Do carbon plated running shoes improve running economy and performance following the bike-run transition in long-distance triathletes?

by

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Abstract

Background Carbon 'super shoes' improve running economy and running performance compared with traditional running shoes. However, the influence of carbon shoes on running economy and performance after prolonged cycling for triathletes remains to be investigated.

Purpose To 1) compare the running economy and muscle oxygenation before and after a 2-hour cycling session wearing carbon 'super shoes' vs standard neutral running shoes, and 2) compare the post-cycle running performance in a self-paced 10-km time-trial wearing carbon 'super shoes vs standard neutral running shoes, in male long-distance triathletes.

Methods Eight active trained male triathletes participated in the study. Participants visited the laboratory on three separate occasions to perform a variety of assessments and trials while wearing either a neutral or carbon shoe during the running assessments. The first visit was a baseline anthropometric measurement that included an incremental bike test for $\dot{V}O_{2peak.}$ Visits two and three were prolonged trials that aimed to replicate triathlon demands. This included a fresh (pre) treadmill running economy assessment, a 2-hour fatiguing cycle on a stationary bike, and a post-cycle running economy assessment, followed by a self-paced 10-km treadmill time-trial wearing either neutral or carbon shoes.

Results There was no *shoe*time* interaction (p > 0.05). However, a significant main effect of *shoe* on both mean running economy relative to body mass ($mL.kg^{-1}.min^{-1}$; p = 0.05, η_p^2=0.49), and running speed ($mL.kg^{-1}.km^{-1}$; p < 0.05, n_p^2=0.55), indicating a lower running economy for carbon shoes compared to neutral shoes during running, was observed. There was a significant difference between the gastrocnemius muscle oxygenation during the 5-min running economy assessment before and after the fatiguing cycle (F=8.206, p < 0.05, n_p^2=0.58). However, for quadriceps muscle oxygenation, there were no significant differences between the two shoe conditions (F=0.931, p > 0.05), in an unfatigued or fatigued state (F=3.781, p > 0.05), and no linear relationship between the two different shoe conditions in an unfatigued or fatigued state (F = 0,099, p > 0.05). The mean post-cycling 10km running performance time when wearing

carbon shoes was significantly faster than neutral shoes (49.0 ± 5.0 for carbon vs 51.6 ± 5.6 min for neutral shoes; 5.0%, p=0.02, Cohen's d=1.06).

Discussion and Conclusion In summary, carbon shoes, when compared to neutral shoes, elicited a main effect indicating enhanced running economy. However, there were no differences in running economy between shoes over time in the unfatigued and fatigued state (pre- and post-prolonged cycling respectively). Despite this, the majority of participants improved their running performance wearing carbon shoes compared to neutral shoes indicating their beneficial effect in recreational and trained triathletes.

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List of Common Abbreviations

$\%SmO_2$	muscle oxygenation or muscle oxygen saturation
AT	anaerobic threshold
ATP	adenosine triphosphate
C	carbon shoes
EC	energy cost
EVA	ethylene-vinyl acetate
G	gastrocnemius
HR	heart rate
LT	lactate threshold
N	neutral shoes
Q	quadriceps
RE	running economy
RER	respiratory exchange ratio
TT	time trial
$\dot{V}O_2max$	maximal aerobic power
$\dot{V}O_2$	steady-state oxygen uptake
$\dot{V}O_2peak$	peak oxygen uptake
VT1	first ventilatory threshold
VT2	second ventilatory threshold

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Attestation of Authorship

“I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a University or other institution of higher learning, except where due acknowledgment is made in the acknowledgments.”

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Ethics Approval

This study was approved by the Institutional Human Research Ethics Committee (AUTEC #22/244) on 28th September 2022 (Appendix 1) and conducted in accordance with the standards of the Declaration of Helsinki 2013. All participants provided written informed consent, and medical and training history prior to their safe participation.

Chapter 1 Introduction

In recent years, the advancement of technology in sport has been rapid and many new products have been developed that have the potential to impact a variety of factors related to performance. In relation to the training of athletes, this includes wearable technology that can capture training load and physiological responses, or clothing and footwear fabrics and composition that aid competitive performance. Recently, there has been much attention on a new type of footwear in endurance running called ‘super shoes’ that have been associated with widespread performance improvements in running ability (Beck, Golyski, & Sawicki, 2020). These shoes are characterised by a thicker and more resilient midsole foam (greater ‘stack height’) and a carbon-fibre plate which impacts energy return and bending stiffness (Fu et al., 2021). The combination of these factors appears to be effective in enhancing running economy (RE) (Joubert & Jones, 2022) which refers to the steady-state oxygen uptake ($\dot{V}O_2$) measured at a specified running speed (Barnes & Kilding, 2015). All else being equal, improved RE allows athletes to run faster for the same energetic expenditure (Joyner & Coyle, 2008), which, in turn, enhances the performance of endurance athletes. Consequently, ways to improve RE is a topic of great interest in the applied running research field.

Nowadays, the materials and characteristics of new technology in running shoes that positively affect runners’ physiology and performance have become a new area of research. Shoe mass is one feature consistently related to enhanced RE and running performance (Hébert-Losier et al., 2020). Hébert-Losier et al. (2020) reported that each 100g increase in shoe mass could lead to a 0.7% to 1.1% increase in energetic cost (EC) during running. This explains why professional runners prefer lighter footwear during races. Bermon et al. (2021) also support this notion, stating that advancements in footwear technology contributed to better performance in elite long-distance events, such as marathons and half marathons, over a three-year period from 2016. Recently, the Nike Vaporfly running shoe has gained significant popularity in long-distance endurance sports and garnered interest from many researchers due to its effects on physiology and performance. A range of studies have sought to quantify the effects of these shoes on physiology (Kiesewetter et al., 2022. Rodrigo-Carranza et al., 2023) and performance (Kiesewetter et al., 2022. Nielsen et al., 2022. Senefeld et al., 2021) in distance running events. The original study reporting the benefits of carbon super shoes was that of Hoogkamer et al. (2018) who observed a 1.1% increase in RE per 100g of shoe mass and a 0.78 % improvement in time of running performance of 3000m per 100g of added shoe mass. These effects have been observed in other studies by Barnes and Kilding (2015) and Senefeld et al. (2021) where improvements in RE in trained runners ranged from 3.0% to 5.4% and performance by 2.4% (Hébert-Losier et al., 2020) equivalent to a 2 minute and 48-second decrease in marathon time, among high-level male marathon runners wearing super shoes. Whiting, Hoogkamer, and Kram (2022) proved that carbon-plate shoes enhanced running performance by decreasing EC by 4%, and 3% of reduction in EC during uphill and downhill running, their statement was supported by Senefeld et al. (2021) saying the marathon performance was faster in the world-class athletes. Another study pointed out the positive effect of carbon (C) shoes on RE due to the increased midsole longitudinal bending stiffness (LBS) (Roy & Stefanyshyn, 2006). Quealy and Katz (2018) suggested that the benefits of super shoes extend not only to elite athletes but also to sub-elite athletes. However, there are some studies reporting that 'super shoes' are not beneficial for everyone (Beck, Golyski, & Sawicki, 2020).

Beyond track and field and road running, RE and movement efficiency are also important in many other cyclic sports, such as cycling and triathlon. Triathlon, an Olympic sport consisting of sequential swimming, cycling, and running with short transitions between disciplines, demands various physical and physiological attributes from athletes. Despite cycling comprising most of the race time, proficiency in all three disciplines is essential for a triathlete to enhance performance (Scorcine et al., 2017). Long-distance triathlon (half ironman and full ironman) requires a high level of efficiency both during cycling *and* running components and the ability to transition from one discipline to the next plays a crucial role in overall performance. In competitive triathlon, a key component is the ability to 'run off the bike' as cycling can induce local muscle fatigue (Millet & Vleck, 2000) and alterations in mechanics (Stewart et al., 2022) that may impact subsequent running physiology (Millet & Vleck, 2000) and running performance (Millet & Vleck, 2000). For example, the respiratory muscle oxygen is reduced for both elite and sub-elite triathletes (Millet et al., 2000) and mechanical efficiency by 6% (Stewart et al., 2022) when comparing 'fresh' versus 'fatigued' (pre-cycle) conditions. Moreover, there is an increment in heart rate (HR) during running after cycling (Olcina et al., 2019). Accordingly, strategies for improving the bike-to-run transition, or that can 'rescue' a reduced running performance, are highly sought after. In this regard, it is essential to explore how C 'super shoes' might impact physiology and performance during running, following cycling of sufficient intensity and duration. Based on the current research evidence, there has been limited investigation into quantifying the effectiveness of C 'super-shoes' on the performance of triathletes after experiencing fatigue induced by prolonged cycling.

Therefore, the aims of this study were to:

1) compare the RE and muscle oxygenation before and after a 2-hour cycling session wearing C 'super shoes' vs standard neutral running shoes (N shoes); and

2) compare the post-cycle running performance in a self-paced 10-km TT wearing C 'super shoe's vs standard N running shoes, in male long-distance triathletes.

We hypothesised that C 'super shoes' would result in improved RE both before and after cycling, when compared to the N shoe, and that the performance TT time would be faster when wearing C shoes.

Chapter 2 Literature Review

The aim of this literature review is to introduce endurance sports, in particular running and triathlon and provide an overview of the key physiology behind triathlon. There is a focus on RE and how the evolution of super-shoe technology can impact physiology and performance in running events and the potential application to triathlon.

Introduction to literature review endurance sports/performance

Endurance sport can be defined by repeated isotonic contractions of large skeletal muscle groups (Morici et al., 2016). Well-known cyclical endurance sports include running, cycling, swimming, long-distance cross-country skiing and skating which are typically performed at a submaximal intensity for a prolonged duration. To be successful in endurance sports the training process must induce a range of adaptations in the heart and muscles, such as increased stroke volume and cardiac output (Morici et al., 2016), increased mitochondrial density and oxidative enzyme, change in fibre types and enhanced muscular capillarisation for more blood and oxygen supply (Morici et al., 2016).

Physiology of endurance and measures of aerobic function

Changes in cardiovascular and metabolic mechanisms following training have an impact on a range of physiological measures that are relevant to sports performance and are often reported in exercise physiology and endurance literature. There are several key measures of aerobic function relevant to endurance performance. These are maximal oxygen uptake ($\dot{V}O_2$ max), anaerobic (or lactate) threshold (AT and LT respectively) (Sleivert & Rowlands, 1996), work efficiency (movement economy) and $\dot{V}O_2$ kinetics (Whipp et al., 1981). The ability to maintain high-intensity exercise is the primary determinant of successful endurance sports such as triathlon competition (O'Toole & Douglas, 1995), it is mainly dependent on two aerobic factors: the maximum oxygen uptake, which is the upper limit for oxygen utilization in the body; and the AT, which is the highest $\dot{V}O_2$ that could be reached without a sustained arterial blood lactic acidosis (Whipp et al., 1981). Besides these main two parameters, the exercise ability of triathletes is also affected by other physiological factors (Sleivert & Rowlands, 1996). Other than these, energy balance, fluid and electrolyte balance, cardiovascular homeostasis and cardiovascular capability are also effective in developing successful triathlon performance (O'Toole & Douglas, 1995). The study also included that chronic physiological adaptation in the training especially cardiovascular and metabolic adaptation improves responses (O'Toole & Douglas, 1995).

Moreover, several current studies indicated that running performance is a multifactorial phenotype (Joyner and Coyle, 2008) and affected by various anthropometric (Maldonado et al., 2002), morphological and neuromuscular characteristics, energy supply and utilisation systems (Gonzalez-Alonso and Calbet, 2003). The key parameters that could affect endurance running performance are the maximal oxygen uptake velocity, blood lactate threshold response to exercise, critical velocity (Denadai, 2022), muscle respiratory capacity and skeletal muscle fibre type (O'Toole & Douglas, 1995). However, the main determinants of running performance are: $\dot{V}O_2$ max, RE and AT (Venturini, 2022) or LT. Therefore, to achieve success in triathlon, high-level athletes will have a high $\dot{V}O_{2max}$ value and a good ability to maintain exercise at a high percentage of $\dot{V}O_{2max}$ because of good movement economy and high anaerobic threshold in all three disciplines (Sleivert & Rowlands, 1996). An emerging idea is that a good RE is essential to improve the performance of high-level triathletes; indeed, while the contribution of RE has been discussed in previous research (Dallam et al., 2005) (Olcina et al., 2019), few studies exist.

Running economy

The term RE is often used and is defined as the steady state $\dot{V}O_2$ measured at a specified running speed (Barnes & Kilding, 2015). RE can also be defined by the $\dot{V}O_2$ (in $mL \cdot kg^{-1} \cdot min^{-1}$)

at a specific running speed, therefore it can also be expressed by the EC of running for 1 km (in $mL \cdot kg^{-1} \cdot km^{-1}$), which is calculated as $\dot{V}O_2$ divided by the velocity (Millet et al., 2011). By considering the body mass of the athletes, runners with good RE usually need less energy expenditure and hence less oxygen than runners with poor RE at the same speed which can have performance advantages in endurance events of longer duration (>20 min). Indeed, RE has been shown to be a better indicator of performance than $\dot{V}O_{2max}$ in high-level athletes (Saunders et al., 2004) and is correlated with long-distance running performance (Morgan et al., 1989).

Running economy is a complex and multifactorial concept that is affected by a range of metabolic, cardiorespiratory, biomechanical, and neuromuscular factors. As highlighted by Barnes and Kilding (2015), several factors could affect RE in genetics, but most of these factors are able to adapt via training (Figure 1). Thus, RE is important to be trained for better performance of athletes, especially for endurance athletes such as triathletes. The efficiency or economy of movement is also important in many cyclical sports.

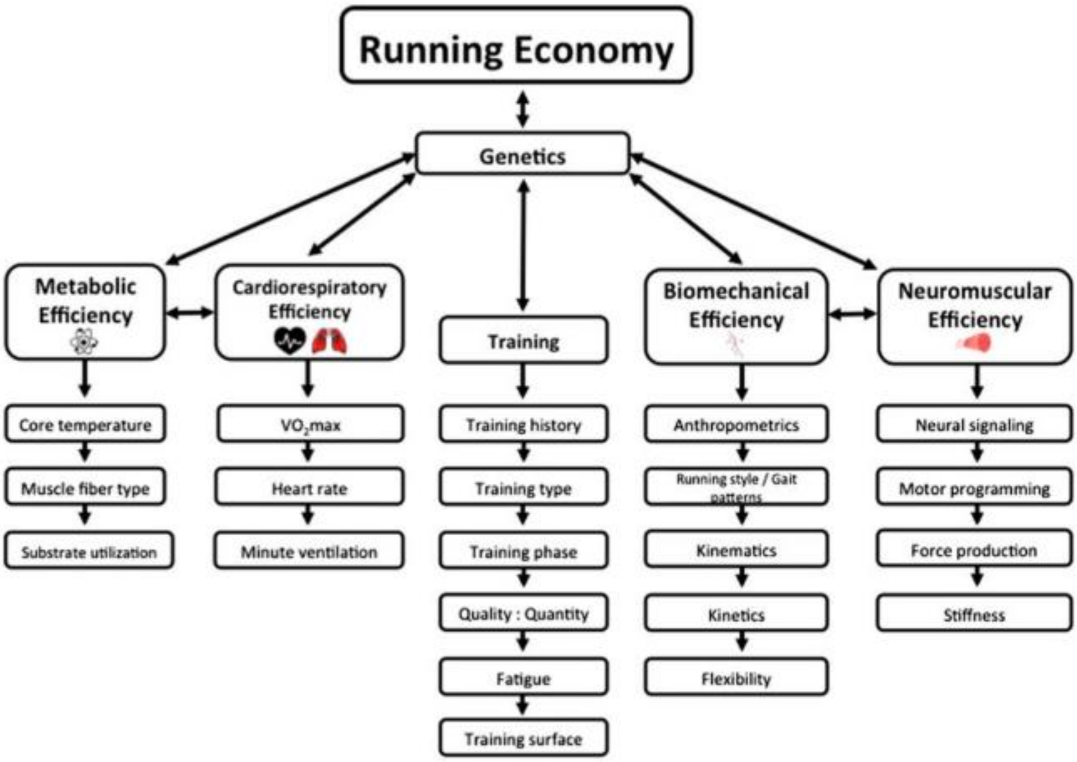


Figure 1. Factors affecting running economy (from Barnes and Kilding, 2015)

Normative values for running economy

Based on the studies to date, it is hard to identify the different classifications of RE based on runners due to the variations of equipment of measurement, such as gas analysis, protocols, maximal aerobic capacity etc. However, there is still normative data (shown below)(Barnes & Kilding, 2015) that provides a reference of different levels of RE from current studies. The lowest RE value reported at $16 km.hr^{-1}$ was $39.0 mL.kg^{-1}.min^{-1}$, with $\dot{V}O_{2max}$ of $63 mL.kg^{-1}.min^{-1}$, from an East African runner (Lucía et al., 2008). The same study also indicates that a typical world record keeper of men's half marathon RE was $150 mL.kg^{-1}.min^{-1}$ at $19 km.hr^{-1}$, which equates to $40 mL.kg^{-1}.min^{-1}$ at $16km.hr^{-1}$ (Barnes & Kilding, 2015). These results suggest those trained athletes all performed a similar percentage of their $\dot{V}O_{2max}$ level. Millet et al. (2011) presented that 174 ±9 and 164 ±8 $mL.kg^{-1}.km^{-1}$ for Olympic distance and long-distance triathletes respectively. Takahashi and Usui (2016) indicated that the average $\dot{V}O_{2max}$ is 67.4 $mL.kg^{-1}.min^{-1}$ which is lower than endurance runners, who had an average of 71.3 $mL^{-1}.kg^{-1}.min$. In comparison, the RE of triathletes evaluated by running cost was identified as higher than that of the long-distance runners, although they had similar running performances (Takahashi & Usui, 2016). However, Swinnen et al. (2018) indicated in their study that runners (1111 ±159 W) had better RE than cyclists (917 ±107 W), but triathletes had RE values in between (1004 ±98 W).

Non-training factors that affect running economy

In addition to the physiological and biomechanical characteristics a given athlete possesses, RE can also be altered by other factors such as the environment (Morgan et al., 1989), surface (Zhou et al., 2021), running style (Barnes & Kilding, 2015) and footwear (Ruiz-Alias et al., 2022. Rodrigo-Carranza et al., 2023. Van Alsenoy et al., 2021). The following section will focus on footwear.

Different types of footwear and their effect on running economy and performance

With regard to footwear, there have been many studies examining the effects of running shoes on RE (Beck et al., 2020. Joubert & Jones, 2022. Rodrigo-Carranza et al., 2023. Ruiz-Alias et al., 2022). Shoe technology has evolved steadily over the last decades from 1990s to the present. Early research showed that the relationship between RE and running shoes started around 1993 indicating that shoe cushioning could affect RE, and hence improve the performance of professional runners in marathons (Morgan et al., 1993). Nowadays, running shoes are investigated by researchers as key functional equipment for runners (Ruiz-Alias et al., 2022).

Several studies identified there might be a positive influence of running shoes with various materials on long-distance running performance. Ruiz-Alias et al. (2022) said that shoe mass and longitudinal stiffness could improve RE. The different material of shoes is effective on the metabolic and performance of triathletes as it directly affects shoe mass, which is shown linked to improvements in their performance. Hébert-Losier et al. (2020) reported that each 100g of extra mass causes 0.7-1.1% increase in the runners' energetic consumption per shoe. Thus, most elite runners prefer lighter runner shoes in the race for maximal results.

More recently, a new shoe design termed 'super shoes' has gained popularity in competitive running communities. Such shoes are lightweight featuring carbon plates in a well-cushioned midsole and a high stack height. The first time that carbon-plate shoes were available in the market for commercial purpose around 1989, designed by Brooks (Hutchinson, 2020). After that, the C shoes were brought again to the front of the world was in the Rio 2016 Olympic Games, whereby the 'energy-returning' Nike Zoom Vaporfly 4% (Taylor, 2021) was worn by the top three athletes in the marathon. The Vaporfly 4% shoe was reportedly able to improve RE by 4%. The studies on the effects of early iterations of the Nike 'super shoes' were boosted after that time with the first published study by Hoogkamer et al . (2017) supporting the manufacturers claims. Since that, increasing numbers of studies have investigated the effects of such shoes on RE in runners of different standard (Bermon et al., 2021. Nielsen et al., 2022) and different shoe companies (Hébert-Losier et al., 2020. Joubert & Jones, 2022).

Effects of super shoes on running economy and energy expenditure

A summary of studies to date on 'super shoes', across a range of manufacturers, in relation to RE is provided in Table 1. These highly cushioned carbon-plate shoes were approved by Roy and Stefanyshyn (2006) who said they could reduce the EC of running by 1%.

Other than peak oxygen uptake ($\dot{V}O_{2peak}$) and $\dot{V}O_{2peak}$ fractional utilization, long-distance runners with better RE could generate better performance than those with similar $\dot{V}O_{2peak}$ and LT (Hébert-Losier et al., 2020). As a result, C shoes become a new choice as the lightweight feature compared to traditional running shoes. Nike Vaporfly Elite shoes came to the population in the year 2017, during the Breaking2 event, which introduced C shoes, that have energy return feature by a thick foam midsole (Hébert-Losier et al., 2020). A study done by Whiting, Hoogkamer, and Kram (2022) indicated that Nike Vaporfly 4% which was one of the most famous C shoes could reduce the metabolic cost of treadmill running by 4%. This effect of advanced shoes would be explained by features with improved technology such as lighter weight, highly compliant, resilient midsole foam and a midsole-embedded curved carbon-fibre plate (Whiting et al., 2022).

Table 1. The effect of different 'super shoes' on running economy

Study	Calibre of runner	$\dot{V}O_{2peak}$ (ml.kg.min)	Running economy running speed (km/h)	Shoe brand and model	Material	Dimensions			Change in running economy (%)
						Heel/stack height (mm)	Forefoot thickness (mm)	Shoe mass (g)	
Barnes &Kilding, 2019	Highly trained	43.4 ± 2.2	14	Nike Vaporfly 4% (VP4)	Nike Zoom X foam (carbon-fibre plate)	31	21	205	↑ 4.2%
		51.3 ± 2.2	16						
		58.9 ± 1.3 (male)	18						
Barnes &Kilding, 2019	Highly trained	45.4 ±2.2	14	Adidas Adios Boost 3	Thermoplastic polyurethane (TPU)	23	13	236	↑ 1.1%
		53.6 ± 2.2	16						
		61.4 ± 1.1	18						
Barnes &Kilding, 2019	Highly trained	44.7 ± 2.2	14	Nike Zoom Matumbo 3	EVA	-	6.35	118	-
		52.4 ± 2.1	16						
		60.5 ±1.6	18						
Dinato et al., 2021	Recreational	42.5 ± 2.6	12	Adidas Energy Boost	Thermoplastic polyurethane (TPU)	31.5	21.5	320	↑ 2.4%

Hébert-Losier et al., 2020	Recreational	33.9 ± 3.7	11.0	Nike Vaporfly 4%	Nike Zoom X foam (carbon-fibre plate)	31	24	211±12	↑ 4.4%
		38.9 ± 2.8	12.9						↑ 4.3%
		44.5 ± 3.6	14.7						↑ 4.4%
Hébert-Losier et al., 2020	Recreational	34.3 ± 3.4	11.0	Saucony Endorphin racing flat	EVA	13	12	153±8	↑ 3.4%
		39.5 ± 3.4	12.9						↑ 3.0%
		45.4 ± 4.2	14.7						↑ 2.7%
Hoogkamer et al., 2018	Highly trained	42.0 ± 2.4	14	Nike Zoom Streak 6	EVA	23	15	203	↑ 2.8%
		50.3 ±2.9	16						
		59.6 ± 3.1	18						
Joubert & Jones, 2022	Trained	51.7 ± 2.1	16	Hoka Rocket X	carbon-fibre plate	35	30	224	No change
Joubert & Jones, 2022	Trained	50.9 ± 1.8	16	Saucony Endorphin Pro	carbon-fibre plate	39	31	239	↑ 1.48%
Joubert & Jones, 2022	Trained	50.1 ± 1.9	16	Nike Alphafly	carbon-fibre plate	40	36	240	↑ 3.03%
Joubert & Jones, 2022	Trained	50.4 ± 1.7	16	Asics Metaspeed Sky	carbon-fibre plate	38	33	209	↑ 2.52%
Joubert & Jones, 2022	Trained	50.3 ± 1.7	16	Nike Vaporfly Next %2	carbon-fibre plate	40	32	211	↑ 2.72%
Joubert & Jones, 2022	Trained	51.0 ± 1.8	16	New Balance RC Elite	carbon-fibre plate	34	24	221	↑ 1.37%

Joubert & Jones, 2022	Trained	51.4 ± 1.7	16	Brooks Hyperion Elite 2	carbon-fibre plate	35	27	229	No change
Kiesewetter et al., 2022	Recreational	207.8 ± 13.1 mL/kg/km	8.0 to 14.2	Puma Fast-FWD	carbon-fibre plate	34	26.3	172.4	-
		209.5 ± 12.8 mL/kg/km		Puma Fast-R		35	28.2	203	
		-		Nike Vaporfly 23Next%		40	29.4	183.1	
Warne et al., 2021	Recreational	42.0 ± 4.7	11	Asics Gel Cumulus 2012	Polyester	37.6	27.9	400	↔ Little or no change

Note: EVA= ethylene-vinyl acetate foam, RE= running economy

The effects of footwear on running performance

As well as the effects on RE, there is considerable interest in how super shoes impact actual performance. A summary of studies to date on 'super shoes', across a range of manufacturers, in relation to running performance are provided in Table 2.

As a typical example of new technology running shoes, Nike Vaporfly was popular in the long-distance endurance sports field and has been investigated by many researchers. Senefeld et al. (2021) indicated a 2.8 min (2%) improvement in marathon finishing times in high-level (world-class) male marathon runners wearing the new running shoes. Hébert-Losier et al. (2020) further introduced the characteristics of these running shoes: thick foam midsole which gives an energy return feature and an inserted carbon plate which enhanced longitudinal bending stiffness (LBS) that contributed to a shorter running time. A current study indicated that RE could be enhanced by about 1% by wearing shoes with an increasing midsole LBS compared to stiffer and more flexible shoes (Roy & Stefanyshyn, 2006). Roy and Stefanyshyn (2006) also explained that enhanced LBS of shoes could minimize energy absorption during running and improve energy retuned. Quealy and Katz (2018) suggested not only elite athletes, but sub-elite athletes could also be benefiting from the new technology footwear. Research indicates that Nike Vaporfly 4% consists of both improvements in midsole thickness and LBS that decreases energy loss during running (Fu et al., 2021). The insertion of carbon fibre plate has improved the shoes' LBS and improved RE by 1% (Fu et al., 2021). This has been supported by Beck, Golyski, and Sawicki (2020) who suggested that the addition of carbon fibres to midsole could enhance RE by 0.8 to 1.1%.

Table 2. Super shoes and their relative effect on running time-trial and time to exhaustion performance

Study	Calibre of runner	Time trial Distance / time to exhaustion intensity	Surface	Shoe	Material	Change in performance (%)
(Hébert-Losier et al., 2020)	Recreational	3 km TT	Treadmill	Nike VF4%	Nike Zoom X (carbon-fibre plate)	↑ 2.4%
(Nielsen et al., 2022)	Recreational	3.5 km TT	Track	Nike VF4%	Nike Zoom X (carbon-fibre plate)	↑ 1.1%
(Senefeld et al., 2021)	World-class	Marathon	Field	Neoteric Nikes	-	↑ 2.0%

Application of super shoes in other endurance sports

Introduction to triathlon

In addition, to track and road running, there are other sports where super shoes could have a positive impact on the performance. One such sport is Triathlon which is an Olympic sport consisting of sequential swimming, cycling and running, with short transitions between disciplines. There are many competitive triathlon distances ranging from super sprint (500m swim, 10km cycle, 2.5km run) to Ironman (3.9km swim, 180km cycle, 42.2km run) (Athurs-Brennan, 2021), which at the professional level corresponds to durations between 45 minutes (Lacke, 2023) to 17 hours, and sometimes even longer (Leitch, 2022). Half Ironman event times range from 3.8 to 7 hours, and full Ironman event duration varies from 8 to 17 hours (Laursen, 2011).

Scorcine et al. (2017) identified that after analysing several races, researchers found that swimming ranged from 10-20% of total race, cycling is about 50-60% and running occupied 30-40% of the total. While all three disciplines are important, research has sought to identify the discipline that contributes most to performance. Sousa et al. (2021) identified that each discipline has a relatively different importance for determining the performance of the entire race based on different triathlon durations. They pointed out that swimming plays a more important role in Sprint- and Olympic-distance triathlon, cycling is more important in Half-Ironman distance, and running for the Full-Ironman distance races. Different triathlon distances rely on different race dynamics and hence result in various contributions of each discipline (Sousa et al., 2021). Although cycling weighted most of the race, mastering all three disciplines is essential for a triathlete to enhance his performance. Even though there are various distances and durations of triathlon, the aerobic system plays a major part in determining overall performance in all distances.

Physiology of triathlon

As a prolonged endurance sport, triathlon requires a high level of aerobic power and efficiency. Based on the estimation of EC in long-distance triathlons, a half-Ironman requires 4500 kcal energy (Gillum et al., 2006) rising for full-Ironman races to 8500 to 11500 kcal (Laursen and Rhodes, 2001; Kimber et al., 2002). In this 'ultra-endurance' duration, the immediate (ATP-CP) and short-term (anaerobic glycolytic) energy systems do not contribute a large proportion of the overall energy expenditure, but the rate and efficiency of oxygen-derived adenosine triphosphate (ATP) repletion are much more important. Carbohydrate and lipid oxidation rates become a key determinant of race success in an ultra-endurance triathlon (Laursen, 2011).

A high $\dot{V}O_{2max}$ is an essential parameter of triathletes' success (Sleivert & Rowlands, 1996). The metabolic and physiological demands of triathlon vary according to differing race duration and intensity (Wu et al., 2014). Compared amongst the three disciplines, the highest VO_{2max} is achieved in running (100%), followed by cycling (94%-97%), and the lowest value is found in swimming (74%-86%) (Schäfer, 2011). This can be explained by the larger muscle groups and mass involved in running, thus higher muscle mass is recruited. Suriano et al. (2010) concluded the relationship between the aerobic threshold and $\dot{V}O_{2max,}$ that is triathletes will have higher $\dot{V}O_{2max}$ if they have a higher aerobic threshold in running than the other two disciplines. These three disciplines require different physical and physiological demands on athletes. Looking into triathlon itself, the demands of each discipline are also diverse as the energy systems are various. Wu et al. (2014) pointed out that the distribution of speed, work, and energy cost in the exercise process is essential to improve the performance of athletes. This means the complex and unique feature of this sport requires triathletes to manage their speed and energy very well in every discipline during races (Wu et al., 2014). Swimming usually starts first among three disciplines (TRIQ, n.d.); middle-distance swimming depends on aerobic capacity and exercise efficiency the most. Other than these two, hydrostatic lifting and buoyancy are also important in swimming. As the last discipline of the whole race, running starts after a massive energy expenditure of swimming and cycling, which generate more muscular fatigue and damage than the other two. Higher energy and metabolic cost generated by the reduced running efficiency after a long time of cycling causes fatigue which influence the performance of athletes (Wu et al., 2014). Nevertheless, running in a triathlon is also different from prolonged distance running in various aspects. Hausswirth and Lehénaff (2001) investigated that $\dot{V}O_2$, expiratory flow, HR and arterio-venous oxygen gradient were higher in the laboratory-based triathlon compared to the 10km run. The energy level and ventilatory flow were also higher than 10km running.

Fatigue in triathlon

Fatigue is a common factor influencing performance during training and races, especially affecting pacing in endurance exercise. Ultra-endurance events of more than six hours could cause a high level of neuromuscular fatigue because of the huge amount of energetic and metabolic requirements, and psychological reasons (Wu et al., 2014). Wu et al (2014) mentioned that in long-distance endurance triathlons, the occurrence of fatigue seems to be related to the dropping of muscle glycogen and neuromuscular activity. Moreover, different disciplines could contribute to various ratios of fatigue. Compared with swimming and cycling, running is more likely to create more muscular damage hence fatigue, although there is a reduction in running efficiency after cycling suggesting a higher metabolic expenditure (Wu et al., 2014). In reality, the race distance has a huge influence on the mechanisms responsible for fatigue, and the triathletes' pacing in the race. In short-distance races, such as 100m to 800m running, the speed reduces progressively due to the accumulation of anaerobic metabolites, which in turn increases muscular acidity, impairing glycolysis, and muscular contractions (Wu et al., 2014). However, in the long-distance triathlon events, fatigue seems to be more likely related to the reduction in muscle glycogen amount and neuromuscular activity (Wu et al., 2014).

When interpreting and applying RE data from runners to triathletes several factors require consideration. The most obvious is that triathletes complete the run stage in a pre-fatigued state having completed a swim and cycle. While triathletes attempt to adapt themselves to running after cycling (practicing the ‘bike-run’ transition), or swimming and cycling training, the impact on RE may still be noticeable (Walsh, 2019). Du Plessis et al. (2020) pointed out that cycling before running raises physiological cost and perceptual responses. Specifically, this study indicated a change in $\dot{V}O_2$ of 1.9±1.2 and change in oxygen cost is 2.5 ±1.3 (Du Plessis et al., 2020). How this reduced economy interacts with the potential improved economy while wearing super shoes remains to be determined and is an interesting area to research.

Conclusion

In summary, RE is an important physiological characteristic for athletes to possess when competing in endurance running events, including triathlon. While many factors determine RE, the evolution of shoe technology and its impact on running mechanics and physiology is becoming widespread with clear benefits reported to RE and performance in running events for a range of distances in the fresh (non-fatigued) state. However, other sports where running is a key component, such as triathlon, have received less consideration and it is not yet known whether super shoes can positively impact RE following a prolonged bout of cycling which is known to disrupt running mechanics and economy. More studies are required to investigate the effect of carbon plate shoes on the economy and subsequent performance of various durations of triathlon races. Moreover, other than the elites, all other level athletes should also be considered when discovering the improvement of C shoes on running performance. Future studies should seek to determine the mechanical and physiological effects of super shoes in a triathlon-specific context.

Chapter 3 Methods

Participants

Eight male club-level (mixed recreational and trained levels) triathletes participated in the study (age: 36.8 ±10.1 years; height: 1.84 ±0.03 m; body mass: 86.1 ±8.6 kg; $\dot{V}O_2$ peak: 56.6 ±6.0 $mL.kg^{-1}.min^{-1}$). An *a-priori* power analysis was run (JASP V 17.2.1) to indicate the power given to the main effect, and as a result, eight age-group triathletes were recruited to participate. The inclusion criteria were that the participants must be injury and illness free for the previous three months, currently training to complete a long-distance triathlon, accustomed to running on a treadmill and not currently wearing orthotic inserts. All participants were invited to participate in the study through social media advertisements, and potential participants contacted the researchers via phone or e-mail. All recruitment and data collection procedures were approved by the institutional human research ethics committee (AUTEC #22244) and conducted in accordance with the standards of the Declaration of Helsinki 2013. All participants provided informed consent, and medical and training history prior to their safe participation.

Experimental design

Participants visited the laboratory on three separate occasions to perform a variety of assessments and trials while wearing either a supplied N or C shoes during the running assessments. The shoe condition was randomised and balanced amongst participants. Laboratory visits were approximately one week (7 days) apart to allow for recovery. Participants were requested to avoid prolonged and vigorous exercise 24 hours before each visit. The pre-trial diet (24hr pre) and within-trial hydration were self-selected, recorded and replicated for each subsequent trial. The first visit was a one-hour baseline anthropometric measurement and familiarisation session. The baseline measurements include height, weight, and an incremental cycling test to determine $\dot{V}O_{2peak}$ and to identify the individualised cycling intensity for the experimental cycling trials. Visits two and three were prolonged trials which aimed to replicate triathlon demands. This included an unfatigued (pre-cycle) treadmill RE assessment, a 2-hour indoor fatiguing cycle on a stationary bike, a post-cycle RE assessment, followed by a self-paced 10-km treadmill time-trial run.

Shoe characteristics

Two different, commercially available running shoes were compared. The C shoe was the Asics Metaspeed Sky (Asics Corporation, Kobe, Japan) and the N shoe was Asics Evoride 3 (Asics Corporation, Kobe, Japan) shoe (Figure 2). Characteristics of the shoes are provided in Table 3.

a) b)

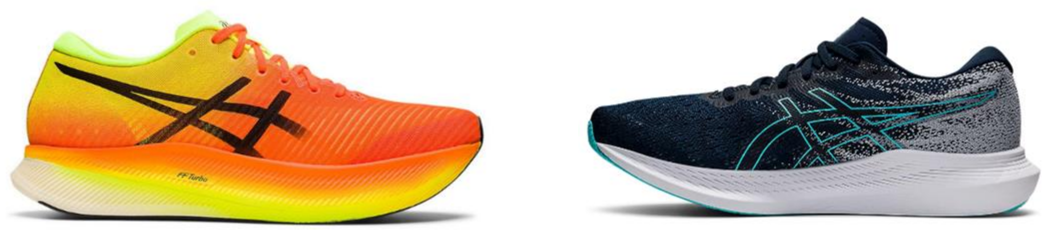


Figure 2 a) Asics Metaspeed Sky (https://www.asics.com/us/en-us/metaspeed-sky/p/ANA_1012B069-800.html); b) Asics Evoride 3 (https://www.asics.com/us/en-us/evoride-3/p/ANA_1011B339-400.html)

Table 3. Characteristics of the neutral and carbon shoes

Shoe	**Carbon: Asics Metaspeed sky**	**Neutral: Asics Evoride 3**
Stack height (mm)	33	26
Carbon-plate	Full length embedded	-
Foam type	FF Turbo	Solyte
Foam density	50	50
Mass (g)	200	210

Procedures

Baseline assessment and familiarisation (visit 1)

Baseline measures were collected upon arrival at the laboratory (age, height and weight). Initially, an incremental cycling assessment took place to determine $\dot{V}O_{2peak}$ and to identify the individualised cycling intensity for the experimental cycling trials. The test was performed on an electromagnetically braked ergometer (Excalibur, Sport, Lode BV, Gromingen, NET) starting at a power output of 95 W for three minutes and increasing by 35 W every three minutes until the respiratory exchange ratio (RER) reached 1.0, and power output was increased by 35 W for every one minute until volitional exhaustion. Expired gas was collected continuously by indirect calorimetry (TrueOne 2400, ParvoMedics, UT, USA). Heart rate was measured via a chest strap (H10. Polar Electro Oy, Kemple, Finland). The $\dot{V}O_{2peak}$ was identified as the highest 30s average $\dot{V}O_2$ measurement during the test. The first ventilatory threshold (VT1) was identified as the first $\dot{V}$O2 breakpoint in the $\dot{V}$O2 vs. $\dot{V}E.\dot{V}O2^{-1}$ relationship. The second VT (VT2) was identified when the $\dot{V}O_2$ at $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ rose with a drop down in $PetCO_{2.}$ These values of $\dot{V}O_2$ were converted to power by using the power versus $\dot{V}O_2$. using the last minute of $\dot{V}O_2$ data from each 3-minute stage. The results of the baseline session would be used to determine the intensity of the two-hour cycling in the following visits.

Experimental trials (visits 2 and 3)

Participants completed a run-bike-run trial on two occasions, separated by seven days. In a balanced randomised order, participants either wore the N (Asics Evoride 3) or C (Asics Metaspeed Sky) shoe during the running components of the trial. All trials were performed under similar environmental conditions in a climate-controlled laboratory (19-21°C and ~65% relative humidity) and at the same time of day (+/- 1 hr) to minimise the effect of circadian variation. A fan, positioned ~1 m in front of the participants, with an airflow that was selected by the participant verbally to the researchers, was used to aid convective cooling.

The run-bike-run trial started, without a warm-up, with a 5-minute sub-maximal bout of running on a motorised treadmill (HP Cosmos Saturn, Germany) set at 0% gradient and at a speed between 10 and 14 km/h, for the assessment of RE. The treadmill speed for this trial component was prescribed based on the self-reported running ability (recent 5km and 10km performance time) of the participants to ensure that a steady-state $\dot{V}O2$ was achieved. The $\dot{V}O_2$ was measured continuously using a Parvo metabolic cart (TrueOne 2400, ParvoMedics, UT, USA) which was calibrated for gases and volume prior to each trial. Heart rate was measured continuously using a chest strap. Percent muscle oxygen saturation (%SmO_2) was measured continuously (second by second) by portable near-infrared spectroscopy (NIRS) monitor (Moxy, Fortiori Design LLC, Minneapolis, MN, USA) designed for use during exercise. These were attached to the vastus lateralis quadriceps (Q) muscle about 15 cm above the knee (Olcina et al., 2019) and on the mid-belly of the gastrocnemius (G) muscle on the right leg. The NIRS measurement quantifies variation in optical transmission by sequentially sending light waves (630–850 nm) from four light-emitting diodes into the tissue beneath the device and recording the amount of returned, scattered light at two detectors that are positioned 12.5 and 25 mm from the light source.

Following the RE assessment, participants immediately removed their running shoes and replaced them with cycling shoes and transitioned to the cycle phase of the run-bike-run protocol. To aid comfort, participants cycled on their own road bikes attached to a stationary ergometer (Wahoo Kickr v5). Participants cycled for two hours at an equivalent intensity of the VT1 power determined from the first visit and reduced by 20W at 1 hour, and another 20W at 1.5 hours. Such a design was to fatigue participants in a similar way to a real long-distance triathlon event. The expired gas was collected continuously at 15-minute intervals during the two hours by indirect calorimetry. Muscle oxygen saturation was measured continuously (second by second) using portable NIRSs monitors. Participants were asked to hydrate and fuel as if they were competing, so the consumption of fluid (water, electrolytes), and fuel (energy gels and bars) were permitted during the cycling phase and the running time trial (TT). The consumption of all fluid and food was recorded and repeated in subsequent trials to allow a valid comparison.

Immediately following the cycle component, participants had three minutes to transition from cycling to running by dismounting the ergometer, removing cycling shoes and fitting the test or neutral shoes in preparation for a 5-minute post-cycle assessment of RE at the same individualised speed (10 to 14km/h) as performed in the pre-cycle RE assessment. Thereafter, participants transitioned immediately into a 10km self-paced TT (Kirkman, 2015) on the motorised treadmill. The treadmill velocity was controlled by the researcher upon visual or auditory cues from the participant.

Data analysis

Various approaches were adopted to extract and analyse raw data for key variables of interest from the run-bike-run protocol.

Running economy

For analysis of pre- and post-cycle RE, $\dot{V}O_2$ data were averaged on a 30-second basis and the mean data from minutes 4 to 5 of each 5-minute assessment was used for RE analysis. The average HR, SmO_2 and tHb between mins 3-5 were also analysed.

Cycling intensity

Mean power, $\dot{V}O_2$, HR and SmO_2 for the 2-hour trials were determined from the mean of the last two minutes of each repeated measured 15-minute block throughout the cycle trial.

Running Performance

Mean speed (km/h) and time to complete (min:ss) the TT was recorded. Muscle oxygen saturation and HR data during the entire two hours of cycling were recorded and averaged at the last minute of every five-minute block. The average percentage SmO_2 of the whole cycle test and 10km TT was calculated. The average SmO_2 between minutes 3-5 was analysed for the 5-minute run tests at 10, 12 or 14km/h.

Statistical analysis

Data are presented as mean ± standard deviation (SD). Extracted data was exported to JASP (v17.2.1) for statistical analysis. Repeated measures two-way ANOVA tests were conducted to analyse the interaction between shoe condition and the fatigue state (time) induced by cycling on RE, SmO_2 of G and Q muscles and performance of running. Partial eta squared, $\eta_p{}^2$, was reported for small, medium, and large effects (Richardson, 2011). Holm correction was used in Post Hoc tests to determine which shoe conditions and fatigue comparisons had significant differences. A paired t-test was used to identify the influence of the shoe condition on TT performance. Statistical significance was set as $p<0.05$ in all analysis.

Chapter 4 Results

Participant baseline characteristics and anthropometrics

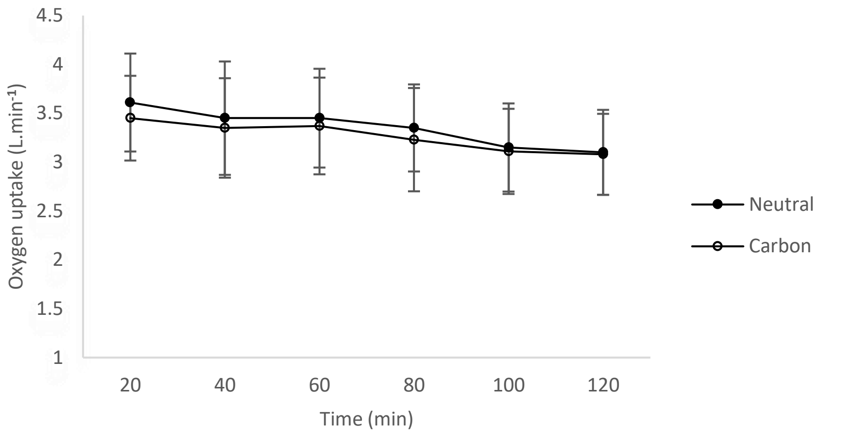
Twelve male age-group long-distance triathletes volunteered to participate in this study. Four were unable to finish the study due to injury (n=1), personal reasons (n=1) or illness (n=2), resulting in eight participants completing the study. The demographics and baseline anthropometrics and fitness of eight participants who completed all trials are shown in Table 4. Additionally, due to complications during data collection, one participant's RE data was removed due to technical issues, and as a result, only seven participants' RE data were analysed. Based on the final number of participants (n=8), α=0.05, and a large effect size of the influence of shoes conditions on TT performance observed in the present study (Cohen's d=1.06), the statistical power of the current analysis was 0.73.

Table 4. Participant anthropometrics and baseline characteristics from a standardised cycling incremental test (mean ± standard deviation).

Age (years)	32.2 ±9.7
Height (cm)	180.5 ±6.1
Weight (kg)	83.9 ±10.3
$\dot{V}O_2$peak ($mL.kg^{-1}.min^{-1}$)	56.5 ±6.3
$\dot{V}O_2$peak ($L.min^{-1}$)	4.8 ±0.7
Peak Power (Watts)	439 ±29
$\dot{V}O_2$ at VT1 ($L.min^{-1}$)	3.6 ±0.6
$\dot{V}O_2$ at VT2 ($L.min^{-1}$)	4.1 ±0.5

Load and intensity of cycling

The two hours of cycling for the N and C shoe conditions were performed at a mean power of 239 ±34 W, and was the same for both trials, as expected, given replicated protocols. The mean %$\dot{V}O_2$peak (68.2 ±4.9% for N vs 66.6 ±6.9% for C shoes), %VT1 (96.0 ±13.6% for N and 93.4 ±12.3% for C shoes) and %VT2 (82.3±7.8% for N and 80.4 ±9.6% for C shoes) were also similar between trials (all $p>0.05$). There was no significant effect between mean cycling $\dot{V}O_2$ for N vs C shoes (3.4 ±0.5 vs 3.3 ±0.5 L.min^{-1}, respectively, p>0.05; Figure 3a) in the prolonged cycling trial. The mean HR (148.8 ±25.4 bpm for N vs 141.5 ±23.7 bpm for C shoes, p>0.05, Figure 3b) and mean % SmO_2 G (48.6 ±15.7% for N vs 65.5 ±18.6% for C shoes, p>0.05, Figure 3c) for the N shoe trial trended to be lower than the C shoe trial whereas the % SmO_2 Q during cycling was similar (45.3 ±21.3% for N vs 46.5 ±11.2% for C shoes, p>0.05, Figure 3d).



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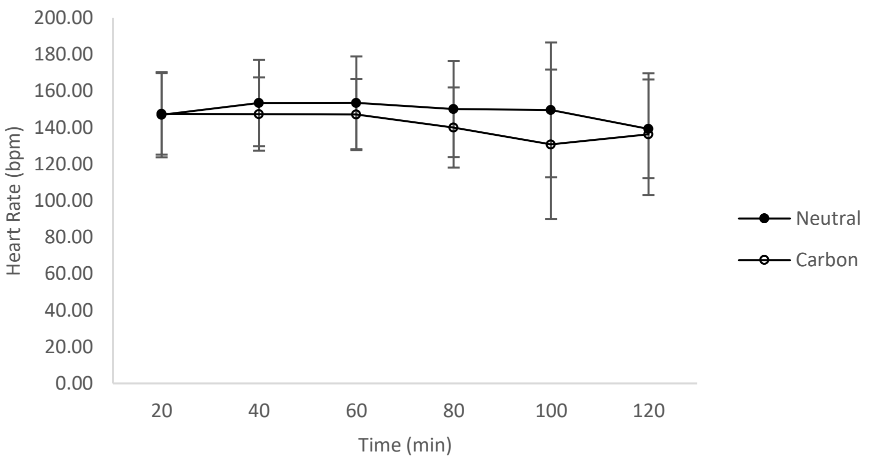

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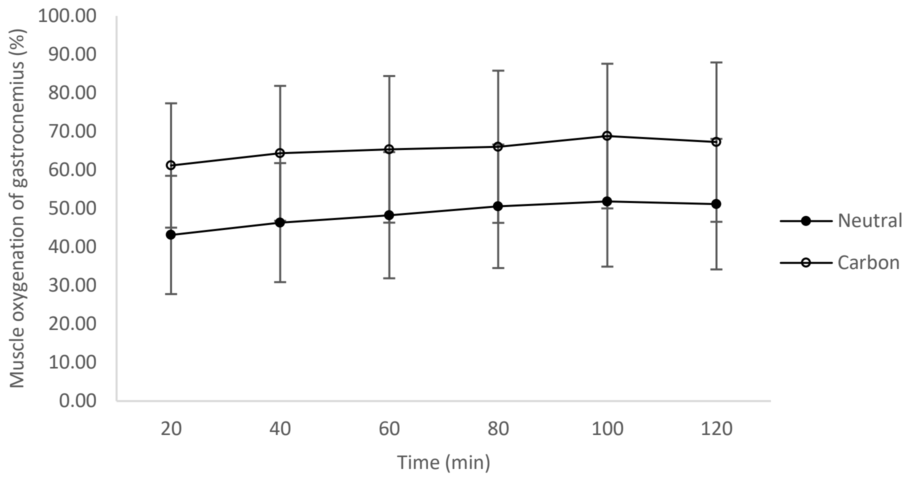

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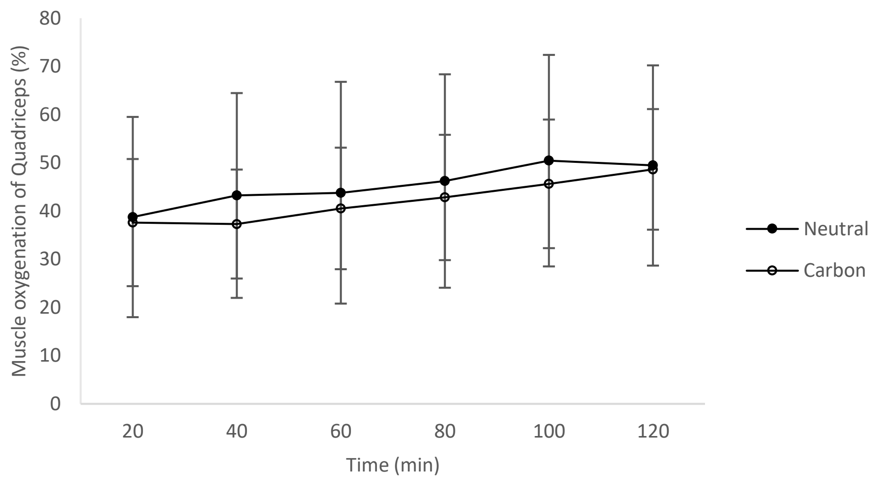

d.

Figure 3. Measurements of mean oxygen uptake (a), heart rate (b), muscle oxygen saturation of gastrocnemius (c) and quadriceps (d) in neutral and carbon shoe conditions for prolonged cycling.

Running economy

The mean RE, expressed relative to body mass and running speed ($mL.kg^{-1}.km^{-1}$), for each shoe condition before and in the fatigued state, with individual responses, are displayed in Figures 4 and 5. There was no *shoe*time* interaction (F=2.6445, p >0.05). However, there was a significant main effect of *shoe* on RE (F=5.838, p = 0.05, η_p^2=0.49), with a lower RE (mean difference=6.7 $mL.kg^{-1}.km^{-1}$, 3.3%) for C compared to the N shoes. There was no main effect for *time* (pre- and post-cycling, F=0.465, p > 0.05). By comparison, N shoes presented a higher RE either before or in the fatigued state (204.8 ±22.1 before vs 201.0 ±22.9 mL.kg^{-1}.km^{-1} in the fatigued state) compared to C (192.3 ±20.3 before vs 200.1 ±15.4 mL.kg^{-1}.km^{-1} in the fatigued state).

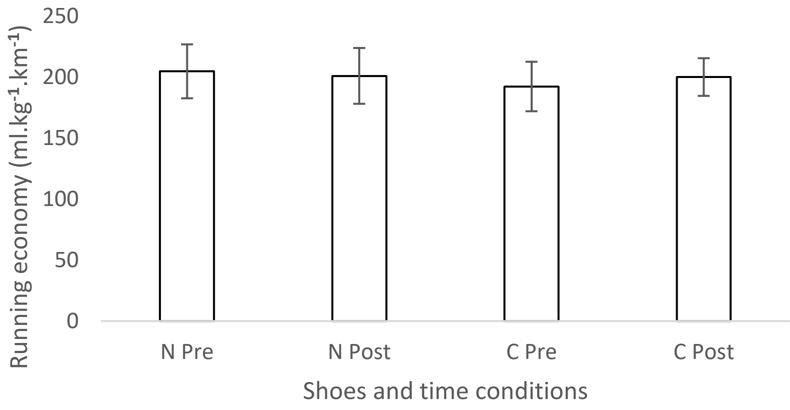

Figure 4. Running economy measured during a 5-minute running economy assessment in neutral (N) and carbon (C) shoes conditions pre- and post- prolonged cycling.

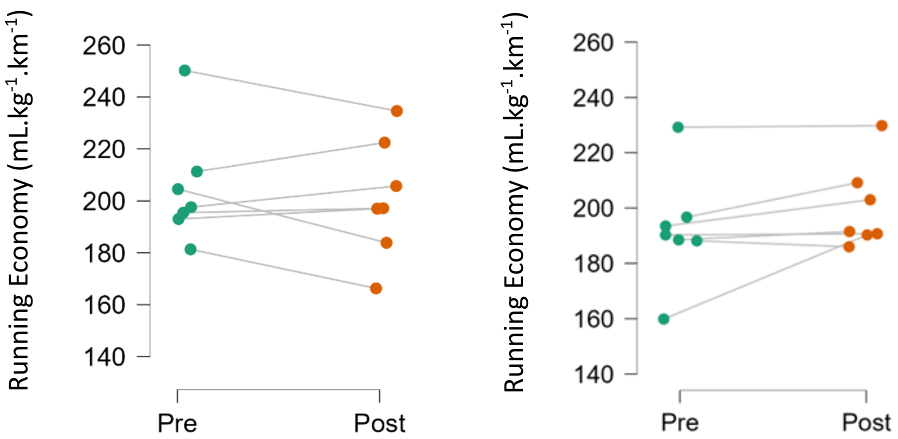

Figure 5. Individual responses of running economy during a 5-minute running economy assessment wearing neutral (a) and carbon shoes (b) pre- and post- prolonged cycling.

The mean RE, expressed relative to body mass (mL.kg^{-1}.min^{-1}), for each shoe condition before and in the fatigued state, with individual responses, is displayed in Figures 6 and 7. There was no *shoe*time* interaction (F = 0.855, p > 0.05). However, there was a significant main effect for the shoe condition, but not time (F= 4.236, p > 0.05), with a lower RE (mean difference 1.87 $mL.kg^{-1}.min^{-1}$, 4.3%, F=7.453, $p < 0.05$, n_p^2=0.55) for C shoes compared to the N shoes.

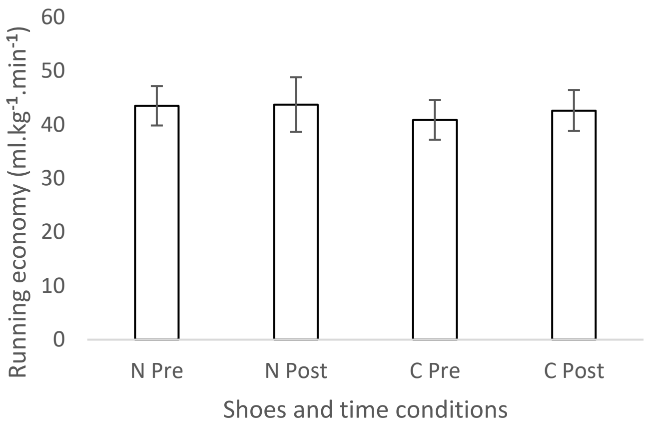

Figure 6. Running economy measured during a 5-minute running economy assessment in neutral (N) and carbon (C) shoes conditions pre- and post- prolonged cycling.

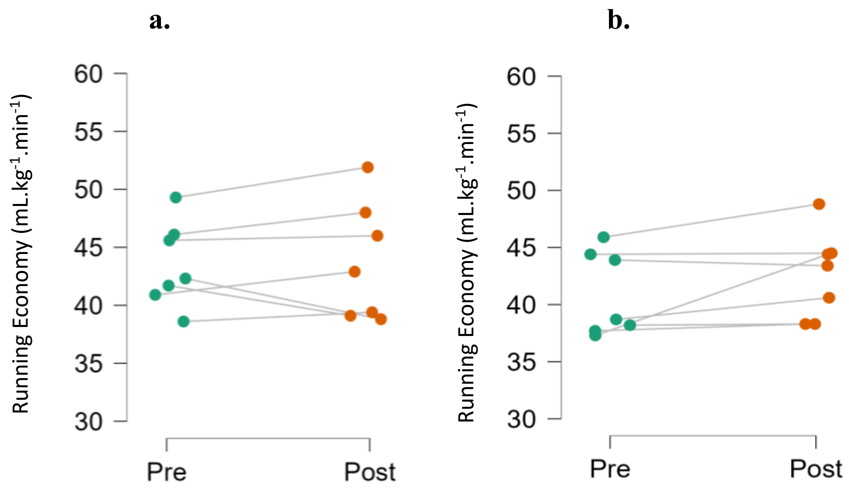

Figure 7. Individual responses of running economy during a 5-minute running economy assessment wearing neutral (a) and carbon shoes (b) pre- and post- prolonged cycling.

Based on the calculated results, the range of individual RE percentage difference was 2.1 to 11.8%. Moreover, the mean individual percentage difference (6.0 ±4.0%) of RE before the fatigued state is higher than the individual percentage difference (2.0 ±8.6%) of RE in the fatigued state. The percentage differences of comparison between conditions were shown in Table 5.

Table 5. Percentage differences in running economy pre- and post-prolonged cycling wearing neutral (N) and carbon (C) shoes (n=7).

Participant	% difference pre N-post N	% difference pre C-post C	% difference pre N-pre C	% difference post N-post C
1	8.30	-19.03	11.84	-14.43
2	-4.12	1.14	4.77	9.58
3	-0.88	-0.23	2.63	3.26
4	-2.07	-4.91	-0.26	-3.05
5	-5.27	-6.32	6.90	5.97
6	6.24	-0.26	8.39	2.05
7	-4.89	-1.59	7.82	10.72
Mean ± SD	-0.39 ± 5.48	-4.46 ± 6.97	6.01 ± 4.00	2.02 ± 8.63

Note: N=neutral shoes, C=carbon shoes, Pre=before prolonged cycling, Post=after prolonged cycling.

Heart rate

The average HR for each shoe condition measured in the two RE tests are presented in Figures 8 and 9. There were no main effects for shoe conditions (F=0.454, $p > 0.05$), or for time (before and in the fatigued state, F= 2.909, $p > 0.05$). There was also no interaction between the two different shoe conditions before or during the fatigued state (F=0.254, $p > 0.05$).

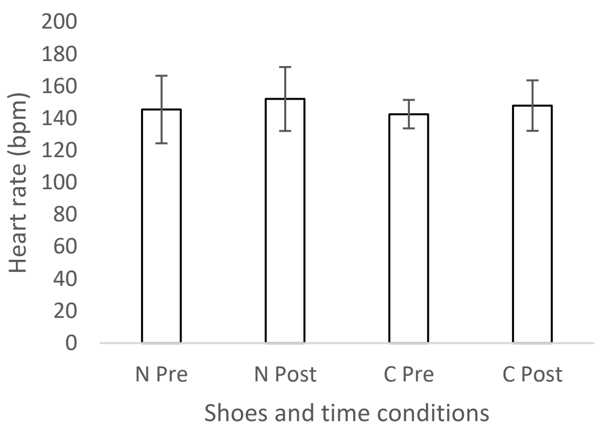

Figure 8. Heart rate measured during a 5-minute running economy assessment in neutral (N) and carbon (C) shoes conditions pre- and post- prolonged cycling.

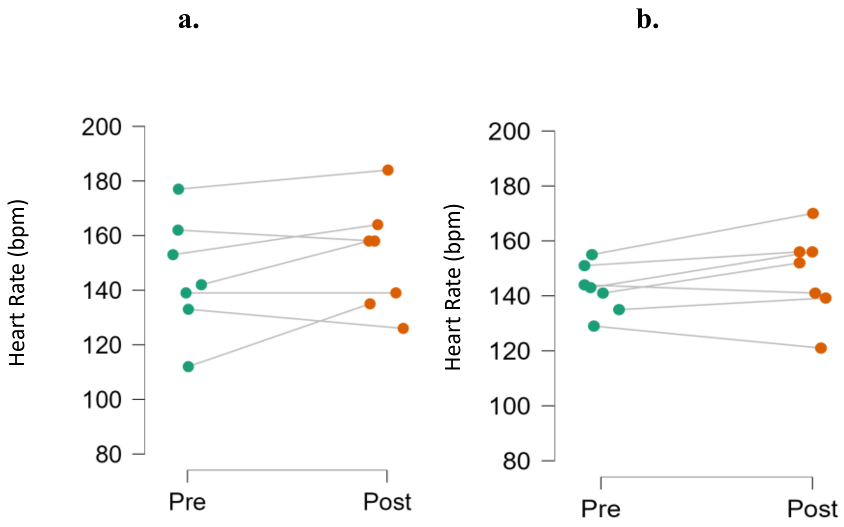

Figure 9. Individual responses of heart rate (bpm) during a 5-minute running economy assessment wearing neutral (a) and carbon shoes (b) pre- and post- prolonged cycling.

Muscle oxygenation

The SMO_2% G for each shoe condition, before and after cycling are displayed in Figures 10 and 11. There was no *shoe*time* interaction (F = 2.298, p > 0.05), however, there was a significant main effect of *time* on %SmO_2 G (pre- and post-cycling, F=8.206, $p < 0.05$, n_p^2=0.578), with a lower %SmO_2 G (mean difference 7.31, 15.1%) for before the fatigued state than in the fatigued state. A post hoc test was conducted, which showed statistically significant differences between the %SmO_2 G before and after the fatigue state (p_{holm} =0.03).

There was no main effect for the *shoe* condition (F=0.036, p > 0.05). By comparison, %SmO_2 G in the fatigued state (58.67 in N and 52.56 in C) in both N and C shoes was higher than before (46.56 in N and 50.06 in C) in general.

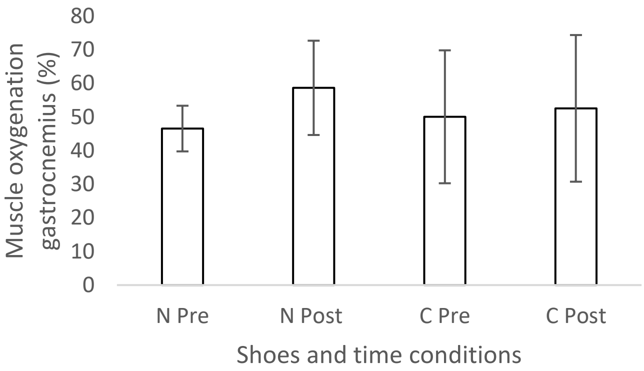

Figure 10. Muscle oxygenation of the gastrocnemius measured during a 5-minute running economy assessment in neutral (N) and carbon (C) shoes conditions pre- and post-prolonged cycling.

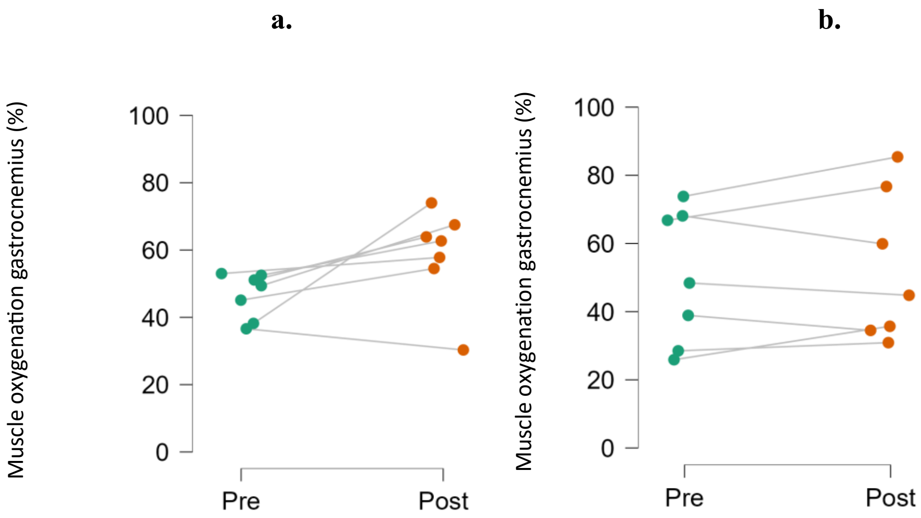

Figure 11. Individual responses of percent muscle oxygenation of the gastrocnemius during a 5-minute running economy assessment wearing neutral (a) and carbon shoes (b) pre- and post-prolonged cycling.

The %SmO_2 Q for each shoe condition is presented in Figures 12 and 13. There were no significant differences between the two shoe conditions (F=0.931, p > 0.05), before and in the fatigued state (F=3.781, p > 0.05), and no linear relationship between two different shoe conditions before and in the fatigued state (F = 0,099, p > 0.05). By comparison, %SmO_2 Q in the fatigued state (47.7% in N and 53.4% in C) in both N and C shoes was higher than before the fatigued state (40.6% in N and 47.4% in C) in general.

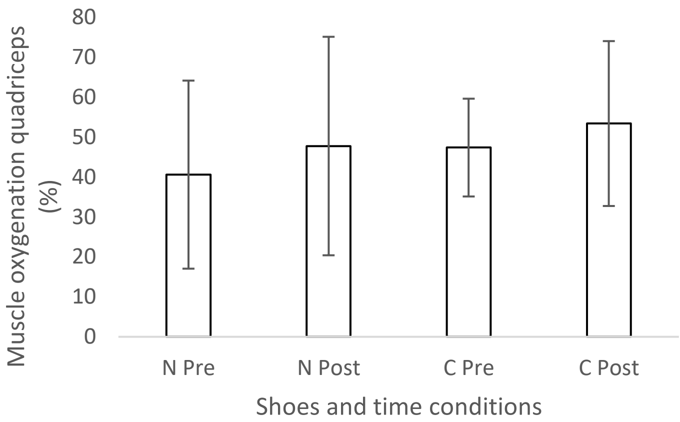

Figure 12. Muscle oxygenation of the quadriceps measured during a 5-minute running economy assessment in neutral (N) and carbon (C) shoes conditions pre- and post-prolonged cycling.

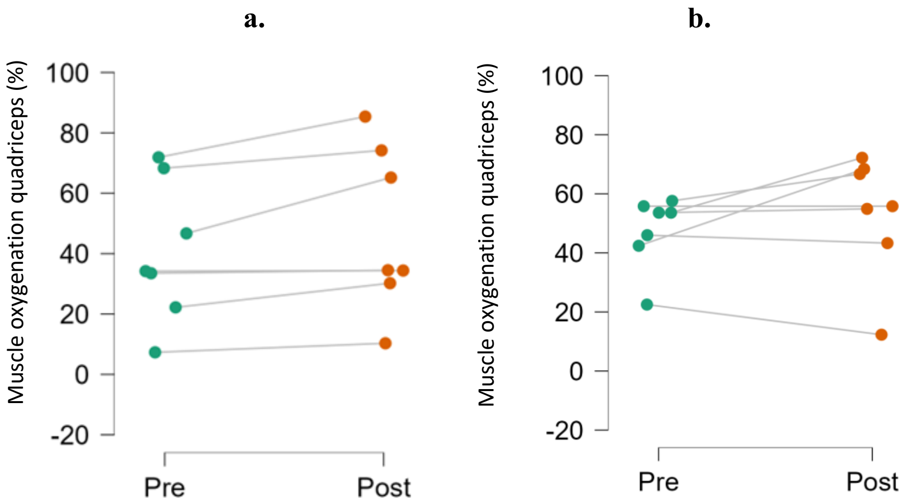

Figure 13. Individual responses of percent muscle oxygenation of the quadriceps during a 5-minute running economy assessment wearing neutral (a) and carbon shoes (b) pre- and post-prolonged cycling.

10 km time trial performance

The mean post-cycling 10km running performance time when wearing C was significantly faster than N (48.97 ±5.0 for C vs 51.56 ±5.58 min for N shoes, Δ5.03%, Table 6, p=0.02, effect size: 1.06). The mean time for 10 km wearing N and C shoes is reported in Table 6 for individual participants, with the variation in differences between shoes illustrated.

Table 6. Individual response and the change of 10km running performance time following prolonged cycling wearing neutral and carbon shoes (n=8).

Participant	Neutral shoes time for 10km (mins)	Carbon shoes time for 10km (mins)	Change in time (mins)	Change in performance (%)
1	42.37	40.62	1.75	4.13
2	55.43	48.32	7.11	12.83
3	57.67	54.08	3.59	6.23
4	50.53	47.82	2.71	5.36
5	47.65	49.71	-2.06	-4.32
6	57.20	55.73	1.47	2.57
7	50.10	46.53	3.57	7.13
8	59.06	55.02	4.04	6.84
Mean ± SD	51.56 ± 5.58	48.97 ± 5.00	2.59 ± 0.59	5.03 ± 10.52

Chapter 5 Discussion

The primary objective of this study was to determine the efficacy of C 'super shoes' in enhancing RE, %SmO_2, and running performance in triathletes. This evaluation encompassed RE assessment both during the pre-fatigue and fatigued state induced by a prolonged bout of indoor cycling, simulating the challenges faced by triathletes in competitive triathlons during the bike-to-run transition. The findings from this research suggest that while there was no shoe*time interaction, there was 1) a main positive overall effect of C 'super shoes' on RE and 2) that running performance was improved in C super shoes following prolonged cycling. Accordingly, athletes and coaches may consider the incorporation of C 'super shoes' as a technological aid to optimize triathlon running performance.

Intensity of prolonged cycling

An important aspect of the current study design was appropriately prescribing the bout of prolonged cycling, prior to RE assessments, so as to approximate the cycling demands of real half ironman triathlons. In this regard, the mean power output in the present study was consistent with that reported previously for actual half-ironman cycling in trained athletes ~241 W (Wu et al., 2015) and a similar HR. Another study by Cejuela & Sellés (2023) reported that triathlon cycling induced a similar %VT2 (78.3 to 90.3%) to ours. Irrespective of intensity, however, the intensity of the 2-hr prolonged cycling was replicated for both trials with N and C shoes to allow valid comparisons.

Running economy

The mean RE values in N shoes for the participants in the current study were consistent with those reported previously in the literature (Barnes & Kilding, 2015) indicating that RE data for this study were representative of the population. The main findings of this acute crossover study indicated that there was an overall (significant main effect) lower RE for the C shoes than the N shoes by 3.3% when expressed either relative to body mass and running speed (6.7 $mL.kg^{-1}.km^{-1}$, p=0.05) and by 4.3% when expressed relative to body mass only (1.87$ml.kg^{-1}.min^{-1}$, p<0.05; Figures 4 and 5). To our knowledge, there are no data in triathletes with which to directly compare though the magnitude of change in RE was consistent with the range reported by Rodrigo-Carranza et al. (2023) which indicated a mean improvement of RE between 2.8 and 4.2% in various calibres of runner in the non-fatigued state. The reasons behind this could be explained by previous studies, Hébert-Losier et al. (2020) and Nielsen et al. (2022) suggest the improvements for higher levels of runners had a wider range (-8.6% - 13.3%) compared to recreational and trained runners (less than 2%). One of the reasons could be the elite runners performed at a higher running speed (14-18 $km.hr^{-1}$) than the recreational and trained runners with at a speed of 10-14 $km.hr^{-1}$ (Rodrigo-Carranza et al, 2023). The study by Barnes and Kilding (2019) compared RE of three types of shoes (Nike Vaporfy, Zoom Matumbo 3 and Adidas Adizero Adios 3), and indicated there were different effects on RE among various types of shoes, even for C shoes. They showed Nike Vaporfy had the largest effect on RE compared with the other two by 2.6% and 4.2% respectively (Barnes & Kilding, 2019). In addition, another reason that could explain the improvement of C shoes on RE as the C shoes had higher stiffness than N shoes, 42% in longitudinal and 550% in three-point bending (Jarboe & Quesada, 2003). Another study showed that an increment in midsole bending stiffness related to improved RE (Hoogkamer et al., 2017), which explained the improvement of RE in C shoes compared with the C pairs.

Despite a main effect for RE, there was no shoe*time interaction (p>0.05) suggesting that the C shoes had no effect on RE, compared to N shoes, across the unfatigued (pre-cycling) and fatigued (post-cycling) states. This is a novel finding as most studies to date have compared RE in runners only in the 'fresh' state (Nielsen et al. 2022, Joubert & Jones, 2022, Hoogkamer et al., 2017, Barnes & Kilding, 2019), and little knowledge exists on how super shoes impact

RE over prolonged period during endurance exercise. A study done by Vercruyssen et al. (2016) also indicated that the relationship between RE and different footwear (minimalist vs traditional) with fatigue was specific in the level of running and results of RE varied with different shoes and also with fatigue states (fresh or fatigue). However, the significant influence of fatigue on RE will be further discussed. There are several proposed mechanisms by which super shoes could improve RE. Super shoes alter the midsole thickness and LBS to decrease energy loss at the metatarsophalangeal joint and might further enhance the peak plantarflexion moment (Fu et al., 2021). Another theory indicates that the carbon plate stiffens the metatarsophalangeal joint therefore decreasing the work rate at the ankle (Fu et al., 2021). Beck, Golyski, and Sawicki (2020) explained that increased footwear bending stiffness did not influence muscle activity of soleus active muscle volume and aerobic power when running for 10km, hence there was no significant RE enhancement. Moreover, Kiesewetter et al. (2022) pointed out that running velocity could affect the extent of differences in physiological and biomechanical parameters. This study indicated that higher running speeds, such as 75-80% of VO_{2max}, resulted in greater changes in physiological and biomechanical parameters (Kiesewetter et al., 2022). Unfortunately, the relative $\%VO_{2max}$ utilised in the present study could not be determined during RE assessments, but the absolute running speeds of between 10 and 14 $km.h^{-1}$ for the present study might be too low for carbon super shoes to be fully effective as slower running speeds would likely not challenge the stiffness properties of the shoes, potentially resulting in fewer differences in physiological variables. In support, the study by Rodrigo-Carranza et al (2023) stated that recreational and trained runners running at 10-14 $km.hr^{-1}$ had a smaller change in RE (less than 2%). The impact of speed on RE changes with C shoes needs further study across a range of speeds with actual data.

Lastly, another aspect to consider is whether running shoes delay the deterioration of RE caused by fatigue following cycling (i.e. can C super shoes ‘rescue’ a deterioration in RE) typically caused by prolonged cycling. Although there was no shoe*time interaction, the mean percent change of RE before and in the fatigued state trended to be different between shoes and varied between individuals. For example, while the mean percent individual difference of RE ($mL.kg^{-1}.km^{-1}$) between shoes unfatigued (6%) was larger than in the fatigued state (2%), between individuals it varied from -0.2% to 11.8% before fatigue and from -14.4% to 10.7% in the fatigued state. The reasons for individual variability in responses to wearing C shoes are poorly understood in the literature but factors that have been proposed to explain variability include the speed chosen for individuals were various which could influence the RE. Based on our process of data collection, it could due to physical conditions such as age, athlete calibre as not all of them were at the same level, physical status on the day of the test, or individual habitual differences such as sleep time and duration and diet.

Muscle oxygenation

There was no shoe*time interaction ($p>0.05$) for %SmO_2 G suggesting that the C shoes had no effect on %SmO2, compared to N shoes, across the unfatigued (pre-cycling) and fatigued (post-cycling) states. However, there was a main effect for %SmO_2 G. There was a statistically significant effect of *time* on %SmO_2 G which was before and after the fatigue state ($p < 0.05$) without considering shoe conditions. However, by comparing the data collected in general, %SmO_2 G in the fatigued state in both N and C shoes was 12.1% higher in N shoes, and 2.5% in C shoes, than before the fatigued state.

Similar to %SmO_2 G, although there were no significant differences between two shoe conditions of SmO_2 Q, before and in the fatigued state, and no linear relationship between two different shoe conditions before and in the fatigued state. However, by comparing the data collected in general, %SmO_2 Q in the fatigued state in both N and C shoes was 7.7% higher in N and 6% in C shoes than before the fatigued state.

In a recent investigation conducted by Kiesewetter et al. (2022), it was elucidated that physiological alterations attributed to different shoe conditions may not necessarily correlate with changes in %SmO_2. This observation was grounded in the argument that, despite shoes having a similar mass, variations in midsole bending stiffness could potentially exist. However, the potential efficacy of distinct midsole stiffness levels in improving physiological parameters remains inconclusive, as current research findings on this matter lack consistency, thus rendering it a point of contention across different studies.

It is essential to highlight that the understanding of how C shoes influence muscle oxygenation was limited in the existing body of literature. Consequently, no available data could serve as a direct comparison for the %SmO_2 levels in the gastrocnemius and quadriceps, as measured in this study when participants used C shoes. Notably, however not in a carbon super shoe context, one study by Olcina, Pérez-Sousa, Escobar-Alvarez, and Timón (2019) did address the impact of prior cycling on %SmO_2 during a 12-minute maximal running protocol. Their findings indicated an effect on %SmO_2 levels during the fatigued state, which they attributed to the accumulation of muscular fatigue induced by cycling. They elucidated that this accrued muscular fatigue potentially led to neural fatigue, resulting in the impaired utilization of circulating intramuscular oxygen and, ultimately, a shift in neuromotor patterns. More research is needed on how footwear impacts %SmO_2 during prolonged exercise, especially following different exercise modes.

Running performance

To our knowledge, there are no data on triathletes with which to directly compare the time used for 10km treadmill running with the current study. Therefore, in the context of a 10km self-paced indoor treadmill time-trial following an extended cycling bout, the utilization of C shoes in the present study led to a statistically significant increase in performance by approximately 5% (~2.6 minutes), compared to when athletes wore N shoes. Our findings are in accordance with prior research, such as that of Hoeft (2023), which demonstrated that trained distance runners experienced a 3.5-second-per-kilometer improvement (equivalent to 35 seconds in a 10km race) when using C shoes for two 30-minute time-trials. However, it is important to note that Hoeft's study involved a different sporting context (distance running) and shorter race distances than the triathlon setting of our investigation.

Other studies, such as Hébert-Losier et al. (2020) and Nielsen et al. (2022), have also reported performance improvements with C shoes in running TTs, albeit in shorter trials than the present study revealing gains of 2.4% and 1.1%, respectively. The discrepancy in performance gains may be due to the greater distance covered in our 10km trial, which is roughly twice the distance of the trials in the aforementioned studies. The findings of Hoeft (2023) where a 3.5-second-faster per-kilometre pace was noted with C shoes support the idea that longer distances may yield more substantial performance benefits. Notably, only one out of eight participants in our study exhibited a negative effect on time-trial performance when wearing C shoes. Hence, for most trained male triathletes, C shoes could enhance treadmill running performance over 10km by an average of ~5% compared to N shoes. This finding was supported by Willwacher et al. (2023) which suggested that maximum running performance enhanced in the male runners between 1.1% and 1.4% for long distance between 10,000 m and the marathon every year.

Mechanistically, the observed performance enhancement inTTs while wearing C shoes may be attributed to the increased LBS of these shoes compared to N shoes, as described by Rodrigo-Carranza et al. (2023). This enhanced stiffness appears to result in kinematic changes, including improved stride length and contact time. Cigoja et al. (2022) suggested an alternative mechanism for improvement, proposing that the delayed onset of joint work redistribution in stiff conditions might lead to reduced muscle activation and, consequently, decreased metabolic cost during running with stiff shoes. In contrast, Hoogkamer et al. (2016) posited that shoe mass had an impact on performance in a 3km time trial, with a 100g increase in shoe mass resulting in a 0.78% negative influence. However, in our study, the mass difference between the N and C shoes was only 10g, indicating that shoe mass was not the primary factor contributing to the significant reduction in 10km running time.

Moreover, another aspect that could explain why there were no significant changes for the individuals' running performance of the TT was the participants changed their running styles to the shoe conditions during the 10km running to reduce the load on the legs without effecting their performance (Kiesewetter et al., 2022). Such as their landing patterns like heel-to-toe drop might vary with the design of higher heels (6-10mm) (Lin et al., 2022). Thus, during the 10km running, there were changes in biomechanical especially the foot strike pattern instead of physiological parameters, there were no effect of shoe conditions on RE, HR or relative oxygen consumption.

Chapter 6 Practical implications, limitations, recommendations for future research and conclusions

Practical implications

Based on the findings of this study, coaches and triathletes should consider carbon-plated shoes during competition given the observed improved running performance compared with traditional running shoes and the overall main effect of C shoes on RE. However, C shoes might not be as effective when the athletes are in a fatigued state compared to the fresh state. Moreover, as there was different response of C shoes among individual participants in this research, coaches could assess if their athletes are 'responders' to C shoes or not rather than assuming a physiological and performance gain is possible. Responses to carbon super shoes could be influenced by various foot and lower limb structures and function, as well as habitual running technique such as whether an athlete is naturally a heel, mid-foot, or forefoot striker. It is acknowledged that evidence of these potential influencing factors is limited and requires further exploration.

Limitations

This study possesses certain limitations that warrant acknowledgment. Firstly, our sample exhibited a degree of heterogeneity, encompassing individuals with varying levels of athletic proficiency, ranging from recreational to trained participants. However, it is worth noting that our sample did not include highly trained or elite athletes. Consequently, the presence of this heterogeneous group, without stratification based on athletic ability, represents a potential variable in the study that could influence its specificity and outcomes.

Moreover, there were some occasional technical errors that occurred during the collection of VO_2 which affected the sample size for some comparisons. Likewise, the Moxy NIRS device for measuring $\%SmO_2$ was unable to capture data on two occasions during running trials, therefore the accuracy of $\%SmO_2$ data might be affected.

In addition, as this study was laboratory-based, running performance and RE could be different compared to real triathlon, outdoors. The differences might because of the surface of running on the treadmill was obviously not the same experience as running overground. The biomechanics of running on the treadmill versus overground are reported to be different (Zhou et al., 2021). Furthermore, although it was self-paced running in the study, the participants were still unable to change their running speed freely as they were required to verbally instruct the researchers of speed changing on the treadmill. This might affect the final performance of the TT and may result in a different performance outcome to outdoor 'free' running. Similarly, cycling on the stationary bike in the laboratory was different from cycling outdoors where there is likely to be a more stochastic power output given altitudes and geographical changes in the road courses used for triathlon. This may impact the energy consumption and the muscle recruitment which may impact on the subsequent running mechanics and could affect the performance of the ensuing RE, %SMO_2 and running performance.

Finally, in this study, there was no consideration of the perception of the prescribed footwear (comfort and athlete familiarity with the ASICS C and N shoes). Indeed, there is evidence indicating that wearing more comfortable shoes is related to improved RE than less comfortable running shoes (Van Alsenoy et al., 2021) so this is an important factor to consider, alongside the technology in the super shoes. Other brands of super shoes may offer a superior fit and experience based on the preferred fit and comfort of the athlete.

Recommendations for future research

In forthcoming investigations, augmenting the study's statistical power could be achieved by enlisting a larger participant pool. The discernible variances observed in performance and RE among individuals warrant a more extensive dataset. In the present study we were constrained by a limited dataset comprising only seven sets of data for RE comparison and eight for evaluating running performance and $\%SmO_2$. Although there were participants from various calibres from recreational to trained, a greater number of recruited participants should be included in each category. Diverse levels of athleticism can yield divergent responses to standardized protocols, possibly influenced by inherent physiological and biomechanical variations arising from varying degrees of chronic training experience. Indeed, whether super shoes are of benefit to all athlete abilities has been highlighted (Reynolds et al., 2023. Willwacher et al., 2023) and requires further research. Consequently, the variable responses of individual participants exerted a considerable influence on the results within the same sample size and this required further exploration in larger samples where standard of runner can be categorised and compared with sufficient statistical power.

The present study was conducted in a climate-controlled laboratory. While this provides a stable and consistent environment, expanding the scope of research to include field and outdoor settings, such as road running or road cycling, could be explored in future studies. Such conditions would more closely mimic the practical training and competition environments faced by triathletes, thereby offering greater ecological validity and results with greater practical applicability to improve performance in actual triathlon races.

Finally, in this study, we exclusively examined one particular type of C shoes. However, it is conceivable that the effects of C shoes from other brands and series could be explored in future research, providing valuable insights into their impact on RE and running performance.

Indeed, Joubert and Jones (2022) pointed out that distinct types of C shoes may yield varying improvements in RE, with differences ranging from 3.0% to less than 1.5%. This implies that the effectiveness of enhancing RE and performance for triathletes may not be uniform across all C shoe varieties.

Conclusions

This study revealed an overall lower RE associated with C shoes compared to N shoes, regardless of the RE expression method ($ml.kg^{-1}.min^{-1}$ or $ml.kg^{-1}.km^{-1}$). However, it is important to note that while C shoes did not significantly impact mean RE when compared to N shoes in both the unfatigued and fatigued states, there were variations between individuals in the percent change of RE before and after cycling. Despite this, the majority of participants in our study improved their 10km running performance by wearing C shoes with an average enhancement of approximately 5% compared to running in N shoes. From a practical standpoint, these findings could prove valuable for athletes and coaches, offering insights into the potential benefits of incorporating C "super shoes" as a technological aid to enhance triathlon running performance.

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Appendices

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Appendix 1. AUTEC approval letter

Auckland University of Technology Ethics Committee (AUTEC)
Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

28 September 2022
Kelly Sheerin
Faculty of Health and Environmental Sciences

Dear Kelly

Re Ethics Application: **22/244 Carbon plated running shoes: Do male triathletes reap the benefits?**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 27 September 2025.

Non-Standard Conditions of Approval

1. Include the full sentence in the Information Sheet 'whereby you will carry out a short run at either 12 or 14 km/h to ensure you are comfortable (condition 6a).
2. Removal of the offer of counselling.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: sam.keats00@gmail.com; zhufangcheng1997@gmail.com; Andrew Kilding; hannah.wyatt@aut.ac.nz; aaron.jackson@aut.ac.nz

Appendix 2. Participant information sheet.

Participant Information Sheet

Project Title: *Carbon plated running shoes: Do triathletes reap the benefit?*

Date Information Sheet Produced: *18/08/2022*

An Invitation

Kia Ora our names are Sam Keats and Fangcheng Zhu, and we are currently studying towards a Masters Degree. Along with our supervisors Dr Kelly Sheerin and Professor Andrew Kilding. We would like to invite you to participate in our research which relates to triathlon performance.

What is the purpose of this research?

Carbon plated running shoes are very popular among both professional and amateur triathletes across all distances. However, very little research exists surrounding carbon-plated running shoe use in triathlon. Furthermore, running off the bike is a very important aspect of triathlon performance that again lacks substantial research. The purpose of this research is to determine the effects of wearing carbon-plated running shoes on a triathlete's physiology, biomechanics, and performance. This study will help identify if these shoes offer benefits to triathletes.

The findings of this research may be used for academic publications and presentations.

How was I identified and why am I being invited to participate in this research?

You have responded to the advertisement about the study and have identified yourself as a male age group triathlete currently training to compete in long-distance triathlon.

Please note: Participants must be injury-free for the past three months. Participants must be currently training to complete a long-distance triathlon within a year. Participants must be male. Participants must be comfortable running on a treadmill and able to run at least 12km/h for 5 minutes. Participants must be happy running in lab-supplied shoes and not currently wearing orthotic inserts. Your US shoe size must be between 8 and 11.5.

How do I agree to participate in this research?

Once you have had the chance to learn more about the study, and have decided that you're keen to participate, we will book you in for the first session. Before you begin the first session we will ask you to sign a consent form.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

This study will take place in the physiology lab at AUT Millennium. The study involves you visiting the lab on three occasions on separate days (7 days apart).

The first visit will involve a cycling VO2peak test and treadmill familiarisation run. The VO2peak test involves cycling at a gradually increasing power output, as controlled by the ergometer. The test starts easy and progressively gets harder each stage until you can no longer continue (i.e. it is a maximal test). During the test you will be asked to wear a face mask/snorkel so that we can measure your expired gases (Figure 1, middle). The result from the VO2peak test will be used to determine your cycling intensity for the following visits

The second and third visits will consist of identical run-bike-run trials wearing either the control (Asics Evoride) or carbon shoe (Asics Metaspeed Sky). First, a 5-minute assessment of running mechanics at 12 or 14 km/h will take place before a two-hour cycle at 85% of the second ventilatory threshold power (determined from Visit 1). You will be required to bring in your own tt/tri bike so we can attach it to our Wahoo Kickr. Immediately following the cycle another short running assessment will be performed (5 min at 12 or 14km/h) before rolling into a 10km self-paced time trial (TT). The treadmill speed will be controlled by the researcher, with you providing visual and auditory cues to increase or decrease the speed. The bike-run transition time (change of footwear) will be standardized to two minutes to replicate real-world scenarios. During the running TT, all participants will run on an indoor treadmill (Cosmos Saturn). We will ask you to record your pre-trial diet (24hr pre) so that it can be replicated for each trial. Please refrain from physical activity for 24 hours prior to your visits to the labs (i.e., arrive at the lab well-fuelled, hydrated, and rested).

A multitude of equipment will be used to gather information during the trials. Plantiga sensors are small inertial sensors that will sit in the insert of your shoe (figure 1 below, left) and will be used to continuously measure running biomechanics. Due to the small size of the sensors, they should not be noticeable when wearing and will not affect your gait. Oxygen uptake will be measured using a Parvo TrueOne metabolic cart (figure 1 below, middle) for the entirety of the VO2peak test, and at 15-minute intervals during the cycling portion of the trials, as well as during the 5 min bouts of running so we can assess you running economy. A MOXY monitor (figure 1 below, right) is a small non-invasive sensor that will continuously measure muscle oxygen saturation and will be attached to your leg during all trials. Heart rate will be measured continuously using a standard chest strap.

Note: it is expected that you will be able to hold a tt position for the majority of the two hours as you would in a race scenario.

Figure 1 (from left to right): Plantiga shoe inserts, Parvo TrueOne metabolic cart, and Moxy Monitor.

What are the discomforts and risks?

It is not anticipated that you will experience discomfort that would be greater than that occurring during your normal training and racing. You may experience muscle soreness following the run-bike-run trials. However, this is not expected to affect any of your training. You will be exposed to a small amount of physical risk of injury, as you will be performing some high-intensity running on a treadmill. However, these risks are minimal, and the tests have been specifically designed and tested for your safety and to reduce the chance of injury.

Note: All equipment that is either touched by, or attached to, participants will either be disposed of or cleaned with a medical-grade cleaning disinfecting product.

How will these discomforts and risks be alleviated?

If you experience discomfort at any stage you are encouraged to inform the researcher at the time in order that they can best address the problem. If you have any questions regarding any risk or comfort that you anticipate, please feel free to address these concerns to the researcher so that you feel comfortable at all times throughout the process.

AUT Student Counselling and Mental Health is able to offer three free sessions of confidential counselling support for adult participants in an AUT research project. These sessions are only available for issues that have arisen directly as a result of participation in the research and are not for other general counselling needs. To access these services, you will need to:

- drop into our centre at WB203 City Campus, email counselling@aut.ac.nz or call 921 9998.
- let the receptionist know that you are a research participant, and provide the title of my research and my name and contact details as given in this Information Sheet.

You can find out more information about AUT counsellors and counselling on https://www.aut.ac.nz/student-life/student-support/counselling-and-mental-health

What are the benefits?

Your participation in this study will provide you with valuable insight into the impact of cycling on subsequent running performance for long-distance triathletes as well as learning how you were affected by the use of carbon-plated shoes. The findings of this proposed research will be valuable for coaches, athletes, and researchers.

Additionally, your participation in this study aids in the researcher's work towards a master's degree.

What compensation is available for injury or negligence?

In the unlikely event of a physical injury as a result of your participation in this study, rehabilitation and compensation for injury by accident may be available from the Accident Compensation Corporation, providing the incident details satisfy the requirements of the law and the Corporation's regulations.

How will my privacy be protected?

The only people who will have access to any of the data collected will be myself, Fangcheng, our supervisors Dr Kelly Sheerin, Professor Andrew Kilding, and co-investigators Mr Aaron Jackson, and Dr Hannah Wyatt. If any of your data are published you will be anonymous. Your name will be coded so that all of your data will be stored under the code name. Your privacy and anonymity will be of primary concern when handling the data.

All data will be stored on password-protected computers or in locked files. Following completion of data analysis, your de-identified data will be stored in the AUT ethics storage room for up to six years.

What are the costs of participating in this research?

There are no monetary costs associated with participating in this research, the only cost being your time. It is anticipated that the first session will last approximately two hours, and the subsequent sessions will last approximately four hours (dictated by your 10km TT).

What opportunity do I have to consider this invitation?

We would appreciate it if you could let us know within four weeks whether you would be available to take part in the study or not.

Will I receive feedback on the results of this research?

We are more than happy to provide you with a summary of your individual findings through email once the analysis is complete.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor, *Dr Kelly Sheerin and Professor Andrew Kilding.*

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, *ethics@aut.ac.nz* , (+649) 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Sam Keats
Masters Student
Auckland University of Technology
vfx7069@autuni.ac.nz

Fangcheng Zhu
Masters Student
Auckland University of Technology
mzp7084@autuni.ac.nz

Project Supervisor Contact Details:

Dr Kelly Sheerin
Sport Performance Research Institute New Zealand,
Auckland University of Technology,
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kelly.sheerin@aut.ac.nz

Professor Andrew Kilding
Sport Performance Research Institute New Zealand,
Auckland University of Technology,
andrew.kilding@aut.ac.nz

Approved by the Auckland University of Technology Ethics Committee on *28.09.22*, AUTEC Reference number *22/244*.

Appendix 3. Study advertisement.

Appendix 4. Consent form.

Consent Form

Project title: Carbon plated running shoes: Do male triathletes reap the benefits?

Project Supervisors: Dr Kelly Sheerin and Professor Andrew Kilding

Researchers: Mr Sam Keats and Miss Fangcheng Zhu

- I have read and understood the information provided about this research project in the Information Sheet dated 28.09.22.
- I have had an opportunity to ask questions and to have them answered.
- I understand that I may withdraw myself or any information that I have provided for this project at any time prior to the completion of data collection, without being disadvantaged in any way.
- I understand my data will be stored securely for a period of 6 years.
- I am not currently suffering from any lower limb injuries, and have been injury free for the last 3 months. I have declared any recent respiratory illness (e.g. flu or Covid-19) to the researchers.
- I understand that if I withdraw from the study then I will be offered the choice between having any and all data belonging to me removed, or allowing it to continue to be used. I also understand that sometimes, if the results of the research have been written, some information about me may not be able to be removed.
- I confirm that I am not currently taught or supervised by a member of the supervisory team.
- I consent to have my name, contact details and demographic details held on file by the primary researcher (for 10 years) for the purposes of being contacted in the future with information on relevant future studies (please tick one): Yes ○ No ○
- I agree to take part in this research
- I wish to receive a summary of my individual study results (please tick one): Yes ○ No ○
  I wish to receive a summary of the overall research findings (please tick one): Yes ○ No ○

Participant signature: ....

Participant name: ....

Participant Contact Details (if appropriate):

Date: ....

Approved by the Auckland University of Technology Ethics Committee on *28.09.22*, AUTEC Reference number *22/244*.

Note: The Participant should retain a copy of this form.

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