised the potential for a placebo effect, this method could not completely blind runners to the footwear worn. Furthermore, running in VP4 compared to other footwear has been shown to influence biomechanics (Barnes & Kilding, 2019; Hoogkamer et al., 2019; Hunter et al., 2019), with typical findings of increased stride length, longer flight times, and decreased peak plantar-flexion velocities in VP4. The RE speeds in this study were slower than those examined previously and in different footwear; hence, investigating the biomechanical adaptation to VP4 could shed light on mechanisms that contribute to improved performance in recreational runners. Finally, individuals vary their responses to surface cushioning (Hardin et al., 2004). Treadmill construction and compliance levels can affect metabolic and biomechanical responses (Gidley et al., 2020), and may not reflect outdoor running on surfaces that are less compliant. It may be that the combined VP4 shoe cushioning and treadmill damping effect attenuated favourable responses to VP4.

Conclusion

Our study provides evidence that VP4 can benefit RE and 3-km TT performance and could potentially represent a viable ergogenic aid in recreational runners; but individual responses were considerable. Only 47% of runners were more economical across intensities in VP4, 61% faster in VP4 in a 3-km TT, and 29% more economical *and* faster in VP4. Certain runners were more economical or performed better in FLAT, whereas no runner was the most economical in

OWN across intensities. One must consider the risks associated with changing biomechanical patterns in uninjured runners (Anderson, Bonanno, Hart, & Barton, 2019) and transitioning to novel footwear too quickly (Ridge et al., 2013). The generalisation of our results from a *hard* treadmill surface to outdoor environments requires further investigation. Overall, we provide evidence that VP4 can meaningfully improve RE and enhance running performance in male recreational runners using laboratory-based data, particularly when compared to runners' habitual running shoes. Lightweight racing flats were also effective in improving RE and enhancing TT performance in some – albeit fewer – runners.

Chapter Three – Final chapter

Summary

Laboratory-based experiments have confirmed RE improvements in high-calibre runners wearing VP4 (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019). Using public race reports and big data from Strava, improvements in half-marathon and marathon times have been reported in runners wearing the commercially available VP4 and Next% footwear in both faster and slower runners (Quealy & Katz, 2019). Analyses indicate that runners wearing these shoes run 4 to 5% faster and are ~72 – 73% more likely to set a personal best compared to wearing other popular racing shoes (Quealy & Katz, 2019). To date, there has been no laboratory-based data on the effect of VP4 on RE and TT performance in recreational runners. In addition, since previous studies have not blinded participants to footwear, it was unsure whether any 'placebo effect' was contributing to the reported benefits of VP4, or whether the improvements stemmed solely from the technological features and lightweight characteristics of the footwear.

Given the non-linear relationship between oxygen uptake and running velocity, for a given percent improvement in RE, a slightly greater percent improvement at running velocities slower than ~11 km·h^{-1} had been predicted (Kipp et al., 2019). Accordingly, it was postulated that recreational runners might reap greater benefits than elite from wearing VP4. Hence, our aims were to compare RE at relative running speeds of 60, 70, and 80% of the speed eliciting $\dot{V}O_{2peak}$ and TT performances of male recreational runners wearing different footwear in a blind, randomised, counterbalanced crossover design.

Our study findings provide evidence that the commercially available VP4 can improve RE and TT in most male recreational runners using laboratory-based data particularly when compared to OWN. FLAT were also effective in improving RE and enhancing TT performance in some runners, albeit fewer. No runner recorded their best RE in their OWN footwear across intensities. There was considerable variability between runners and intensities, with 47% of runners demonstrating enhanced RE across all intensities, 61% improved TT performance, and 29% improved in both RE and TT when wearing VP4 compared to OWN and FLAT. These figures do not support a generalised benefit of VP4 in male recreational runners seeking to improve performance; and rather, are suggestive of individual responses to VP4.

Limitations

A limitation of the experimental study of this Thesis is that only male runners were tested, notably because of shoe cost considerations and sample homogeneity. However, recreational female runners would likely respond similarly given the findings of similar responses to VP4 footwear between sexes in highly-trained (Barnes & Kilding, 2019) and Strava (Quealy & Katz, 2019) cohorts of runners. The recreational nature of the participants testing means that results may not be transferable to elite or sub-elite runners, and groups with lower activity levels. Recreational runners were selected because this cohort is the most representative of the individuals likely to purchase VP4.

Treadmill construction and compliance can affect running-related variables (Gidley et al., 2020), with treadmill running not necessarily reproducing effects that would be observed running outdoors. It may be that the combined VP4 shoe cushioning and treadmill damping effects resulted in less favourable responses to VP4 in the examined cohort of male recreational runners. The surface stiffness of the motorised treadmill used for testing was quantified. This stiffness value is reflective of the hard treadmill surface condition (350 kN·m^{-1}) examined by Hardin et al. (2004); and presumed comparable to existing scientific literature on footwear and RE.

The size, shape, weight, and feel of the experimental shoe conditions meant that participants were not completely blinded to footwear conditions. The majority of participants had not previously run in FLAT footwear. Given the greater difference between OWN and FLAT versus OWN and VP4, it may be that 3-km TT performance was negatively affected due to discomfort, unfamiliarity to sensations, and greater alterations in biomechanics to FLAT footwear (Barnes & Kilding, 2019; Hardin et al., 2004; Hoogkamer et al., 2019; Hunter et al., 2019). Conducted TT on treadmills, albeit reliable, had limitations. The TT difference between VP4 and OWN equates to approximately one speed increment difference for the duration of the trial, with non-treadmill TT performances more ecologically valid in terms of simulating racing conditions. To minimise these limitations, the experimental study used a blinded, randomised, counterbalanced crossover design and confirmed a non-significant effect of time (i.e., visit number) on the key outcome parameters.

Strengths

Lead pellets were not added to equalize shoe mass as done elsewhere (Barnes & Kilding, 2019; Hoogkamer et al., 2018) to maintain the integrity of the shoe and reflect how runners would wear shoes in real-life. This approach maintains ecological validity to the study findings.

There is a *U*-shaped curvilinear association between speed and RE (Black et al., 2018). This relationship indicates that fitter runners have enhanced RE in comparison to less fit runners (Morgan et al., 1995; Pollock, 1977). For this reason, the effect of footwear at speeds relative to $\dot{V}O_{2peak}$ was examined as opposed to absolute speeds. This approach is more generalisable to a spectrum of runners than using absolute speeds.

Blinding of time and distance is important in providing an accurate comparison of treadmill TT results (Driller et al., 2017). This approach was used in conducting the 3-km TT to limit alterations in pacing strategies across shoe conditions. Participants had to base their pace solely on their perceptions, how far they had run, and how much further they had to run during the 3-km TT.

Future directions

The RE speeds in this study were slower than those examined previously and in different footwear; hence, investigating the biomechanical adaptation to VP4 could shed light on mechanisms that contribute to improved performance in recreational runners. Consistent with previous research (Hoogkamer et al., 2018), non-rearfoot strikers appeared to respond less favourably to VP4, although the sample size was insufficient to further explore this topic. Research specifically examining responses to VP4 footwear based on footstrike pattern is warranted to elucidate the interaction between footstrike characteristics and performance enhancing effects of footwear.

Further investigation to identify whether VP4 would enhance performance in other sports, such as track and field events, football, off-road running, and basketball, etc., would be valuable to

the scientific community. Hoogkamer et al. (2018) noted enhanced energy returned in VP4 compared to other footwear. Whether this energy return provides an ergogenic aid in other sports, including Olympic weight lifting events, is an area for future research.

The optimal habituation time to maximise the effects of VF4 on RE and performance variables are unknown and could be investigated in future studies. Previous research has shown the acute benefit of VP4 in improving RE and altering biomechanics (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hoogkamer et al., 2019; Hunter et al., 2019). However, the chronic RE and performance benefits, as well as the long-term biomechanical adaptations, of running in VP4 remains undetermined. The longevity of the midsole properties and structural integrity of the upper shoe material of the VP4 also warrant further examination. Research in these areas will contribute to answering how long the VP4 continues to offer improvements in RE to those who positively respond to the shoes.

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Appendix A – Ethics application approval

18-12-2018

Kim Hebert-Losier
By email: kim.hebert-losier@waikato.ac.nz

Dear Kim

UoW HREC(Health)2018#81: Running economy, biomechanics, and performance in three different running shoes

Thank you for submitting your amended application HREC(Health)2018#81 for ethical approval.

We are now pleased to provide formal approval for your project within the parameters outlined within your application.

Please contact the committee by email (humanethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Regards,

_____

Karsten Zegwaard PhD
Acting Chairperson
University of Waikato Human Research Ethics Committee

Appendix B – Running economy, RPE, Lactate data collection

LACTATE DATA COLLECTION SHEET

NAME		DATE	
TIME		HUMIDITY	
TEMPERATURE		PRESSURE	
ANALYSER		RESTING [La]	
START POWER		STEPS	
HEIGHT (cm)		WEIGHT (kg)	

STAGE	TIME	RPE	HR	[La]
60%				
70%				
80%				

COMMENTS:

Appendix C – Shoe comfort and experience VAS

SHOE EXPERIENCE SCALE

Traditional shoe running

|---|

    No experience at all (beginner)   **Maximal experience (expert)**

Minimal shoe running

|---|

No experience at all (beginner)   **Maximal experience (expert)**

Barefoot running

|---|

    No experience at all (beginner)   **Maximal experience (expert)**

SHOE COMFORT SCALE

Traditional shoe running

|---|

Not comfortable at all   **Maximal comfortable**

Minimal shoe running

|---|

Not comfortable at all   **Maximal comfortable**

Barefoot running

|---|

Not comfortable at all   **Maximal comfortable**

Appendix D – Shoe comfort VAS

SHOE COMFORT SCALE 1st Test

Overall comfort　　　　　|---|

　　　　　　　　　　　　Not comfortable at all　　　　　　　　　　　　**Maximal comfortable**

3km PERORMANCE 1st Test

Running Shoe Performance　|---|

　　　　　　　　　　　　Much Worse　　　　　　　　　　　　　　　**Much improved**