Super-Shoes: Do Male Triathletes Reap the Benefits?

A Dissertation submitted in partial fulfilment

of the requirements for the degree of

Master of Sport, Exercise and Health (MSEH)

at

Auckland University of Technology

by

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2023

School of Sport and Recreation

Abstract

Background: Running performance is the greatest contributor to overall race time in long-distance triathlon. Therefore, triathletes are constantly on the search for strategies to enhance their running performance, and recent advances in running footwear ('super shoes') appear to offer a potential solution. There is evidence from studies of runners to support a positive impact of super shoes on performance, but there is no evidence to suggest that these improvements necessarily carry over to long-distance triathletes, where their effect could be moderated by the preceding cycle. Additionally, much of the running-related evidence is related to elite-level athletes, and there is a need to examine the effects of super shoes in age-group (non-elite) athletes.

Objective: The broad aim of this study is to determine if male age-group triathletes reap the benefits of super shoes, with the specific research question being: Do carbon-plated running shoes improve running performance and performance-related kinematic variables in a simulated cycle-run transition in age-group long-distance triathletes?

Methods: Eight male age-group long-distance triathletes visited the laboratory on three occasions in an acute randomised balanced crossover design. The first session served as a characterisation trial, which involved a maximal incremental cycling assessment. Sessions two and three were experimental trials, consisting of an initial treadmill running economy assessment, a two-hour fatiguing cycle on a stationary bike, a post-fatigue running economy assessment, and finishing with a 10km treadmill time-trial in either a super shoe (Asics Metaspeed Sky) or a control traditional racing shoe (Asics Evoride 3). Running economy and biomechanical variables were recorded during both running economy assessments.

Results: Time-trial performance was significantly better in the super shoe compared to the control shoe (p=0.002). Mean ground contact time (p=0.001, η_p^2 = 0.793) and running economy (p=0.034, η_p^2 =0.554) were significantly different between shoe conditions when averaged across the pre- and post-fatiguing cycle. The fatiguing cycle significantly differed in mean cadence (0.011, η_p^2 =0.630), flight time (p=0.006, η_p^2 =0.677), and stride length (p=0.012, η_p^2 =0.621).

Conclusion: Super shoes improve running performance and influence biomechanical variables of running performance in male age-group long-distance triathletes.

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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 (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Samuel Keats
June 2023

Acknowledgements

I would like to take the time to express my sincerest gratitude towards the following people who have, in one way or another, aided in the completion of this dissertation. This would not have been possible without you.

To Dr Kelly Sheerin, my primary supervisor. Your guidance and wealth of knowledge has taught me so much through this journey. I truly appreciate the time and effort you spent to help me produce a dissertation I can be proud of.

To Associate Professor Andy Kilding, my secondary supervisor. I greatly appreciate the time of day you gave me, and my half thought out ideas, throughout this journey and particularly the guidance which developed them into the dissertation presented below.

To Asics and Brittain Wynyard & Co NZ for kindly supplying the shoes used in this dissertation. Without your help this would have been an incredibly expensive venture which would have likely interfered with the integrity of the study.

To Movement Solutions NZ and Motus Plus for supplying the Plantiga innersole used for the collection and analysis of biomechanical data. Not only was using such equipment a great learning opportunity, but it also proved invaluable in the man hours it saved me from reviewing footage. Its ease of use and reliable metrics made data collection a breeze.

To Dr Matt Cross for your guidance in data analysis and Fangcheng Zhu for your help during data collection.

To all the participants who gave up their time and subjected themselves to our demanding protocols, all in the name of science. I pray that these conclusions can benefit you directly.

And finally, to my parents, whose love, support, and encouragement made not only this dissertation, but also my passion for triathlon, possible.

Ethics Approval

Ethical approval for this research was granted by the Auckland University of Technology.

Ethics Committee (AUTEC) on the 27th September 2022 for a period of three years.

22/244 - Carbon plated running shoes: Do male triathletes reap the benefits?

Chapter 1: Rationale

Purpose of the dissertation

Super shoes as we know them today consist of lower mass, larger stack height, advanced midsole foam, greater longitudinal bending stiffness, and greater curvature of the forefoot sole profile (Figure 1) compared to traditional racing shoes. Nike launched the first super shoe in 2017 with the Nike Vaporfly 4% and since then every world record from 5km to the marathon has been broken by super shoe wearing athletes(1). Research has also consistently confirmed that super shoes offer a performance benefit to runners when compared to traditional racing shoes (Table 2).

Triathlon was invented by the San Diego Track Club in the early 1970s as an alternative training method to running on the track(2). The sport evolved quickly and made its Olympic debut during the Sydney Games in 2000 and has remained part of the Olympic programme ever since. The distances raced at the Olympics include a 1.5km swim, 40km cycle, and 10km run. However, this thesis will concentrate on long-distance triathlon, which was invented in 1978, and constitutes a 3.8km swim, 180km cycle, and 42.2km run. As running performance is the greatest predictor of overall triathlon performance(3) there is much research into how prior cycling can negatively impact running performance (Table 1). Even though the evidence is conflicting, it is generally accepted that cycling does have a negative effect on running economy, with the conflicting findings likely a result of differing methods.

The current literature surrounding super shoes focuses primarily on elite level runners and collects data when those runners are unfatigued (Table 2). This literature base is not relevant to age-group (non-elite) athletes who do not have the same physiological and biomechanical capabilities as elites(4). The few studies that use age group populations do share comparable findings, however they too are investigating unfatigued athletes (Table 2). Only one study exists that investigates the benefit of super shoes under fatigue, reporting as little as 30 minutes of running enough to reduce the performance benefit of super shoes from 3.7% to 2.5%(5). During a long distance triathlon, age-group triathletes on average spend 79 minutes swimming, 379 minutes cycling before beginning a marathon lasting 294 minutes[6]. Therefore, it is impossible to assume that the current literature surrounding super shoes is relevant to this population.

Furthermore, it is accepted that prior cycling negatively impacts running performance, yet the current literature is again not applicable to age-group long-distance triathletes. Studies investigating this phenomenon base their protocols around Olympic distance triathlon whose demands differ significantly to that of long-distance triathlon (Table 1). Similarly to that of super shoe literature, the majority of research is carried out on elite populations (Table 1). Consequently, it is unknown how prior cycling influences running performance in age-group long-distance triathletes.

Based on the current literature it is impossible to say with certainty that super shoes positively influence the run portion of a long-distance triathlon in age-group populations. Therefore, the aim of this investigation is to answer the following questions:

1. Do carbon-plated running shoes improve running performance in a simulated bike-run transition in age group long-distance triathletes?
2. Do carbon-plated running shoes improve performance-related kinematic variables in a simulated bike-run transition in age group long-distance triathletes?

To the best of the authors knowledge this is the first study to perform such an investigation.

Structure of the dissertation

This dissertation is presented in accordance with Auckland University of Technology's Format One structure. This format contains chapters for the rationale, literature review, methods, results and discussion and conclusion. Chapter one provides rationale for the investigation. Chapter two is a review of the current knowledge of endurance running, running following cycling, and the influence of super shoes on running performance and biomechanics. Chapter three contains the methods utilised in this study to investigate the effect of super shoes on running performance and performance-related kinematic variables in a simulated cycle-run transition in age group long-distance triathletes. Chapter four presents the results of the study and chapter five is a discussion of the key findings, including limitations of the study and practical applications and recommendations. A reference list is included for the entirety of the dissertation and follows Vancouver standards.

Chapter 2: Literature review

Introduction to Triathlon

Long-distance triathlon began in 1978 when John and Judy Collins led 15 competitors to the inaugural IRONMAN triathlon on the 'big island' of Kailua-Kona, Hawaii(7). Since then, IRONMAN triathlon has expanded to include over 150 races across 50 countries. Countless other long-distance triathlon races exist with the likes of Challenge Family hosting over 30 long-distance triathlons around the globe every year. Whilst those who pioneered long-distance triathlon back in 1978 might have been looked at as crazy, today this sport is embraced by thousands worldwide(7). With such a notable rise in worldwide popularity, it is no surprise that there has been an increased interest in optimising training and performance.

Although a triathlon denotes an event with a swim followed by a cycle and a run, there are many different distances ranging from super sprint (0.5km swim, 10km cycle, 2.5km run) to IRONMAN (3.8km swim, 180km cycle, 42.2km run). Rather intuitively, the different distances place different physiological and biomechanical demands on the body. For the purposes of this thesis, long-distance triathlon will refer to the half-IRONMAN distance and above and will be referred to simply as 'triathlon'.

Performing the three triathlon distances separately leads to different outcomes than when performed sequentially(3). Most triathletes report a feeling of awkwardness and loss of coordination when running after cycling(8), with some likening the cycle to run transition to having legs like jelly(9). It has been suggested that the cycle-run transition is one of the critical elements for success in triathlon, especially in short-distance races(10, 11). However, within long-distance triathlon the cycle-run transition is less important given that any time lost can be made up during the comparatively longer run leg. Therefore, performance, and subsequently success, depends predominantly on a triathlete's ability to run at maximum efficiency, with minimum negative influence on physiological and biomechanical components, from a preceding cycle(12).

Key determinants of endurance running

Running performance is the greatest contributor to overall performance in triathlon[13, 14], and therefore understanding the nuances of long-distance running performance is a priority for ultimate success. It has been suggested that success in marathon running depends on athletes' ability to maintain physiological and biomechanical efficiency while resisting fatigue. Elite running is reliant on skill and precise timing in which all movements have purpose and function[15]. Extensive research exists investigating the skill of runners in a non-fatigued state[16-21], but understanding how fatigue influences key parameters of performance may give greater insight into performance capabilities. It has been reported that ultra endurance running performance is limited by alterations in physiological, neuromuscular, biomechanical, and cognitive features[22]. However, the effect of fatigue within long-distance triathlon has yet to be critically evaluated[23].

In general, higher performing runners have less vertical oscillation of their centre of mass (COM), longer strides, greater hip flexion in swing, proportionally less time in the stance phase, and less change in velocity during ground contact compared to lower-performing counterparts[4]. Researchers suggest that decrements in running economy following fatiguing exercise are likely a result of physiological factors, such as increase in core temperature, ventilation, and blood lactate concentration[15]. Conflicting evidence exists where biomechanical variables make up a substantial portion of the variance in maximal oxygen consumption during running[4]. A major source of energy use in running is the vertical oscillation of the COM with each gait cycle[24]. An increase in this vertical motion of the COM, indicates a lowered efficiency in running gait and a suboptimal running technique. The specifics of the fatiguing protocol will impact the extent to which performance variables are altered. It has been proposed that short-duration high-intensity activities mainly lead to peripheral fatigue, such as failure of the excitation-contraction coupling[25], whereas longer-duration activities, especially prolonged running, can lead to central fatigue, such as reduced neuromuscular activation[26], in addition to structural and metabolic changes.

Greater leg stiffness is associated with reduced ground contact times and decreased vertical oscillation of the COM[27]. The calf muscle complex performs an important role in regulating lower limb stiffness to allow the body to tolerate and absorb high impact during the early braking phase[17, 28]. A reduction in neuromuscular capacity due to central fatigue with prolonged running negatively impacts lower limb stiffness, and subsequently the activation of the stretch-shortening cycle[29, 30]. Small-to-moderate reductions in leg stiffness with fatigue during running have been reported in a comprehensive meta-analysis[31]. Both non-exhaustive and fixed speed protocols indicate leg stiffness significantly reduces over the duration of a run. As runners enter the later stages of a run, reductions in leg stiffness may be associated with increased metabolic cost[32]. Acute fatigue leads to a lowered pre-activation of the calf muscles, which in turn compromises the ability of the musculoskeletal system to absorb the energy from impact, sustain impact loads, and return stored elastic energy in a coordinated manner during propulsion[33]. Increases in contact time, in association with muscle fatigue, indicate the push-off force is distributed over a longer duration, with a decrease in the max ground reaction force[30]. It seems that most of the biomechanical changes to running due to the onset of fatigue may be linked to the reduced effectiveness of the stretch-shortening cycle[34-37].

When analysing runners throughout a near-maximal 10km run, Willwacher and colleagues[38] reported that most runners demonstrated more pronounced hip adduction, ankle eversion, knee valgus and internal rotation during the last kilometre compared to the first. Changes in non-sagittal plane kinematics were observed for most, but not all variables as a linear function of running distance. The exceptions included hip adduction and rearfoot eversion angles, which showed a more rapid increase within the first two kilometres compared to the rest of the run. It is clear that fatigue plays a vital role in the performance decrements seen during endurance running by way of biomechanical changes[30-33]. However, the characteristics of an economical runner may not be related to any one specific variable, but instead result from an overall combined effect from many variables adopted during the optimisation process to best suit their own anatomical and physiological constraints[4]. Based on this, it would be unwise to assume that all runners fatigue in the same way and it is likely a more individualised process.

Key physiological determinants of Triathlon

Running economy (RE) is the energy cost for a given distance (or velocity), and is most commonly expressed as the rate of oxygen consumption (ml.kg.$^{-1}$min^{-1})[39]. It is assumed that a lower energetic cost, or better economy, allows an athlete to run faster over a given distance or run longer at a given velocity[39]. Consequently, RE is commonly used in research investigating the influence of a prior cycle on running performance, either as the main variable or as baseline measure to which exploratory variables are compared. Many studies have reported that RE is negatively affected by prior cycling [13, 39-44] with others reporting no differences[45, 46] (Table 1). Even with the conflicting evidence, it is generally accepted that cycling does have a negative effect on RE, with the conflicting findings likely a result of differing methods. Those studying elite-level triathletes, or whose intervention does not replicate the fatiguing nature of racing, fail to report changes to RE. RE reductions of 1.6-16.9% have been observed across a range of studies[39].

Table 1: Changes in running economy following cycling.

Reference	Participants	VO_{2max} (ml.kg.$^{-1}$min^{-1})	Cycling Protocol	Change in Running Economy
Du Plessis, et al.[39]	n=17	56 ±7	60-min variable intensity @ 61% MAP.	1.9 ±1.3% higher VO_2. (p=0.002)
Berry, et al.[40]	n=7	67 ±6	30km @ 98% of VT.	-1.4km/h to meet VT. (p<0.05)
Bonacci, et al.[13]	n=17	63 ±7	5 intervals of 2-10 min.	No change. (p=>0.05)
Bonacci, et al.[41]	n=18	63 ±7	5 intervals of 2-10 min.	5 impaired. 8 no change. 5 improved.
Etxebarria, et al.[42]	n=9	63 ±4	60-min constant power profile or 60-min variable power profile equivalent to 65% MAP.	Unclear differences.
Millet, et al.[43]	n=8 E (1 M/7 F) n=18 S (14 M/4 F)	E = 74 & 58 ±5 S = 71 ±5 & 59 ±1	70W start increasing 70W/3min until 280W then 35W/2min.	E = -3.7 ±4.8% S = -2.3 ±4.6% (p=<0.01)
Olcina, et al.[44]	n=10	N/A	20 min at 3.4 ±0.4W/kg.	195m less over 12 min. (p=0.00)
Bonacci, et al.[45]	n=7	N/A	20 min low intensity with varying cadence. 50 min high intensity with max effort intervals.	Low intensity: -0.4 ±2.2% High intensity: -0.1 ±2.4%
Note: ml.kg.$^{-1}$min^{-1}= millilitres/kilograms/minute, Min= minutes, MAP= maximal aerobic power, VT= ventilatory threshold, W= watts, E = elite, S = semi-professional, M = male, F = female, N/A= not available.				

Key biomechanical determinants of running after cycling

The effect that cycling has on stride length and stride frequency varies and is heavily influenced by the research protocols[44, 47, 48] (Table 1). Olinca and colleagues[44] found that a 20-minute high-intensity cycle resulted in a decrease in stride length of 0.1m, but no change in stride frequency in 10 triathletes. Contrasting this, it has been reported that 30-minutes of high-intensity cycling was associated with adverse effects on both stride length and frequency[48]. In all cases, any changes initially observed in stride length and frequency eventually returned to baseline values through the course of the run, indicating that any effects of cycling may be transient[44, 47, 48]. A supplementary observation is that these effects on biomechanics are more common in age-group (non-elite) triathletes[44]. It is likely that the continual lengthening of stride length beyond control run values as observed by Gottschall and Palmer[48] is due to overall fatigue and not caused by the cycle intervention.

The protocols and participant samples used when investigating sagittal plane joint kinematics are likely to be the cause of inconclusive findings. Following cycling, hip flexion has been found to increase during the stance phase, while hip extension decreases during toe-off[13, 49-51]. Although overall race time is preserved when investigating elite triathletes, it is hypothesised that these alterations of hip kinematics would hinder performance when extrapolated to age-group triathletes due to their reduced muscular capacity[45]. Research suggests the angle of the ankle at foot contact to be an important factor in predicting changes in RE after cycling, with 67% of the variance in oxygen consumption being explained by this variable[13]. A more dorsiflexed ankle is associated with overstriding, which occurs when initial contact is made in front of the athlete's COM. Overstriding can cause an increase in braking forces, which in turn can increase the metabolic cost and injury risk during running[15, 52, 53]. Another factor that impacts changes in RE following cycling is the reduction in function of the stretch-shortening cycle (SSC) of the lower extremity, especially the Achilles tendon. When split into groups of those who present a decrease in SSC function following cycling and those who do not, those with a decrease in SSC function had an increase in oxygen uptake and ventilation following 10 minutes of cycling (90% ventilatory threshold) compared to those whose SSC function remained unchanged. However, SSC function returned to baseline (isolated run) levels after 13-15 minutes[29]. SSC function has been found to be positively related to long-distance running performance[54].

Super shoe characteristics.

Running shoe technology has advanced dramatically in the last five to ten years, and the most advanced high-performance shoes are currently referred to as 'super shoes'. While there are many components and characteristics that make up these shoes, the presence of a carbon plate within the midsole is typically a key feature. Herbert-Losier and Pamment[55] propose five key characteristics that define super shoes, and differentiate them from traditional racing shoes. These features are low mass, larger stack height, advanced midsole foam, greater longitudinal bending stiffness, and greater curvature of the forefoot sole profile (Figure 1). The final four of these features act together to create what is described as the 'teeter-totter' effect[55].

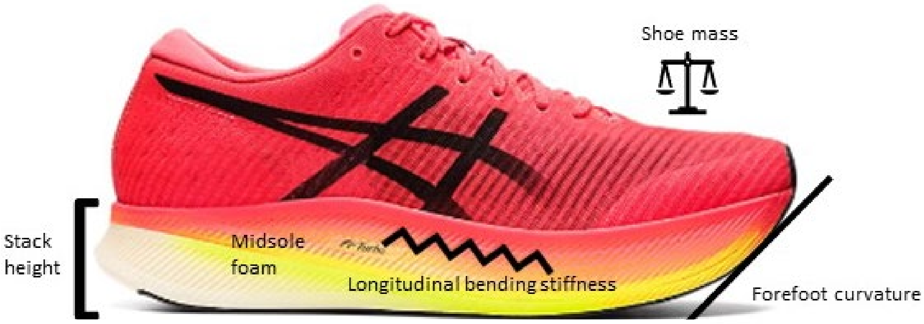


Figure 1: Super shoe features

The enhanced midsole foam is lighter, as well as more resilient and more compliant compared to traditional ethylene-vinyl acetate (EVA) foams[21, 56]. It has previously been demonstrated that for every 100g added to shoes the energetic cost of running increases by 0.9-1.2%[19, 57], it would therefore not be possible to achieve the added thickness, and therefore stack height, without advancements in midsole material technology. Recently developed foams have also been shown to return up to 87% of the mechanical energy stored during stance compared to the 66% of traditional EVA foams[56]. As well as mechanical advantages, the greater stack height found in super shoes effectively increases the leg length of runners, over and above that of traditional running shoes, subsequently increasing stride length and improving RE[18, 56, 58].

The influence of super shoes on biomechanics

As previously noted, the inclusion of a carbon plate is an integral feature of super shoes. The plate has the effect of increasing the longitudinal bending stiffness (LBS) of the whole shoe, which is thought to reduce the loss of mechanical energy, particularly at the metatarsal-phalangeal joint[59, 60]. This serves to decrease the metabolic energy required to generate the muscular force needed to run at a given velocity[61]. Ortega et al.[62] suggested that the carbon fibre plate does not act so much as a spring as previously thought in light of carbon plates only returning a third of the stored mechanical energy, and only contributing 0.3% of the positive work done at the ankle[59]. Instead, it is hypothesised that the main function of the carbon plate is to stiffen the metatarsal-phalangeal joint (MTP). A stiffer MTP slows dorsiflexion angular velocity[59, 60] and reduces MTP dorsiflexion[59, 60, 63, 64] which works to improve energy return and thus running performance. Cigoja and colleagues[65] demonstrated that increased stiffness resulted in an earlier onset of MTP plantarflexion. As such, a reduction in the negative power phase allows more time for positive power to be generated. It is important to note that plate curvature and location influences its relationship with the MTP[62, 66].

Curved plates result in the greatest saving of mechanical energy with flat plates increasing negative power amplitude[66]. Flores and colleagues[67] found a bottom-loaded plate resulted in higher moments at the MTP, ankle, knee, and hip as compared to a top-loaded plate. Interestingly, plate location only affected the positive work performed at the knee, suggesting a reduction in joint angular velocities elsewhere. Two possible mechanisms help explain these findings. First, a flat plate moves the point of ground reaction force application more distally, creating a larger moment arm, and increasing the plantarflexion moment. In comparison, a curved plate allows for the ground reaction force to be applied closer to the MTP joint, reducing dorsiflexion moment while still limiting dorsiflexion angular velocity. A second mechanism is that a curved plate allows the plate to be located further from the MTP joint. Therefore, when plates have the same stiffness, a curved plate has a higher effective stiffness since it acts further from the point of rotation, creating a larger resultant moment[62].

The calf muscle is estimated to consume between 22-32% of the total whole-body metabolic energy[68]. Theoretically, the metabolic effect of increased longitudinal bending stiffness on the calf muscle-tendon unit appears to be an interplay of two phenomena: 1) Increased bending stiffness likely increases the external moment arm of the ground reaction force around the ankle joint, which likely increases the ankle joint moment and the force demand (increasing metabolic demand). 2) The increased external ankle moment arm also likely reduces the ankle angular velocity and the muscle fascicle shortening velocity (reducing metabolic demand). If a change in longitudinal bending stiffness can induce a reduction in calf muscle metabolic energy consumption, it will likely result in a reduced whole-body metabolic energy consumption and thus better RE(62).

During prolonged running, positive work contribution shifts from the ankle towards the knee(69, 70), possibly explaining deteriorations in RE observed during prolonged running(71). Increased LBS has been shown to delay the onset of joint work redistribution from the ankle to the knee joint(70). The delay in joint work redistribution could be in part attributed to the altered gearing ratio and ankle joint moment. Gearing ratio is the ratio of the moment arm of the external ground reaction force to the internal muscle–tendon unit moment arm(72). The ground reaction force moves considerably during ground contact, whereas the muscle–tendon unit moment arm undergoes much less change during ground contact, implying variable gearing (73). Increasing LBS will shift the point of force application more anteriorly, increasing a runner's gear ratio(64, 72, 74).

Running in shoes with greater LBS increases ground contact time (GCT)(21, 64, 65, 72, 75, 76). This greater GCT is likely due to reduced ankle plantarflexion velocity which in turn induces slower calf muscle-tendon unit contraction(62). Slower muscle contractions are more force efficient and reduce a muscle's metabolic energy consumption(77). This phenomenon was shown when a subset of runners who enhanced their RE when running in shoes with greater LBS demonstrated reduced angular velocity of the ankle joint whereas runners whose RE worsened had no change in ankle angular velocity(63). Shoes with added LBS have failed to find a difference in soleus muscle operating length, contraction velocity, pennation angle, force, or activation while running(75). The lack of findings could be due to their carbon fibre plates being added as insoles to Adidas Adios BOOST 2 and not embedded into the foam of the midsole. Alternatively, tricep surae strength may have influenced results. Two strategies have been identified by which runners adapt when wearing shoes with greater LBS. Either ankle joint moment increases and GCT remains constant or does not increase joint moment but increases push-off time[62]. This individual difference may reflect triceps surae strength capabilities, with subjects increasing ground contact time instead of increasing ankle joint moment lacking strength[62].

Whilst there is plenty of literature investigating LBS effects on foot and ankle kinematics, less exists focusing on the knee and hip joints. Studies have shown reduced lever arms at the knee during push-off[72], decreased positive work at the knee[65], and no change in knee power[59]. The difference in findings between the studies investigating knee power could be due to the shoe stiffness used. Specific stiffness ranges from twice as stiff[59] to ten times stiffer[65] than the control shoe. The limited literature suggests that increasing LBS can redistribute positive lower joint work from the knee to the MTP joint[62]. No differences in knee angle[59, 63, 75], angular velocity[59, 63], moment[59, 74, 75, 78], negative work[59, 65, 78], or power[74] have been found. Only one study has reported changes with increased LBS at the hip joint[72], specifically, hip moment arm increased. Others have found no difference in angle[59, 75], angular velocity[59], moment[59, 74, 75, 78], work[59, 78], or power[74]. Overall, these results suggest that longitudinal bending stiffness primarily affects MTP and ankle mechanics, with small, if any, effect on the knee and hip joints.

The influence of super shoes on running performance

Super shoes made quite an impact when Nike launched the Vaporfly 4% in 2017, with claims of 4% energetic savings when compared to standard running shoes[21]. Always on the lookout for technological performance gains, professional athletes have become frequent users of super shoes. As the popularity of super shoes has increased, and they've become more widely available, age group athletes have followed in the footsteps of the professionals. Whilst there is proven benefit for runners at a range of performance levels[55, 79], the ability of these shoes to hold up to the demands of long-distance triathlon is yet to be fully documented. To date, there have been 10 studies that have directly compared super shoes to traditional running shoes, from either a physiological or biomechanical perspective, in runners (see Table 2).

Table 2: Running physiological, biomechanical, and performance changes with super shoes

Reference	Participant details	Shoe condition	Running assessment details	Key results
Barnes, et al.[16]	12 M 5km >15min 12 F 5km >17.15min	NVF, ADI, NVF+ Randomised crossover	M: 5 min @ 14, 16, 18km/h F: 14, 15, 16km/h	Phys: 4.2% (p=<0.008) and 2.9% (p=<0.001) improvements in RE for both NVF and NVF+ compared to ADI, respectively. Trivial-small differences between sexes (ES=0.11-0.38). Bio: NVF vs ADI, M: 0.7% stride length increase (p=0.54), 0.2-0.9% longer GCT (p=>0.17), no change in stride rate (p=>0.57). F: Stride rate 1-1.7% slower (p=<0.08), 1% stride length decrease (p=0.1), 1.8% longer GCT (p=<0.05).
Hebert-Losier, et al.[80]	18 M VO_2Max 55.8 ±4.4 $ml.kg.^{-1}min^{-1}$ 5km 21:18.61 ± 1:58.22	NVF, FLAT, OWN Randomised crossover	3 min @ 60, 70, 80% VO_2max 3km TT	Phys: Improvements in RE comparing NVF to OWN (4.3-4.4%, p=<0.002) but not NVF to FLAT (1-1.7%, p=0.292). TT performance enhancements in NVF vs. OWN (2.4%) and FLAT (1.8%).
Hebert-Losier, et al.[81]	16 M VO_2Max 55.2 ±4.3$ml.kg.^{-1}min^{-1}$ 5km 20-25mins	NVF, FLAT, OWN Randomised crossover	3 × 3-min @ 60%, 70%, 80% $\dot{V}O_2$peak	Bio: NVF involved longer flight times across intensities (6.7-10 ms). Longer step lengths at 80% (2.2-4.2 cm). Longer contact times vs OWN across intensities (6.7-10ms).
Hoogkamer, et al.[21]	18 M 10km >31min	NVF, ABI, NZS Randomised crossover	6 x 5 min @ 14, 16, 18km/h	Phys: 4.15% and 4.01% (p=<0.001) improvements in RE in the NVF compared to NS and ABI.
Hoogkamer, et al.[59]	10 M 10km >35min	NVF, ABI, NZS Randomised crossover	5 min @ 16km/h	Bio: Step frequency was slower (0.05 steps/s to NZS, 0.04 to ABI p=<0.001), step length was longer (1.7%), GCT was unchanged, and flight time was longer (0.004 ms to NZS, 0.005ms to ABI, p=0.009)

Table 2: Running physiological, biomechanical, and performance changes with super shoes (continued)

				running in the NP shoes than in the NZS and ABI shoes.
Hunter, et al.[82]	19 M 10km >32min	NVF, ABI, NZS Randomised crossover	Phys: 5 min @ 16km/h Bio: 3 min @ 16km/h	Phys: Significant improvements in RE against ABI (2.8%, p=<0.001) and NZS (1.9%, p=<0.001). Bio: Stride length was significantly longer in NVF (0.04m ABI, 0.02m NZS). Ground contact time was unchanged.
Joubert and Jones[83]	12 M 5km 16min or equivalent	NVF, HRX, SEP, NAF, AMS, NRC, BHE, AHS Randomised crossover	8 x 5 min @ 16km/h	Phys: compared to control (AHS) AMS (2.52%, p=<0.001) resulted in similar improvements in RE compared to NVF (2.72%, p=<0.001). Bio: compared to control ground contact time was greater in the AMS (2ms, p=<0.05) and unchanged in the NVF (1ms), cadence and stride length were unchanged.
Reynolds, et al.[79]	12 M and 18 F 4.8km 4+ x/week	NVF, NAP Randomised crossover	800m @ controlled stride frequency	Bio: Stride length increase in NVF (0.12m, p=<0.000). Stride frequency, contact time, and flight time unchanged. 0.2 m/s faster in NVF (p=<0.00).
Nielsen, et al.[84]	32 M and 5 F 35 ±23km/week	NVF, ADI. Randomised crossover	6 min @moderate intensity 3.4km TT	Phys: Metabolic Power 0.2 W/kg less in NVF (p=<0.001). TT 1.1% faster (p=<0.001).
Winke and van Winkle[5]	9 F Well trained collegiate runners	NVF, NZS Crossover	5 min @ 10.8 km/h pre and post 30 min self-paced run	Phys: NVF had greater RE (3.7%, p=<0.05) compared to NZS in a pre-fatigued state. NVF had greater RE (2.5%, p=<0.05) compared to NZS in a fatigued state.
Note: M: male, F: female, NVF: Nike Vapor Fly, ADI: Adidas Adizero Adios 3, NVF+: Nike Vapor Fly weight matched to ADI, RE: running economy, Phys: physiology, Bio: biomechanics, FLAT: Saucony Endorphin racing flats, OWN: own shoes, TT: time trial, ABI: Adidas Adios boost 2, NZS: Nike zoom streak 6, GCT: ground contact time, HRX: Hoka One One Rocket X, SEP: Saucony Endorphin Pro, NAF: Nike AirZoom Alphafly Next%, AMS: Asics Metaspeed Sky, NRC: New Balance Fuel Cell, BHE: Brooks Hyperion Elite 2, AHS: Asics Hyperspeed, NAP: Nike Air Zoom Pegasus 38.				

Only a relatively small number of studies exist investigating super shoe and they are varied in terms of approach. Six studies included elite runners[5, 16, 21, 59, 82, 83] while four investigated recreational runners[79-81, 84], with two drawing from the same cohort[80, 81]. Most of the testing was carried out with male participants, with only 44 of the total 184 participants being female (Table 2). In each study, a control shoe was used taking the form of a traditional racing shoe, most commonly an Adidas Adios[16, 21, 59, 82, 84]. Across the 10 studies, 15 super shoes were compared - typically in a randomised crossover design, with the most frequently tested shoe the Nike VaporFly (all 10 studies).

All running assessments were carried out at submaximal steady-state pace, although the specific speeds differ between investigations. Six studies used a predetermined pace, most commonly 14-16 km/h[21, 32, 59, 82, 83], while two used a percentage of physiological thresholds[80, 81], and two used a self-selected pace[79, 84]. The studies that included elite runners typically adopted the predetermined pace, whereas self-selected pacing was used with age-group (non-elite) runners.

Six of the seven studies investigating physiological variables reported RE[5, 16, 21, 80, 82, 83] to compare efficiency changes between shoes, with one study opting to report metabolic power (MP)[84]. Super shoes improved RE between 1-4.2% across the studies[5, 16, 21, 80, 82, 83], and reduced MP by 0.2 W/kg[84]. One study investigated the effect of fatigue on performance benefit finding a reduction from 3.7% to 2.5% following 30-min of self-paced running[5]. The influence of a super shoe on time-trial (TT) performance was investigated in two of the nine studies. TT performance was measured over 3 and 3.4km with improvements of 1.8-2.4% and 1.1%, respectively[80, 84]. When controlled for stride frequency super shoes demonstrated 0.2 meters/second faster speeds across 800-m[79].

The Nike Vapor Fly is the super shoe with the most evidence to support its benefit over traditional racing shoes[5, 16, 21, 59, 79-84]. However, the Asics Metaspeed Sky and the Nike Alphafly have been shown to elicit similar improvements in RE[83]. Of the four studies that involved female participants, only two compared RE changes between male and females.

Both studies reported trivial-small differences in RE improvements between males and females(16, 79). The one study that exclusively investigated females reported a 3.7% improvement in RE. Barnes and Kilding(16) hypothesise that the slight differences in RE improvements between males and females could, in part, be due to the differences in mass between the participants. Heavier male runners will likely elicit greater ground reaction forces compared to lighter female runners, which in turn would generate greater mechanical energy storage and subsequent return from the midsole foam(16).

Summary

Running performance Is the greatest contributor to overall race time in long-distance triathlon(3). Therefore, triathletes are constantly on the search for strategies to enhance their running performance, and recent advances in running footwear appear to offer a potential solution. There is evidence from studies of runners(16, 55, 85) to support this, but there is no evidence to suggest that these improvements necessarily carry over to long-distance triathletes, where their effect could be moderated by the preceding cycle. Additionally, as much of the running-related evidence is related to elite-level athletes, there is a need to examine the effects of super shoes in age-group (non-elite) athletes. Therefore, the broad aim of this study is to determine if male age-group triathletes reap the benefits of super shoes, with the specific research question being: Do carbon-plated running shoes improve running performance and performance-related kinematic variables in a simulated bike-run transition in age-group long-distance triathletes?

Chapter 3: Methods

Participants

Using Jasp software a priori power analysis was run to indicate the power given to the main effect. Based on eight participants, $\alpha = 0.05$, and a large effect size of 1.04 (time trial performance), the power of the current analysis is 0.71. All participants were recruited through advertisement on social media (Appendix D). All participants were active long-distance triathletes and were free of musculoskeletal injury and respiratory illness for at least three months prior to testing. Participant descriptors are provided in Table 3. Procedures were approved by institutional human research ethics (AUTEC #15181), and participants signed written informed consent.

Table 3: Participant details (mean ±SD)

Age (years)	**Height (m)**	**Mass (kg)**	**VO_2 peak ($ml.kg.^{-1}min^{-1}$)**
36.8±10.1	1.843±0.028	86.1±8.6	56.6±6.0

Study design

Participants visited the laboratory on three occasions in an acute randomised crossover design, approximately seven days apart having refrained from vigorous exercise for 24 hours prior to each visit. The first session served as a characterisation trial, which involved a maximal incremental cycling assessment. Sessions two and three were experimental trials, consisting of an initial treadmill running economy assessment, a fatiguing cycle on a stationary bike, a post-fatigue running economy assessment, and finishing with a 10km treadmill time-trial (Figure 5) in either a super shoe (Asics Metaspeed Sky, Asics Corporation, Kobe, Japan) or a control traditional racing shoe (Asics Evoride 3, Asics Corporation, Kobe, Japan). The order of shoe presentation was randomised. Participants were asked to record their food and fluid intake and replicate it exactly for the experimental trials.

Characterisation trial

Cycling commenced on an electromagnetically braked ergometer (Excalibur Sport, Lode BV, Groningen, NET) at 95 W, and the power output initially increased by 35 W every three minutes. Expired gases were collected continuously using indirect calorimetry (TrueOne 2400, ParvoMedics, UT, USA), and heart rate was measured using a chest-strap (H10, Polar Electro Oy, Kempele, Finland). When the respiratory exchange ratio exceeded 1.0 and clear signs of increased $\dot{V}E.\ \dot{V}O_2^{-1}$ emerged, power output was increased by 35 W every minute until participants could no longer continue. The $\dot{V}O_2$peak was identified as the highest 15-s average $\dot{V}O_2$. The first ventilatory threshold was identified as the $\dot{V}O_2$ which causes the first rise in the ventilatory equivalent of oxygen ($\dot{V}E/O_2$) without a concurrent rise in the ventilatory equivalent of carbon dioxide ($\dot{V}E/CO_2$). The second ventilatory threshold was identified as the $\dot{V}O_2$ at which $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ increased alongside a reduction in $PetCO_2$. These $\dot{V}O_2$ were converted to a power output by linear ft of the power output vs. $\dot{V}O_2$ relationship. Estimation of maximal lactate steady state (MLSS) was achieved through established protocols[86]. The results of the characterisation trial were used to determine the cycling intensity for the following trials. The mean length of the characterisation trial was lasted 23:57 ±2:02 minutes.

Experimental trials

The first and second experimental trials were identical other than the shoe condition. The experimental trials commenced with a five-minute baseline assessment of running economy at a fixed speed of either 10, 12 or 14km/h on a treadmill (Saturn, h/p/cosmos, Germany), depending on running calibre. Running calibre was determined *a-priori* as a consultation between the athlete and the primary researcher. A selection was made between 10, 12 or 14km/h in line with the athlete's estimated race pace. Running economy speed remained consistent across the two experimental trials allowing direct comparison between shoes. Expired gases were collected continuously during the five-minute assessments, and at 15-minute intervals during the two-hour cycle, using indirect calorimetry. Average VO_2 collected during minutes 3-5 of each collection period were used for analysis.

The initial running economy assessment was followed by a two-hour cycle, designed to fatigue participants in a similar way to what would be experienced in a long-distance triathlon event. The cycle was carried out in a climate-controlled laboratory (~20 °C) on the participants' own bikes, attached to a stationary controlled power ergometer (Kickr, Wahoo Fitness, Atlanta, USA). The intensity was set at the participant's estimated MLSS determined from the characterisation trial, and reduced by 20W at 60 minutes, and a further 20W at 90 minutes. For six participants the protocol was unsustainable, therefore power was reduced earlier and repeated exactly between trials.

After the fatiguing cycle participants had three minutes to transition to the test or control shoes, before undergoing a second five-minute running economy assessment, identical to that previously conducted. This was immediately followed by a self-paced 10km time-trial, an assessment method previously shown to be reliable for the assessment of physiological parameters[87]. Treadmill speed was controlled by the participant through visual and auditory cues to the researcher. Time-trial distance and time were recorded via the indoor treadmill. Verbal encouragement from the researcher, music, and video were provided to all participants.

Participants completed the experimental trial once in a super (test) shoe and once in a traditional (control) shoe in a randomised order. The characteristics of the two are detailed in Table 4.

Table 4: Characteristics of intervention and control shoe.

Shoe	**Test: Asics Metaspeed Sky**	**Control: Asics Evoride 3**
Stack height (mm)	33	26
Heel-toe drop (mm)	5	5
Carbon-plate	Full length embedded	-
Foam	FF Turbo	Solyte
Foam density	50'	50'
Mass (g)	200	210

Running biomechanical variables of cadence, ground contact time, and flight time, were recorded continuously by two small (42mm x 47mm x 3.4mm) inertial measurement units (sampling at 416 Hz) attached to innersoles (Plantiga, Vancouver, Canada) inserted into the test shoes (Figure 6). These instrumented innersoles have previously been shown to have good to excellent 1-week reliability for measuring spatiotemporal running gait characteristics (ICC range = 0.84 – 0.98). Stride length was calculated as per the following formula: Stride length (m) = (Velocity (m/s^{-1})/Cadence (steps/s))*2. Only data collected during minutes 3-5 were used for analysis.

Figure 2: Plantiga inner sole and measurement unit.

Data processing

Data were recorded onboard the sensors and downloaded at the conclusion of the session for further analysis. Data collected from the inertial measurement units were downloaded at the conclusion of each session to the Plantiga Cloud for access via the web application. Data collected during the running economy tests were averaged over the final two minutes of the assessment. Expired gas data and time-trial times were exported to Excel (Microsoft Corporation, Washington, USA).

All data were subsequently imported into JASP[88] statistical analysis software for further analysis.

Data analysis

Descriptive statistics are reported as mean ± standard deviation unless stated otherwise. To answer the first research question 'Do carbon-plated running shoes improve running performance in a simulated bike-run transition in age group long-distance triathletes?' a paired t-test was run. The Shapiro-Wilk test for normality was not significant (W=0.941, p=0.617) suggesting the pairwise differences were normally distributed, and the assumptions were not violated, therefore, parametric paired-samples t-test was used. Cohen's d was interpreted using thresholds of <0.2, 0.2, 0.5, and 0.8 for trivial, small, moderate, and large. Percentage differences were calculated as condition one minus condition two, divided by condition two. For example, control shoe TT time minus test shoe TT time, divided by test shoe TT time.

To answer the second research question, 'Do carbon-plated running shoes improve performance-related kinematic variables in a simulated bike-run transition in age group long-distance triathletes?' repeated measures ANOVA tests were used to analyse the interaction between shoe condition and cycling fatigue on running economy, cadence, ground contact time, flight time, and stride length. No variables violated Shapiro-Wilk or Levene's Equality of Variances assumptions. Sphericity tests could not be performed because there were only two levels of repeated measure factors. Participant identity was the between-subject error term, and the repeated measures factors were added in two levels as 'shoe' (control, test) and 'fatigue' (pre, post). Partial eta squared (n_p^2) was reported for effect sizes with a magnitude of small (0.01), medium (0.06), and large (0.14)[89]. Bonferroni correction was used in Post Hoc Comparisons to determine which shoe and fatigue comparisons differed significantly. Statistical significance was set at p<0.05 in all analyses.

Chapter 4: Results

Participant details

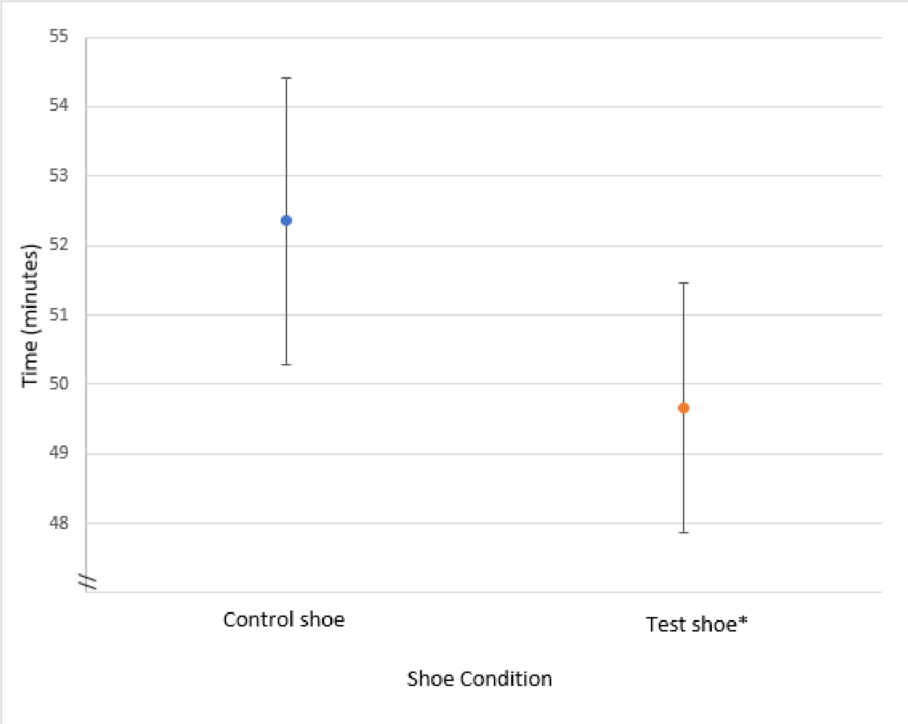
Twelve male age-group long-distance triathletes volunteered to be participants in the present investigation. Four participants were unable to complete the trials due to illness (n=2), injury (n=1), and personal reasons (n=1), resulting in eight athletes fulfilling all elements of the study. Due to complications during data collection, an outlier was recorded for one participant's test shoe RE data, and therefore this participant's RE data for both shoes was not included in the analysis.

Fatiguing cycle

The power profile was replicated exactly between trials for each participant. Average power ranged between 189-285w. On average participants worked at 68% of their VO_{2peak} for the duration of the fatiguing cycle.

Time-trial performance

The 'shoe' condition significantly affected time-trial (TT) performance by 2.69 ±0.92 minutes (95% CI [0.518,4.864], p=0.022, Figure 3). Triathletes ran their 10km TT with an average speed of 11.4 km/h wearing the control shoe and 12.2 km/h wearing the test shoe. The superior TT performance in the test shoe versus the control shoe was of large magnitude (ES=1.04). The order of intervention did not affect the outcome (p=0.586, η_p^2=0.052).



*Note: *p=<0.05 difference to control shoe.*

Figure 3: 10km time-trial performance following fatiguing cycle (mean ±SD).

Biomechanical variables

Shoe condition

Mean ground contact time (p=0.001, $\eta_p^2 = 0.793$) significantly differed by shoe condition both pre- and post-fatigue with a large effect size (Table 5).

Fatigue condition

Mean cadence (p=0.011, $\eta_p^2 = 0.630$), flight time (p=0.006, $\eta_p^2 = 0.677$), and stride length (p=0.012, $\eta_p^2 = 0.621$) significantly differed by the fatiguing cycle with moderate effect sizes (Table 5).

Table 5: Mean (±SD) running economy and biomechanical data pre- and post-fatiguing cycle.

	Control shoe		**Test shoe**	
	Pre-Fatigue	Post-Fatigue	Pre-Fatigue	Post-Fatigue
Cadence (steps/min)	173.2 ±13.3	176.1 ±13*	173.8 ±10.8	175.3 ±11.4
Ground contact time (ms)	222.6 ±35.3	228.5 ±36.5	215.1 ±33.4*	221.2 ±35.1**
Flight time (ms)	146.5 ±15.9	130.4 ±18.8*	149.1 ±23.3**	139.7 ±22.3
Stride length (m)	2.45 ±0.2	2.41 ±0.2*	2.44 ±0.2	2.42 ±0.2
Running economy ($ml.kg.^{-1}min^{-1}$)	43.5 ±3.7	43.7 ±5.1	40.9 ±3.7	42.6 ±3.98
Note: *p<0.05 difference to control shoe pre-fatigue. **p<0.05 difference to control shoe post-fatigue.				

Only control shoe flight time ($p=0.009$, $M=16.6$), cadence ($p=0.014$, $M=-2.9$), and stride length ($p=0.016$, $M=0.04$) significantly differed due to the fatiguing cycle. There were no significant differences observed for these variables in the test shoe (Table 6). Ground contact time was the only variable that displayed significant differences between shoe conditions pre- and post-fatigue (control/test pre, $p=0.005$, $M=7.5$. control/test post, $p=0.006$, $M=7.3$) (Table 6).

Physiological variables

Mean running economy ($p=0.034$, $\eta_p^2=0.554$) significantly differed by shoe condition pre- and post-fatigue with a moderate effect size. However, P_{bonf} showed that the only significant difference was between the pre-cycle RE in the test shoe and the post-cycle RE in the control shoe (unreported). There was no significant difference for RE between shoe conditions (Table 6).

Table 6: Comparison of running economy and biomechanical variables from the running economy assessments (Cohen's d effect size and Bonferroni correction) between shoe conditions.

			Cohen's d	**95% CI**	**P_{bonf}**
Control, Pre-Fatigue	**Control, Post-Fatigue**	Cadence (steps/min)	-0.237	[-0.554-0.080]	0.014*
		Ground contact time (ms)	-0.168	[-0.527-0.191]	0.591
		Flight time (ms)	0.797	[-0.174-1.768]	0.009**
		Stride length (m)	0.224	[-0.079-0.526]	0.016*
		Running economy (ml.kg.$^{-1}$min^{-1})	-0.055	[-0.860-0.749]	1.000
Control, Pre-Fatigue	**Test, Pre-Fatigue**	Cadence (steps/min)	-0.048	[-0.339-0.243]	1.000
		Ground contact time (ms)	0.214	[-0.046-0.473]	0.005**
		Flight time (ms)	-0.125	[-0.708-0.458]	1.000
		Stride length (m)	0.049	[-0.243-0.341]	1.000
		Running economy (ml.kg.$^{-1}$min^{-1})	0.641	[-0.467-1.749]	0.183
Test, Pre-Fatigue	**Test, Post-Fatigue**	Cadence (steps/min)	-0.121	[-0.370-0.128]	0.441
		Ground contact time (ms)	-0.175	[-0.537-0.187]	0.524
		Flight time (ms)	0.463	[-0.311-1.236]	0.203
		Stride length (m)	0.112	[-0.127-0.351]	0.505
		Running economy (ml.kg.$^{-1}$min^{-1})	-0.425	[-1.333-0.484]	0.583
Control, Post-Fatigue	**Test, Post-Fatigue**	Cadence (steps/min)	0.069	[-0.226-0.363]	1.000
		Ground contact time (ms)	0.207	[-0.047-0.460]	0.006**
		Flight time (ms)	-0.459	[-1.166-0.247]	0.107
		Stride length (m)	-0.063	[-0.357-0.232]	1.000
		Running economy (ml.kg.$^{-1}$min^{-1})	0.272	[-0.672-1.215]	1.000

Note: CI: confidence intervals. *p<0.05. **p<0.01. Cohen's d was interpreted using thresholds of <0.2, 0.2, 0.5, and 0.8 for trivial, small, moderate, and large.

Chapter 5: Discussion and Conclusions

The aim of this study was to determine whether super shoes improve running performance and performance-related kinematic variables in age-group long-distance triathletes during a simulated bike run scenario. The main findings indicate that the Asics Metaspeed Sky super shoe improved running performance (10km TT) by 5% on average, compared to a traditional racing shoe. These findings are in line with the findings of other studies, which showed improvements of 1.1-2.4% in TT performance when comparing super shoes to traditional racing shoes[80, 84]. While the results of the current study are in agreement, they are substantially greater in magnitude than those previously reported (mean difference of 9-16 vs 127s). One of the reasons for these differences may be the greater TT distance used in the current investigation compared to previous studies[80, 84]. Whilst previous studies compared shoes over distances of 3-3.6km, 10km was used in the current study to better replicate the demands of long-distance triathlon. Another potential reason for the differences in TT performance gain in the super shoe is the state of fatigue of the participants. Previous research has investigated TT performance in an unfatigued state[84], or after nine minutes of running at either 60, 70, or 80% of VO_2peak[80], compared to the two-hour fatiguing cycle of the current study. These findings provide the first evidence that super shoe benefit is potentially a function of running distance for age-group athletes, and that as fatigue develops the benefit that super shoes offer increases.

There was considerable individual variation in TT performance between shoe conditions, with seven participants producing faster times in the super shoes, ranging from 1.3 to 7 minutes, and one running 2 minutes slower (resulting from personal circumstances unrelated to the shoe condition). The order of shoe presentation was randomised, balanced, and the analysis showed that the order of shoe presentation did not impact TT performance. The individual variation reported in the current study is in line with other studies which reported 83% of participants gaining a performance benefit from super shoes[84], compared to 7 of 8 in the current study. The findings of the current study add to the evidence that the phenomenon of responders vs non-responders[63] exists and further highlight the need for caution when buying a super shoe as everyone will respond differently.

The biomechanical variables investigated in the present study of stride length (SL), cadence, ground contact time (GCT), and flight time (FT) varied in their response to shoe conditions and cycling fatigue. These variables were chosen due to their association with running performance[48, 90, 91] and the potential that they may provide insight into understanding how super shoes are effective. The current study is one of only six studies[16, 59, 79, 81-83] that have investigated the effect of super shoes as an entity on biomechanical variables of running performance.

There was no significant difference in stride length and cadence between shoe conditions in an unfatigued state. These findings are in agreement with other research that reported either no changes[83], or small changes (e.g. 0.02-0.04m or 0.7-1.7%)[16, 59, 81, 82] in SL, as well as either no changes, or small reductions (0.04 steps/s) in cadence in super shoes, compared to traditional racing shoes[16, 59, 79, 83]. The small differences in SL and cadence between shoe conditions are likely due to the controlled running assessment pace as SL and cadence together determine running velocity[92].

The fatiguing cycle only affected cadence and SL in the control shoe, with cadence increasing by 3 steps/min and SL decreasing by 0.04m. Cadence and SL remained unchanged in the test shoe. Previous research has reported both no changes[44], and increases in[47, 48] cadence following cycling. Somewhat surprisingly, the decrements of SL in the control shoe are the same size as those reported elsewhere[44], despite the cycle being three times longer. The more demanding cycling protocols have tended to result in a greater magnitude of change in biomechanical variables, however, an eventual return to pre-fatigue levels are typically observed[44, 47, 48]. Running biomechanical variables were not reported during the TT, so it is not possible to confirm any changes to SL or cadence between shoe conditions, however given the trends observed, it would lead us to believe that SL and/or cadence were affected. Based on the current understanding it is likely that SL was greater in the test shoe during the TT due to the relationship between increased stack height and SL[18, 56, 58]. Interestingly, cadence and SL were unchanged by the fatiguing cycle when using the test shoe, indicating that athletes could maintain cadence and SL following a fatiguing cycle. Therefore, it is unlikely that a change in these biomechanical variables is the reason for the increased physiological demand of running following cycling in the test shoe. The maintenance of SL following the fatiguing cycle in the test shoe could be one of the main contributors to the improvement in TT performance. SL has significant correlations to running performance, with evidence to suggest those that are able to maintain SL perform better compared to those who SL decreases due to fatigue[93]. Furthermore, a maintenance of SL reduces injury risk when running in a fatigued state[94].

In the current study, RE differed between shoe conditions with the test shoes associated with 6% average improvement before the fatiguing cycle, and a 2.5% improvement after cycling. Although these were not statistically significant differences in the current study, it is anticipated that with greater participant numbers the same trend would occur. The improvements in RE in the pre-fatigued assessment are greater than previous reports which range from 1-4.2%[5, 16, 21, 80, 82, 83]. The difference in these findings could be due to differences in running speed[95], participant population[32], treadmill properties[96], the properties of the shoes[83], individual responses to the shoe conditions[63], or in fact a placebo effect[57, 82]. The reductions in RE found in the current study align with those from Winke and Van Winkle[5], who reported a 2.5% to 3.7% reduction in RE improvement following a 30-min self-paced run. The differing protocols and participant populations would explain why we displayed a greater loss of RE benefit following fatigue, however, this adds to the hypothesis that RE improvements from super shoes are of diminishing return as fatigue is developed. Although our study involved a 120-min fatiguing cycle, the cycling portion of long-distance triathlon racing lasts on average 390-min for age-group triathletes[6], meaning that in a true competitive situation, the benefit from super shoes may be less than reported in the current study. Interestingly, following the fatiguing cycle, no change in RE was observed in the control shoe condition, whereas in the super shoe trial RE worsened by 4% and returned towards control shoe RE values. Although some studies have reported no differences in RE after cycling[45, 46], the majority of prior studies support the idea that prior cycling negatively impacts RE, with reductions of 1.6-16.9%[13, 39-44]. The studies that failed to show differences have included elite-level triathletes, and a cycling protocol that did not replicate the fatiguing nature of racing. The current investigation consisted of age-group (non-elite) triathletes, following a cycling protocol that appears to produce the greatest fatigue reported. Further research is required to understand how RE is affected by the characteristics of shoes, and how this is impacted by fatigue.

With the design of the current study, it was not possible to determine the exact mechanisms that explain the differences in outcomes between shoe conditions, but likely a result of the combined effect of the larger midsole stack height and increased LBS, that create the teeter-totter effect of super shoes.

GCT is directly related to the metabolic cost of running[90], however, it is disputed whether longer[4, 97] or shorter[98] GCTs are more beneficial. In the current study, GCT was significantly different between shoe conditions, whereby athletes displayed shorter GCT when in the test shoes compared to the control shoes. This finding is in contradiction with the literature which consistently reports longer GCTs in super shoes[21, 59, 64, 65, 72, 75, 76, 81, 83]. Additionally, flight time was 2% longer in the test shoe compared to the control shoe in a non-fatigued state, which is in agreement with, though smaller in magnitude, to the differences observed by Hoogkamer (3.2%)[59] and Herber-Losier (10ms)[81]. The smaller magnitude changes observed in FT in the current study is likely due to differing assessment speeds (10, 12, and 14 vs 16 km/h) with a linear relationship between running speed and FT existing[99]. There are numerous potential reasons for the conflicting findings related to GCT in the current study and what has been published by others. The previously reported increases in GCT are thought to be a result of the phenomenon that increased LBS reduces ankle plantarflexion velocity[62], however Oh and Park[62] hypothesise that only individuals who lack the relevant calf muscle strength capabilities to increase ankle joint moment present an increase in GCT. It is possible that the triathletes in the current investigation possessed greater calf muscle strength than other participant populations due to differing habitual training methods. As previously highlighted, it is not possible to differentiate the relative contribution of each super shoe characteristic to performance changes, and to predict how they may interact with the participants. It is likely a unique combination of characteristics of the super shoe, and how these differed to the control shoe, used in this study that have resulted in a relative difference in the GCTs.

Our findings concerning the influence of fatigue on GCT align with the current understanding that GCT increases due to a fatiguing intervention. Curiously, GCT increased in similar magnitude for both shoe conditions. It is likely then that the changes in GCT are a result of deterioration in muscular and/or neuromuscular function during cycling. This could be due to reductions in the stretch-shortening function of the calf muscle-tendon unit or reduced strength capabilities of the calf muscle. The fatiguing cycle significantly decreased FT in the control shoe by an average of 16ms whilst the test shoe reduced by 10ms to no significant effect. To the best of the author's knowledge, this is first study to investigate the effect of a fatiguing cycle on FT during running. The results are intuitive given the accepted changes to GCT, cadence, and stride length following fatigue[44, 48]. The smaller reduction of FT in the test shoe is again likely to be related to the teeter-totter effect of super shoes.

Previous research has attempted to investigate the effect of individual features of super shoes by matching them in weight to the control shoe[16] or by adding a supplementary carbon plate[67]. These approaches were not taken in the current investigation for two reasons: 1) the primary research question addresses the interaction between super shoes in their entirety and age-group athletes, and 2) to reflect the reality of commercially available choices where all shoes have differing shapes, weights, and construction.

The findings of the current study point toward shorter GCT during stance, alongside longer flight times being the cause of the improvement in RE between the test and control shoe. The slight increase in GCT and decrease in FT in the test shoe following the fatiguing cycle could explain why RE reduced, given that cadence and SL remained the same. However, this line of thought does not carry over to the control shoe as RE remained stable following the fatiguing cycle, despite FT decreasing in a greater magnitude to the test shoe. Therefore, there is a clear difference in the interaction between the shoe and the athlete when it comes to super shoes and traditional racing shoes. Again, further research is required to understand how RE is affected by the characteristics of shoes, and how this is impacted by fatigue.

Limitations

There are a number of limitations of the current study that should be considered alongside the results. Firstly, the limited number of participants weakened the power of the study, secondly, only male participants were recruited - limiting the ability to apply the findings to females. Thirdly, the participants were not blind to the footwear conditions, and although the analysis showed that the order of shoe presentation did not impact TT performance, a placebo effect cannot be fully discounted. Another limitation is the unknown variability in the 10km time trial performance of these age-group athletes, especially in the unfamiliar environment of the laboratory and while running on a treadmill. While the study was designed to replicate long-distance triathlon as closely as possible, all data were collected in a laboratory, there are differences between treadmill and overground running, as well as stationary cycling and cycling outdoors. The combination of the environment, and the equipment used will have impacted the results in ways that can't be determined. The protocol of the fatiguing cycle was over-estimated and proved unsustainable for some participants. Finally, substantial inter-individual variation in response to shoes with greater longitudinal-bending stiffness exists, and the design of this study did not allow for the analysis of results in this way.

Practical implications

The findings of the current study give assurance to age-group long-distance triathletes that the considerable cost of super shoes is worthwhile, from a performance perspective. However, caution should be taken as to which super shoe is chosen. Based on the results on this and other studies, the Nike Vaporfly, Nike Alphafly, and Asics Metaspeed Sky offer the greatest potential for improved performance. These findings also highlight the differences in pre- and post-cycling running economy and biomechanics and reiterate the need to practice cycle-to-run sessions in training to minimise the negative effect of prior cycling.

Recommendations for future research

Further research is needed to understand the effects of advanced shoe designs on performance in age-group long-distance triathlon. Studies with larger subject numbers, female athletes, and a wider selection of shoes are required. Making use of advancements in wearable technology, researchers should now look to take studies out of the lab, and include exercise segments of longer duration to better represent the competitive environment. Developing a quantitative measure of individual response to different LBS indexes will further benefit the decision-making for shoe manufacturers, as well as the athletes who buy these shoes.

Conclusion

Shoes with advanced midsole foam, higher stack height and embedded carbon plates are being widely used in the triathlon community, with limited research into their potential benefit with different types of athletes. This is the first study to investigate the effectiveness of super shoes enhancing running mechanics and performance in a simulated long-distance triathlon context. A greater magnitude of change in biomechanical variables following cycling compared to previous research indicates that the current literature is not relevant to long-distance triathletes and that more specific research is needed, taking into consideration the influence of cycling on subsequent running. In conclusion, super shoes improve running performance in age-group long-distance triathletes.

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Appendices

Appendix A: Ethical approval

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
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E: ethics@aut.ac.nz
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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 B: 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.

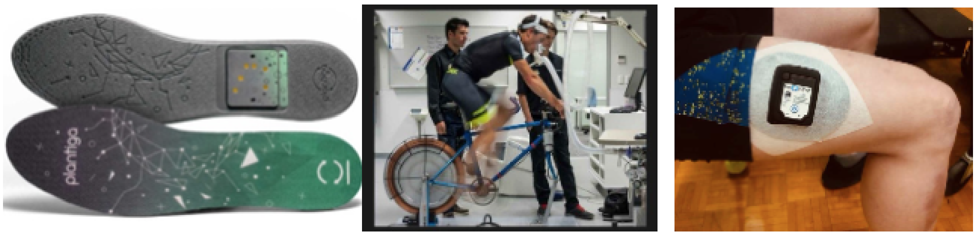
What will happen in this research?

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 three 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:

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Fangcheng Zhu
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Project Supervisor Contact Details:

Dr Kelly Sheerin
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Professor Andrew Kilding
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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 C: Study advertisement

Appendix D: Social media advertisement