Effect of Carbon Plated Running Shoes on Half-Hour Treadmill Time Trial Performance

A Thesis

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BY

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Abstract

Purpose: Performance in distance running events has been substantially impacted by innovative shoe technology using a combination of carbon fiber plates and lighter, more resilient cushioning materials. Times have been getting faster at a rapid rate, and it has been established that these shoes reduce the energetic cost of running. Very limited research has attempted to quantify these savings in terms of speed or pace, which are the most relevant performance outcomes. This study was designed to examine the performance effects of carbon plated racing flats on speed and pace compared to a non-plated racing flat, providing a quantitative estimate of how much faster these shoes make distance runners. **Methods:** This study used a randomized order, crossover design, with participants blinded to their running speed. Eight trained distance runners (m=5, f=3) completed two 30-min treadmill time trials, approximately one week apart. One time trial was run in a carbon plated shoe (Nike Vaporfly or Asics Metaspeed Sky), and the other was run in a non-plated flat. Average speed, running economy, RPE, RER, and HR were measured during both trials. **Results:** During the carbon plated time trial, participants covered 0.1188 km (+/- 0.14), ran 0.2373 kph faster (+/- 0.2462), and averaged 3.5 seconds per km faster ($p<0.05$), and saw no significant change in running economy (RE), RPE, RER, or HR. These improvements indicated a 1.5% (+/- 1.54%) speed improvement in carbon plated shoes. Additionally, a 3.17% improvement in RE was observed during a submaximal warmup period when participants were wearing the carbon plated shoe ($d = 0.276$), though this difference was not significant ($p = 0.184$). **Conclusion:** These data provide a scientific estimate of the performance benefits of carbon plated racing flats. The 3.5 seconds per km identified in this study can provide a basis for coaches, athletes, and distance running regulatory bodies to establish rules, and to contextualize performances between eras and shoes conditions.

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Chapter 1: Introduction

Running performance is determined by a multitude of factors including physiological, biomechanical, and psychological variables. Running shoes have been one of the sole areas of technological improvement for centuries in a sport which doesn't feature much equipment. In an age of ever-increasing science and technology, the last 5 years have seen an enormous leap in shoe technology. The integration of carbon plates and Pebax foams into marathon racing shoes has flipped the running shoe world on its head. World records, and top historical performances have been vastly increasing in frequency in the last 5-6 years since the aforementioned 'boom' in running shoe technology. The years 2017-2019 saw the largest performance jump of any three-year period in distance running events (Goss et. al, 2022). While this jump can't solely be attributed to shoe technology (training paradigms and fueling strategies also are likely contributors), it certainly is playing a role in improving performance on a large scale.

History of Running Shoes

Prior to this latest exponential advancement of running shoe technology, there had been a steady improvement in shoe technology since the 1970s when Bill Bowerman started Nike. Bowerman pioneered running shoes oftentimes molding rubber in his own waffle iron. These original Nike training and racing shoes featured super thin soles that beat up runners that would use them on the road, but the lightweight nature of them allowed for faster speeds to be accessed. The next few decades of training shoe evolution featured ever increasing cushion and protection from the road. Racing shoes were also often made of materials that added unnecessary weight and low resilience foams. From here, the way shoe companies made their road racing shoes faster was by trying to shed weight wherever possible. Franz, Wierzbinski, and Kram discovered that for every 100g added to a shoe, a 1% increase in oxygen consumption followed (Franz, Wierzbinski & Kram, 2012). Findings such as these drove companies to create lighter shoes for road racing. But a 2015 meta-analysis concluded that there were many areas to potentially improve shoe technology and proposed future studies focus more on measures of running performance (Fuller et al, 2015).

Sub 2-Hour Marathon Implication on Shoe Technology

Meanwhile, a few years prior to this meta-analysis, the limits of human performance were being called into question. Dr. Michael Joyner released a highly controversial paper estimating the human body could run a 1:57 marathon, at a time when the world record was 2:03 (Joyner, Ruiz, & Lucia, 2011). With this gauntlet of sorts laid down by Joyner, research into factors to improve human performance was pushed to the forefront of the exercise physiology world. Optimization of nearly every factor implicated in endurance performance would have to be accounted for to make this project a reality. Aerodynamic drafting patterns, altitude, weather, pacing strategies, and fueling strategies were all extensively researched and findings were applied to what came to be known as the Sub-2 Hour Project (Hoogkamer et. al, 2018). With a sub 2-hour marathon still seeming light years away, scientists knew that an improvement in shoe technology could help assist, and may be the crucial factor, in an athlete becoming the first under the 2 hour barrier (Hoogkamer, 2017). This research led to the creation of the first marathon racing shoe that included pebax foam with a carbon plate embedded in the midsole. With Nike leading the way, other brands slowly caught up over the course of the next 2-3 years with a carbon plated racing shoe of their own.

A recent study from Stephen F Austin University examined 7 carbon plated shoes from different brands. Every single one of these carbon plated shoes was shown to improve running economy compared to a traditional road racing shoe (Joubert & Jones, 2022). Clearly, carbon plated shoes improve running economy, thus decreasing the energetic cost to run at a specific pace. But, what do these savings actually translate into? Hoogkamer, Kram, and Arrellano, 2017 estimated that the 4% energetic savings from the Vaporfly may translate into 3.4% improvement in speed at marathon world record pace. Not only is this an estimation, but only applies to a handful of runners in the world. There is a gap between establishing energetic cost savings and determining how much time this actually saves a runner in a race setting. Time, speed, and pace, are the most directly relevant parameters for performance, and little to no research has been done examining these. It has been established that improving running economy, and lowering the energetic cost, directly translates into improved distance running performance (Hoogkamer et. al, 2016). It also has been shown that for every 100g addition to a running shoe, 3,000m performance time slows by 0.78% (Hoogkamer et. al, 2017). Aside from this limited research, there hasn’t been research that illustrates what these energetic cost savings actually translate to in a performance metric (i.e. speed).

This research will focus on determining what the energetic savings provided by a carbon plated shoe actually translate into in terms of time, or speed. Based on findings from Joubert & Jones, 2022, this study will include the Nike Vaporfly Next%, Nike Alphafly Next%, and Asics Metaspeed Sky as the carbon plated shoes being tested. These were shown to have the largest, and a similar, effect on energetic cost of running compared to four other current carbon plated models. These shoes will be compared against a more traditional, non-plated racing flat in which no specific models are required.

Chapter 2: Review of Literature

Running Performance

Running performance is influenced by a multitude of factors, some that have been extensively researched, and others in which research has been quite limited. Runners and coaches have been searching for performance gains ever since competitive running began, as with all endurance sports. Optimizing training strategies, fueling, technology, and ergogenic aids all are common avenues identified to improve performance, especially at elite levels. At elite levels, any small advantage proves to be the difference between placing at major championships and Olympics, which has major contract and financial implications for these athletes. Miniscule differences, on a large scale, matter little. But at the most competitive settings in the sport of running, this is what makes major differences. For example, at the 2022 World Athletics World Outdoor Track & Field Championships, all medal positions for the men's and women's 5,000m and 10,000m were within 1 second of each other ("World Athletics," 2022). This illustrates how important every small advantage can be in competitive running contexts. Whether these advantages come from fueling strategies, training paradigms, or shoe technology, no stone can go unturned by these athletes and coaches on an elite level.

Running Economy and Energetic Cost

Running economy (RE) is a pillar of running performance and is one of the most significant measurements collected in exercise physiology. RE is defined as the energy requirement for a given intensity or speed of running (Saunders et. al, 2004). This is typically measured in oxygen consumption, but when measured at or near maximal intensities that occur above lactate threshold, the anaerobic contribution must be accounted for as well to determine RE (di Prampero & Ferretti, 1999). Since power and velocity are being partially fueled by anaerobic metabolism, di Prampero & Ferretti established a model to estimate oxygen cost of exercise based on lactate concentrations. This allows for the reporting of running economy even at intensities eliciting respiratory exchange ratios greater than 1.0. The model establishes that any 1 mM increase in blood lactate concentration is equivalent to the energy released by the consumption of 3.3 ml O_2 per kg of body mass (di Prampero & Ferretti, 1999). Running economy helps describe the efficiency of running at a certain intensity. A lower RE at any given intensity implies higher efficiency since the athlete would be able to produce higher intensities with less fuel resources.

$VO_{2\ max}$

$VO_{2\ max}$ is defined as the maximal oxygen uptake by an individual which indicates aerobic capacity. This typically is determined by completing a graded exercise test (GXT) to volitional exhaustion. This test is typically conducted using a metabolic cart to measure expired gasses and a motorized treadmill. $VO_{2\ max}$ can be expressed in absolute and relative terms. The absolute units are $L*min^{-1}$, and the relative units are $mL*min^{-1}*kg^{-1}$. Both metrics are useful, but relative units provide more context when comparing between individuals. A traditional stage protocol and a ramping protocol are two of the most common ways to determine $VO_{2\ max}$. The stage protocols include 1-3 minute stages at a set speed before a jump in speed or incline. A ramping protocol however, sees increases and speed and incline occur much more gradually, with shorter stages. A ramping protocol may increase speed by 0.1 mph every 15 seconds, while a stage protocol may increase speed by 1.0 mph every 2 minutes. A ramping protocol has been shown to elicit further advantages compared to stage protocols including easier ventilatory threshold identification, and $VO_{2\ max}$ identification (Boone & Bourgeois, 2012). While $VO_{2\ max}$ was traditionally thought to be the most important parameter for performance, modern research illustrates more complexity for performance prediction including variables such as lactate threshold and running economy (Midgely et. al, 2007). The importance of $VO_{2\ max}$ however remains important as it provides insight into the aerobic capacity of an athlete. Clinically, there are a number of validated procedures to estimate $VO_{2\ max}$. The Rockport Walk Test, Mcardle Step Test, and 1.5 mile run test, are all validated ways that indirectly estimate $VO_{2\ max}$ (Kumar & Goswami, 2019; Weiglein et. al, 2011). Competitive runners often use recent race performances to correlate with $VO_{2\ max}$ values. In instances where extreme specificity is unnecessary, it provides an adequate estimation of performance most commonly by using VDOT charts created by Jack Daniels (Daniels, 2013). VDOT charts have been shown to be perhaps the best easily accessible method to convert between performance data and $VO_{2\ max}$ data (Charles, 2020).

Physiological Thresholds

Another extremely important parameter in endurance training and performance is the point where certain physiological thresholds occur. This topic has created a world of debate, confusion, and uncertainty over definitions, importance, and practical use over many years. The two most common ways to identify certain thresholds are by measuring blood lactate, and monitoring ventilatory gas exchange. The ventilatory turnpoints very closely correlate to the lactate turnpoints ($r = 0.92$), but they are not an exact match (Anderson & Rhodes, 1989) . Since this review is focusing on the broader scope of thresholds as they relate to endurance performance, they will be discussed interchangeably. The first threshold an athlete hits as they ramp up their intensity is their aerobic threshold. This is also referred to as the first ventilatory threshold, or LT_1 in some cases (Seiler, 2010). This threshold corresponds with the lowest intensity at which one starts to see a steady increase in blood lactate levels from baseline. The second threshold occurs when blood lactate levels start to become unstable and there is a rapid increase in lactate concentration (Seiler, 2010). This often occurs around 4 mMol and at the point where CO_2 production begins to rapidly outpace O_2 utilization (Heck et al, 1985). Ventilatory threshold can also be identified by visually examining the ventilatory equivalents for oxygen and carbon dioxide. When an increase in the ventilatory equivalent for oxygen increases without subsequent increase in the ventilatory equivalent for carbon dioxide, the first ventilatory threshold (typically corresponding with anaerobic threshold) has been reached (Neves et. al, 2022). A second identifying mark comes from an increase in respiratory exchange ratio (RER) and increased end tidal oxygen pressure ($PetO_2$) (Neves et. al, 2022). Along with VO_2 max, which often is described as the "size of the engine," lactate tolerance is an extremely important parameter for endurance performance. Lactate accumulation occurs in the blood alongside an accumulation of hydrogen ions, which create an acidic environment and contribute to muscle failure and fatigue (Magness, 2014). By training these thresholds, one adapts to tolerate lactate concentrations at higher velocities, thus improving performance.

Psychological Factors

While it is simplistic to look at endurance running performance as a function of physiology, the more we learn about the brain, the more we understand how much impact the psychology of performance plays a role. Racing and training requires sustaining periods of extreme discomfort, and continuing to endure under such circumstances (Salwin & Zajac, 2016).

It has been shown that pain tolerance, pain threshold, and self-efficacy are all elevated in trained distance runners (Johnson et. al, 2012). These factors all play an important role in any race result, or performance result of a distance runner. Coping with the discomfort is a skill that not all endurance athletes excel at, but it is crucial for performative success. Avoiding maladaptive coping strategies has been shown to be significantly correlated with improved performance in ultramarathons (Alschuler et. al, 2020). Alschuler et al additionally showed that the pain distance runners experienced was mostly of the same intensity, but those who were better equipped with coping strategies experienced better outcomes.

There has been a long-standing debate on the Central Governor Model (CGM) originally theorized by Tim Noakes (Noakes et. al, 2001). Noakes argues that there is a neural governor that inhibits certain physiological functions such as skeletal muscle activation that contributes to fatigue. Noakes argues that an intelligent neural governor regulates skeletal muscle, and other systems, "in anticipation" to maintain homeostasis (Noakes, 2010). A proposed alternative to the CGM is the psychobiological model Samuele Marcora proposes. This multifactorial model proposes running time trial performance is a function of self-regulation based on factors such as motivation, perceived effort, distance remaining, and previous experience (Marcora, 2010). While the exercise physiology field hasn't come to a clean conclusion one way or the other when it comes to these theories, the importance of psychology and neural networks are clearly extremely important.

Running Shoes

Weight

The weight of a running shoe clearly has large impacts on the speed an athlete can sustain over any period of time. As previously mentioned, Hoogkamer found a correlation between shoe weight and 3,000m time trial performance in a 2017 study. With every 100g addition of shoe weight, time trial performance slowed 0.78% (Hoogkamer, 2017). It has also been demonstrated that a 100g increase in shoe weight increases the oxygen cost of running by approximately 1% (Franz et. al, 2012). While this was traditionally considered the best way to increase performance, due to the highly resilient 'superfoams' in carbon plated shoes, this 'knowledge' is being challenged. Due to the higher resilience of Pebax foams, especially when coupled with a carbon plate, it's possible that the more materials (i.e. weight) a shoe company puts into their technology, the faster and more efficient it will be. This is in part why World Athletics has introduced stack height restrictions in competitive racing shoes (O'Grady & Gracey, 2020).

Minimalist/Barefoot Running

Minimalist running shoes are a category of running shoes that aim to mimic barefoot or "natural" running mechanics. After the release of *Born to Run* by Christopher Macdougall, barefoot and minimal shoes saw a jump in popularity. Proponents claimed a decrease in injury, an increase in efficiency, and better performance (Lieberman, 2012). Since the early 2010's much research has been conducted to investigate these claims. Minimalist shoes share many similarities with non-plated racing flats used for much of the last five or six decades. These shoes are stripped down to the bones, while providing some protection from the ground. Some evidence shows that minimalist shoes or barefoot running may result in a lower metabolic demand at submaximal paces (Hanson et. al, 2011). But these data are far from conclusive. Many factors are at play that may contribute to the efficiency of a stride in minimal footwear. It is likely that the cause of an increase in efficiency would be due to the increase in elastic energy storage in the longitudinal arch of a foot (Perl et. al, 2012). These findings can be linked to the implementation of carbon plates to increase the longitudinal stiffness of carbon fiber plated racing flats. The increase in stiffness likely leads to a quicker transition of forces through the longitudinal arch by expediting the stretch and recoil of forces (Ortega et. al, 2021). The most significant and research-backed finding to come from the minimalist shoe field is the reduction in ground reaction forces (GRF) when running in a minimalist shoe, or barefoot (Divert et. al, 2005). This has driven some companies towards creating shoes where one's foot sits at a more even rear foot to forefoot plane, also known as a low heel to toe drop. This is seen in many carbon plated shoes which often have a 4-6mm heel to toe offset, considered to be "low" by most.

Maximalist Running Shoes

On the opposite side of the spectrum from minimalist shoes, maximalist shoes are growing in popularity rapidly during the early 2020's. Companies such as Hoka started to market high cushioned shoes, often with a slight 'rocker', to reduce injuries and keep athletes healthy. A rocker, which is now common in many training and racing shoes, is a general arc geometry that effectively rolls a runner, through a hinge-action, from their landing point on their foot, to their toe off. This keeps momentum moving forward and quickens the midfoot to forefoot transition associated with propulsion in a running stride (Hutchins et. al, 2009). While no conclusive evidence supports these claims, maximalist running shoes certainly have an effect on the kinematics of running (Becker & Borgia, 2020). An increase in impact loading forces, a decrease in dorsiflexion, and higher gluteus medius activation all result from maximalist shoes (Becker &

Borgia, 2020). Additionally, an increase in leg stiffness has been shown to occur when running in maximally cushioned shoes (Kulmala et. al, 2018). This increase in leg stiffness is associated with increased impact loading. While most of the research pertaining to maximalist shoes examines the shoes from an injury risk perspective, shoe developers are starting to look at cushion as a performance enhancer. Because of the development of ultra-resilient foams, many carbon-plated racing shoes feel similar to maximalist shoes recently released.

Carbon plated racing shoes generally attempt to take the best elements from the minimalist movement, and the best elements of the maximalist movement, and blend them to help make a more efficient shoe.

Influence of Running Shoes on Performance

Carbon Plate Implementation

There were two aspects of shoe technology that were hypothesized to improve performance; a carbon plate embedded in the midsole, and the utilization of ultra-resilient foams.

While the existing research is still extremely new and limited when it comes to carbon plates, ultra-resilience foams, and "supershoes", a number of studies since 2017 have explored all aspects of this new technology. Some of these data will be discussed below. While there is a general consensus that the shoes are performance enhancing (although to different degrees), there is a bit more debate and discussion regarding the mechanisms behind the improved efficiency. The general idea behind adding a carbon plate into a shoe is to increase the longitudinal bending stiffness of the shoe (Roy & Stefanyshyn, 2006). Longitudinal bending stiffness refers to the flexibility of the shoe in the transverse plane. A higher longitudinal bending stiffness means a shoe would flex less, and a lower bending stiffness would result in a highly pliable and flexible shoe. This increase in longitudinal bending stiffness has been thought to lower the cost of running at certain speeds. Some studies have found benefit to only increasing the longitudinal bending stiffness, while others have found more nuance and shades of grey. Flores et. al found that by increasing the longitudinal bending stiffness of a shoe, energy return improved, but this didn't necessarily translate into lower energetic cost of running (Flores et. al, 2018). There is certainly an optimal bending stiffness, carbon plate curve placement, and curve to the anterior of the actual shoe midsole, but extensive research is currently lacking in this area (Nigg et. al, 2021). Additionally, there seem to be 'responders' and 'non-responders' to benefit from increasing longitudinal bending stiffness (Madden, 2016). Furthermore, the idea of variability in responsiveness levels to carbon plated technology has been shown to exist in all levels of athletes. Elite distance runners (mean half marathon time 59:30), have shown 11.4% economy improvements at submaximal intensities, but also have shown 11.3% drawbacks as well (Knopp et. al, 2023). Amateurs have shown to respond to the level of a 9.3% submaximal economy improvement, but have also seen 1.1% drawback (Knopp et. al, 2023). These findings are extremely significant and display the paradigm of having 'responders' and 'non-responders' to carbon plated technology. The mechanisms behind this phenomenon have yet to be studied extensively. The location in the midsole that the carbon plate is inserted into seems to have some sort of impact on the improvement in efficiency as well. Including the carbon plate in a "high" position directly under the insole seemingly improved performance more than at a "lower" location (between the midsole and the outsole) at multiple speeds (Flores et. al, 2019). To add to the nuance found in the research, the effect of the plate on the metatarsophalangeal (MTP) joint has an effect on the improvement in performance. If the addition of a stiff plate does not affect

MTP joint flexion, a carbon plate will improve performance. (Oh & Park, 2017). Other mechanisms likely are at play in contributing to the performance enhancing effects of carbon plated shoes. The "teeter-totter effect" occurs when a properly constructed curved carbon plate comes in contact with the ground. The aforementioned curve in the plate often is designed to sit immediately beneath the metatarsals to provide a fulcrum point in which the runner can use to propel themselves forward. The ground reaction force (i.e. landing force) from a footstrike results in an upward 'reaction force' due to the stiff nature of a carbon plate. This then results in a downward force applied at the front end of the carbon plate, anterior to the fulcrum point where the "teeter-totter effect" takes place (Nigg et. al, 2021). The "teeter-totter effect" helps facilitate transition to the forefoot for a quicker toe-off and quicker cadence, and also helps translate force in a more efficient manner from the landing phase to the propulsion phase of a footstrike. According to Nigg et. al (2021), the teeter totter effect is the most important mechanism behind carbon plate performance enhancement. While there are plenty of nuances in determining if carbon plates improve running performance, there is a general trend towards the simple answer of 'yes.' A meta-analysis done by Rodrigo-Carranza et. al, determines that an increased longitudinal bending stiffness improves running economy up to a certain point. There is an "optimal" stiffness and the plate must run the length of the shoe, but a carbon plate certainly seems to somehow improve efficiency. The authors of this meta-analysis hypothesize that a plates' effect on the MTP and ankle joint is the biomechanical mechanism behind this economic improvement (Rodrigo-Carranza et. al, 2021). There still needs to be research done to identify specific mechanisms behind the effect of a carbon plate.

While much of the research focuses on how, and by how much, carbon plated shoes improve performance, there is a growing body of research examining the other side of this double edged sword. The injury risk of training and racing in carbon plated shoes has not been extensively studied, but it is reasonable to assume that the rapid growth of carbon plated technology, and the biomechanical changes that follow, may lead to injuries not typically seen as frequently. A case series examining carbon plated footwear's effect on injury hypothesizes that these shoes put more stress on the navicular and metatarsal bones (Tenforde et. al, 2023).

Pebax "Superfoams"

Running shoe foams have varied levels of resilience and shock absorption. Both of these are important factors that vary based on the type of running shoe. Traditionally, road racing shoes had very low volumes of cushion to decrease the weight of the shoe. They were made mostly of EVA foam which had lower resilience and was denser than what has now been termed "superfoam" (Burns & Tam, 2020). EVA foams absorb more energy and return less to a runner, resulting in slight amounts of energy loss adding up with every step (Almkvist, 2021). Due to the low resilience of traditional EVA foams, by using less foam, one loses less energy to the foam in the shoe. New foam technology, however, has started to challenge this notion of 'less is more.' If shoe companies found a way to increase softness, while also increasing resilience, this would result in increased running economy (Worobets et. al, 2015). The material that has emerged as a lighter and more resilient foam is a Pebax foam. This material is both lighter and more resilient than classic running shoe foams, EVA and TPU (Burns & Tam, 2020). In fact, this foam has been shown to return 32% more energy than TPU or EVA foams (Burns & Tam, 2020).

Both the addition of a carbon plate and the utilization of Pebax foam have been shown to increase running performance, but there is some mixed research when just a carbon plate is used (Joubert & Jones, 2022). This study by Joubert & Jones (2022) examined a number of carbon plated shoes, but not all models had Pebax foam. The shoes that didn't utilize a Pebax foam performed similarly to the non-plated control flat. The 'magic' lies when you add both Pebax foam *and* a carbon plate to a shoe. This is exactly what Nike did in 2017 when it launched the Nike Vaporfly 4%. It is also the blueprint for all running shoe companies in the modern market. This combination of an ultra-resilient foam, to an ultra-stiff midsole lead to one of the greatest leaps in shoe technology in the modern era (Hoogkamer et. al, 2018). This technology also led to a dichotomy shift in the running shoe market. Instead of trying to shed weight and make racing shoes as minimal as possible, shoe companies started cramming as much material as they could into a shoe to maximize the savings (Almkvist, 2021). Racing shoes were limited in their stack height to add standardization in how much material could be used by companies.

Current Carbon Plated Shoes

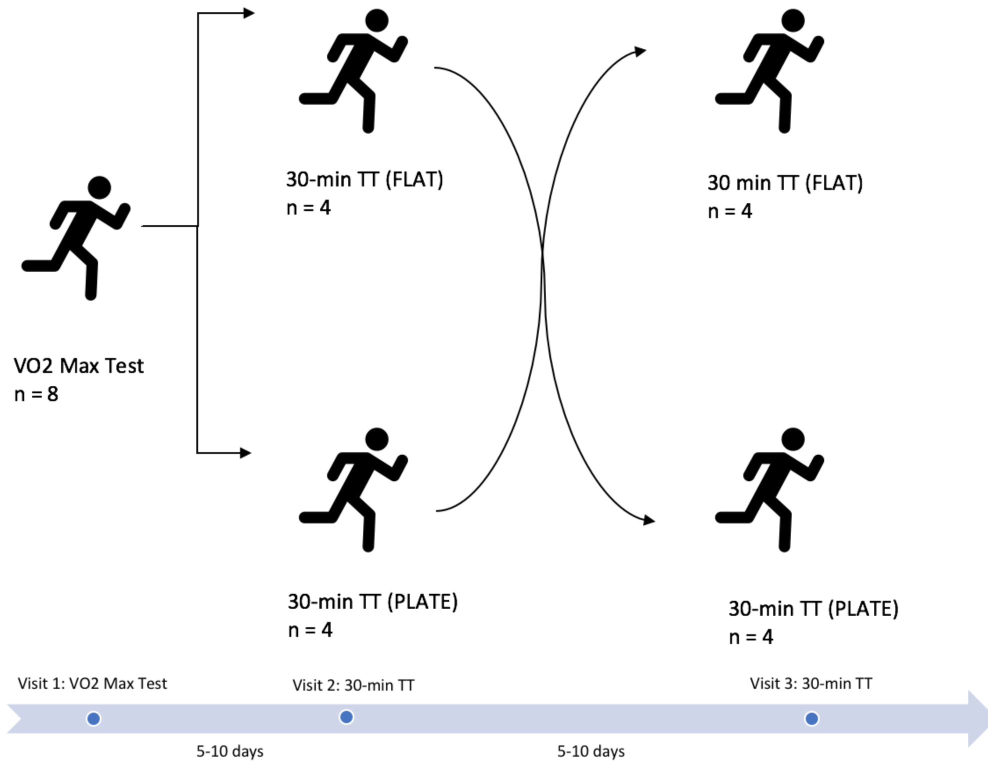
As previously mentioned, the Nike Vaporfly 4% was a huge leap in shoe technology. It was deemed to be 4% more efficient than the fastest racing shoe on the market at the time (Hoogkamer et. al, 2017). The combination of Nike's Zoom X foam with their carbon plate embedded in the midsole allowed for the energetic cost of running to be reduced by 4%. This shoe was ultimately the shoe (although updated) that Eliud Kipchoge ran the world's first sub 2 hour marathon in when he ran 1:59:40 on October 12, 2019 (Snyder et. al, 2021). These shoes have since become perhaps the most popular road racing shoe for distances 5,000m and up. Further scientific studies have backed up Hoogkamers' findings from 2017. Additional research looked at the Nike Vaporfly specifically, finding 2.6% (Barnes & Kilding, 2019) and 2.8% (Hunter et al., 2019) improvements in oxygen consumption (i.e., RE). Following the creation of the Vaporfly, other brands unveiled carbon-plated models of their own to remain competitive in the space. Carbon plated shoes, regardless of brand, improve running economy across a multitude of speeds when compared to non-carbon plated shoes (Hebert-Losier, 2020). Additionally, the efficacy of carbon plated shoes applies when running up and down hills. A 3% economy improvement is seen for both uphill and downhill running, which has practical implications for road races with undulating terrain (Whiting et. al, 2022). While most of the early research on carbon-plated shoes focused on elite athletes, their efficacy for recreational athletes have also been demonstrated (Nielsen et. al, 2022). This study had a sample size of 37, and describes their population as "recreational." Both metabolic power and 3k time trial performance were increased in the carbon plated shoe condition in Neilsen's 2022 study. This study found a mean 3k time trial improvement of 9 seconds in the carbon plate compared to traditional flat (p=0.001, effect size = 0.09) (Nielsen et. al, 2022). Additional analysis was completed to see if the changes seen in metabolic power were correlated with the changes in time trial performance, and no correlation was discovered. This suggests that the improvement in time trial performance likely comes from other factors. Another recent study examined 3k time trial performance in a carbon plated shoe versus a traditional flat. 3k time trial performance was improved by 13-16 seconds in the Nike Vaporfly and Saucony Endorphin Pro respectively, compared to a non-plated shoe (Hébert-Losier et. al, 2022). High amounts of variability in running economy improvements, and time trial improvements again suggest that certain athletes respond better to carbon plated technology than others. While it is useful to examine 3k time trial, as seen in multiple recent studies (Nielsen et. al, 2022) (Hébert-Losier et. al, 2022), carbon plated shoes are more frequently used, and marketed for use in longer race distances. This is the rationale for using a novel, 30-minute time trial in our study. The speed most runners can sustain for 30 mins, is relatively close to what they can sustain for common distances such as half marathons and marathons. The speed an athlete can sustain for a given distance is not a linear relationship as race distance increases, so a 30-minute time trial offers relatively similar speeds to the practicality of using carbon plated shoes for long road races (half and full marathons).

Chapter 3: Methods

Study Design

This study protocol was approved by the University of Minnesota Institutional Review Board, and consent was obtained from all participants. Participants visited the Human Sport and Performance Lab (HSPL) three times separated by 5-10 days between each visit. The first visit started by obtaining informed consent from each participant followed by a graded exercise test (GXT). $VO_{2\,max}$, heart rate, and basic anthropometric measurements (height and weight) were collected during the initial visit. Visits two and three consisted of a 30-minute time trial; one in a carbon plated racing shoe (PLATE), and one in a non-plated racing flat (FLAT). Each time trial was preceded by a standardized warmup. VO_2, lactate, RPE, HR, and distance covered were collected for each time trial. The time trial conditions were randomized with a cross over design.

Figure 1: Experimental Design



Participants

A power analysis was conducted based on a study comparing the energetic cost of running in non-plated and carbon-plated racing shoes (Hoogkamer et. al, 2018). Based on means and standard deviations from this paper along with its' performance implications estimated in Hoogkamer 2019, at least 8 individuals needed to be recruited in order to observe differences in time trial performance based on shoe type. This would be sufficient to obtain 80% power at an alpha level of 0.05. Effect size was used to further validate any differences between groups. Participants were recruited through the use of social media, local running stores with permission from owners and employees, and word of mouth. Participants were required to have an average training volume of a minimum of 4 hours per week (running) for the 3 months prior to study enrollment. They also were required to have completed a race or time trial of a distance between 1500m and 26.2 miles over the course of the past year.

Graded Exercise Test

The graded exercise test was completed in the HSPL. Participants were informed to abstain from tobacco/nicotine and vigorous exercise for at least 24 hours prior to testing, and from caffeine use 12 hours prior. After informed consent was obtained, participants' weight was collected on an electronic scale (Etekcity Personal Scale; Anaheim, CA, USA), and height was collected using a stadiometer (ACCUSTAT; Genentech, San Francisco, CA, USA). A ten-minute warmup at a self-selected "easy" pace run on a motorized treadmill (Woodway USA; Waukesha, WI, USA) was completed for each participant prior to the $VO_{2\,max}$ protocol. The treadmill was set at a 1% incline throughout all flat running stages to simulate wind resistance and drag experienced outdoors (Jones & Doust, 1996). A five-minute break followed the warmup prior to testing. A validated Polar (Schaffarczyk et. al, 2022) chest strap heart rate monitor (Polar H10; Polar Electro, Kempele, Finland) and neoprene face mask were then fitted to each participant for collection of respiratory data. The metabolic cart (Medgraphics, St. Paul, MN, USA) was calibrated with a three-liter syringe and standard gasses prior to each session.

Each $VO_{2\,max}$ test followed a ramping protocol. This started at an easy pace and progressed to 2-mile pace based on equivalent performances using race data from the past year. The specific paces for each participant were determined using VDOT charts from Daniels' Running Formula and their most recent race performance (Daniels, 2013). The treadmill was increased 0.1 mph every 15 seconds until an estimated two-mile pace. Once this was achieved, the treadmill incline increased 0.5% every 15 seconds until volitional exhaustion was reached.

Termination of the test was signified by the participant placing their hands on the treadmill handles and stepping off the belt. Throughout the test expired gasses were collected breath by breath using the metabolic cart and gas analyzing software (Breeze, 8.6.0.56; Medgraphics, St. Paul, MN, USA). Heart rate data were also collected continuously through the use of the heart rate monitor chest strap and streamed to a mobile app (Elite HRV; Austin, TX, USA).

Experimental Visits

Both experimental visits followed an identical protocol, one simply took place with the carbon plated shoe, while the other took place in the traditional flat. The carbon plated models used were the Nike Vaporfly Next%, the Nike Alphafly Next%, and the Asics Metaspeed Sky. These models were selected based on the findings of Joubert & Jones, 2022 which established these three as being the most efficient carbon-plated models currently available. The order in which the shoe condition was set for participants to complete the visits was randomized. The shoes for both experimental visits were provided by the participant, and all had less than 150 miles of use. Shoes were provided by the participants to ensure familiarity. Participants fasted for two hours prior to the experimental visits. When participants arrived, they were weighed by an electronic scale, measured for height by a stadiometer, and fit for a Polar HR chest strap monitor. Experimental shoes were weighed prior to the visit.

Each experimental visit began with a 5-minute warmup at a self-selected easy pace, with a pair of self-selected shoes. No measurements were taken during this time. Following the warmup, participants were instructed to switch into the carbon plated shoe or the traditional flat. Both experimental shoes were weighed prior to the visit. Participants then started a standardized warmup where they ran for 10 minutes at 70% of the velocity at $VO_{2\,max}$. Expired gasses and HR were recorded during this time for assessment of submaximal RE. A three-minute rest period was given immediately after the standardized warm up.

During the 30-minute time trial, the participant was blinded to speed and incline, and only provided with a countdown timer. Participants were told that their 30-minute time trial would start at their 'theoretical 10k pace' as estimated by their $VO_{2\,max}$ that was converted to a race estimate (Daniels, 2013). Additionally, participants were told the goal was to cover as much distance as possible in the 30-minute duration of each time trial. Participants were able to freely adjust the speed by 0.1 mph increments for the duration of the time trial. No additional encouragement from the lab staff was given to any participant. Gas exchange and heart rate data was collected for the entire 30-minute time trial, RPE was collected every 10 minutes using the Borg scale (Chen et. al, 2002), and blood lactate concentration was collected every 10 minutes including immediately before and after the time trial. Lactate concentration was measured using a portable lactate meter (Lactate Plus; Nova Biomedical, Waltham, MA, USA). This specific lactate meter has been extensively studied to assure reliability and validity (Hart et. al, 2013).

Following the completion of the 30-minute time trial, participants were allowed a five-minute cool down at a self-selected pace. No measurements were taken during this time, except for heart rate.

Ventilatory Data

Breath by breath data that was collected during the visits was averaged using a mid 5-of-7 averaging method. Ventilatory data was collected during the GXT of the initial visit, as well as during the standardized warmup and 30-min time trial for each experimental visit. This data will be analyzed for changes in running economy at submaximal, and maximal velocities. For running economy data at specific time points, a one-minute average was taken to provide a snapshot of the participants' running economy, while also including enough data to combat outliers.

Lactate Measurements

Lactate measurements were taken immediately after the standardized warmup, and at 10, 20, and 30 minutes during the 30-min time trial. Measurements were taken using the portable lactate meter previously mentioned. Measurements were taken from the index finger and taken while running for the 10, and 20-min measurements. The 30-minute sample was taken immediately upon conclusion of the time trial. Blood lactate concentration collection followed the following protocol.

1) Participants' finger was cleaned with an alcohol prep pad.
2) Finger was dried with a gauze pad.
3) Index finger was pricked using a single-use lancet.
4) The initial drop of blood on the finger was wiped away with a gauze pad.
5) The next drop was used for collection and analysis.

Running Economy

Running economy was calculated in units of (ml O_2*kg^{-1}*km^{-1}). The estimated oxygen cost (ml O_2*kg^{-1}*min^{-1}). was calculated by using the aforementioned equation from di Prampero & Ferretti (1999) by factoring in changes in lactate concentration from baseline levels. By expressing running economy in these units, speed was factored in to determine oxygen use and metabolic rate in terms of speed. For clarification, running economy refers to the energetic cost to produce a given speed. So in these contexts, a higher running economy is associated with lower efficiency, and vice versa.

Statistical Analyses

All statistical analyses were conducted on RStudio. Paired sample t-tests were used to analyze changes of RPE, RER, speed, distance covered, and RE between the FLAT and PLATE conditions. Cohen's D effect size was also calculated for these parameters between tests. A repeated measures ANOVA was also conducted to examine differences between and within groups' running economy during the 30-minute time trial.

Chapter 4: Results

Eight participants (n=3 female) completed the study; Table 1 includes participant characteristics relevant to the outcomes. All participants were highly trained distance runners that completed at least four hours of training per week for the previous three months prior to enrollment.

Table 1. Participant Characteristics

		Female	**Male**
	N	3	5
Age (yrs)	Mean (SD)	29.33 (0.71)	30 (8.89)
	Maximum	32	45
	Minimum	27	23
Weight (kg)	Mean (SD)	55.76 (3.56)	70.85 (2.78)
	Maximum	58.42	74.84
	Minimum	51.71	67.59
VO2 max ml O_2*kg^{-1}*min^{-1})	Mean (SD)	55.4 (1.56)	57.38 (5.87)
	Maximum	57.2	63.6
	Minimum	54.4	49.7
Plated Shoe	Nike Vaporfly Next% (196g/164g)	3	4

	Asics Metaspeed Sky (207g/181g)	0	1
Non-Plated Shoe	Nike Streak 6 (181g/154g)	1	2
	Nike Streakfly (170g/151g)	0	2
	Hoka Mach 5 (232g/193g)	1	0
	NB 1400 v6 (201g/176g)	0	1
	NB Fresh Foam Tempo v2 (258g/222g)	1	0

*weights provided for US M9/W8 size (g)

Between the two 30 min time trials, effort was held constant as no statistically significant changes in RPE (p = 1, d = 0), HR (p = 0.2755, d = -0.374), and running economy (p = 0.8179, d = -0.050) during the final time point of the time trial (30 mins) illustrate a consistent effort between both trials. Some small effect sizes (Cohen's d) were observed between trials, which can be seen in Table 2a/b. HR at the 20 and 30-minute time points were slightly lowered in the FLAT condition, both of which had small effect sizes (d = -0.392, -0.374). The RER data throughout the time points of the 30-minute time trial also showed small effect sizes. RER was higher in the PLATE condition at the 20 and 30-minute time points (d = -0.373, -0.469), and lower at the 10-minute time point (d = 0.293). Similar to RER, small effect size differences in RPE were observed, but the direction of effect varied by timepoint. RPE is likely unaffected since the differences between FLAT and PLATE were seen in both directions at different time points, and since no statistical significance was found.

Table 2a. Group means in distance covered, speed, RE, respiratory exchange ratio (RER), heart rate (HR), and rate of perceived exertion (RPE), between FLAT and PLATE conditions. PLATE is the reference variable in this table.

Variable	FLAT	PLATE	p	d
Distance Covered (km)	7.87	8.00	0.02979	-0.135
Speed (kph)	15.74	15.98	0.02979	-0.135
Pace (min/km)	03:48.7	03:45.3	0.02979	-0.135
Running Economy (ml O_2*kg^{-1}*km^{-1})				
Warmup	199.74 (14.30)	193.98 (16.56)	0.184	0.372
10 min	245.59 (39.29)	237.44 (32.50)	0.4274	0.226
20 min	245.32 (26.91)	233.43 (30.11)	0.1304	0.417
30 min	240.88 (25.24)	239.49 (30.54)	0.8179	0.050
HR				
10 min	180.13 (7.92)	179.63 (9.44)	0.7363	0.057
20 min	181.00 (4.14)	183.75 (9.00)	0.1981	-0.392
30 min	185.75 (4.86)	188.63 (9.74)	0.2755	-0.374
RER				
10 min	1.020 (0.082)	0.999 (0.062)	0.1008	0.293
20 min	1.015 (0.075)	1.041 (0.066)	0.1184	-0.373
30 min	1.058 (0.072)	1.088 (0.054)	0.2126	-0.469
RPE				
10 min	15.00 (2.20)	14.50 (1.77)	0.1705	0.25
20 min	16.38 (1.50)	16.88 (1.36)	0.1036	-0.349
30 min	18.38 (1.19)	18.38 (1.69)	1	0

Table 2b. Differences in distance covered, speed, RE, respiratory exchange ratio (RER), heart rate (HR), and rate of perceived exertion (RPE), between FLAT and PLATE conditions. PLATE is the reference variable in this table.

Dependent Variable	Mean Difference	*T*	*df*	*P*	*D*	95% CI
Distance Covered (km)	-0.1188	-2.7194	7	0.02979***	-0.135	[-0.278, -0.019]
Mean Speed (kph)	-0.2373	-2.7194	7	0.02979***	-0.135	[-0.278, -0.019]
RE 10	8.148	0.84235	7	0.4274	0.226	[-14.726, 31.023]

RE 20	11.893	1.7133	7	0.1304	0.417	[-4.521, 28.308]
RE 30	1.398	0.23909	7	0.8179	0.050	[-12.431, 15.228
RE Warmup	5.75125	1.4739	7	0.184	0.372	[-3.475, 14.978]
HR 10	0.5	0.35044	7	0.7363	0.057	[-2.874, 3.874]
HR 20	-2.75	-1.4218	7	0.1981	-0.392	[-7.324, 1.824]
HR 30	-2.875	-1.1828	7	0.2755	-0.374	[-8.623, 2.873]
RER 10	0.02125	1.8889	7	0.1008	0.293	[-0.005, 0.049]
RER 20	-0.02625	-1.7794	7	0.1184	-0.373	[-0.061, 0.009]
RER 30	-0.03	-1.3713	7	0.2126	-0.469	[-0.082, 0.022]
RPE 10	0.5	1.5275	7	0.1705	0.25	[-0.274, 1.274]
RPE 20	-0.5	-1.8708	7	0.1036	-0.349	[-1.132, 1.132]
RPE 30	0	0	7	1	0	[-0.894, 0.894]

Distance Covered and Speed

Statistically significant changes in distance covered and speed were observed between the FLAT and PLATE trials. Table 2b illustrates a mean difference of 0.1188 kilometers further in the PLATE condition (p = 0.02979, d = -0.135). This translates into a speed improvement of 0.237 kilometers per hour in the PLATE condition (p = 0.02979, d = -0.135). This indicates a 1.5% speed improvement during the 30 min time trial PLATE condition. This also equates to an average of a 3.5 second per kilometer improvement in the PLATE condition.

Table 3. Individual and mean distance covered, speed, and kilometer pace between FLAT and PLATE conditions.

Participant ID	Distance Covered FLAT (km)	Distance Covered PLATE (km)	Average Speed FLAT (kph)	Average Speed PLATE (kph)	Average km Pace (FLAT)	Average km Pace (PLATE)	% Speed Change
1	9.17	9.40	18.35	18.80	03:16.2	03:11.5	2.46
2	8.40	8.64	16.80	17.28	03:34.3	03:28.3	2.87
3	8.51	8.61	17.03	17.22	03:31.4	03:29.1	1.13
4	7.26	7.42	14.52	14.84	04:08.0	04:02.6	2.22
5	8.48	8.38	16.96	16.77	03:32.2	03:34.7	-1.14
6	7.26	7.40	14.52	14.81	04:08.0	04:03.1	2.00
7	6.81	6.78	13.62	13.55	04:24.4	04:25.7	-0.47
8	7.08	7.29	14.16	14.58	04:14.2	04:06.9	2.95
Mean	7.87	8.00	15.74	15.98	03:48.7	03:45.3	1.50

Table 4. Individual and group differences in distance covered, speed, and pace.

Participant ID	Difference in Distance Covered (km)	Difference in Average Speed (kph)	Difference in Average Km Pace (seconds per km)
1	0.23	0.45	-00:04.7
2	0.24	0.48	-00:06.0
3	0.10	0.19	-00:02.4
4	0.16	0.32	-00:05.4
5	-0.10	-0.19	00:02.4
6	0.14	0.29	-00:04.9
7	-0.03	-0.07	00:01.3
8	0.21	0.42	-00:07.3
Mean Difference (sd)	0.1188 (0.1400)	0.2373 (0.2462)	-00:03.5
P	0.02979	0.02979	0.02979
D	0.135	0.135	0.135

Figure 2. Individual differences in distance covered during the 30-minute time trial between the PLATE and FLAT conditions.

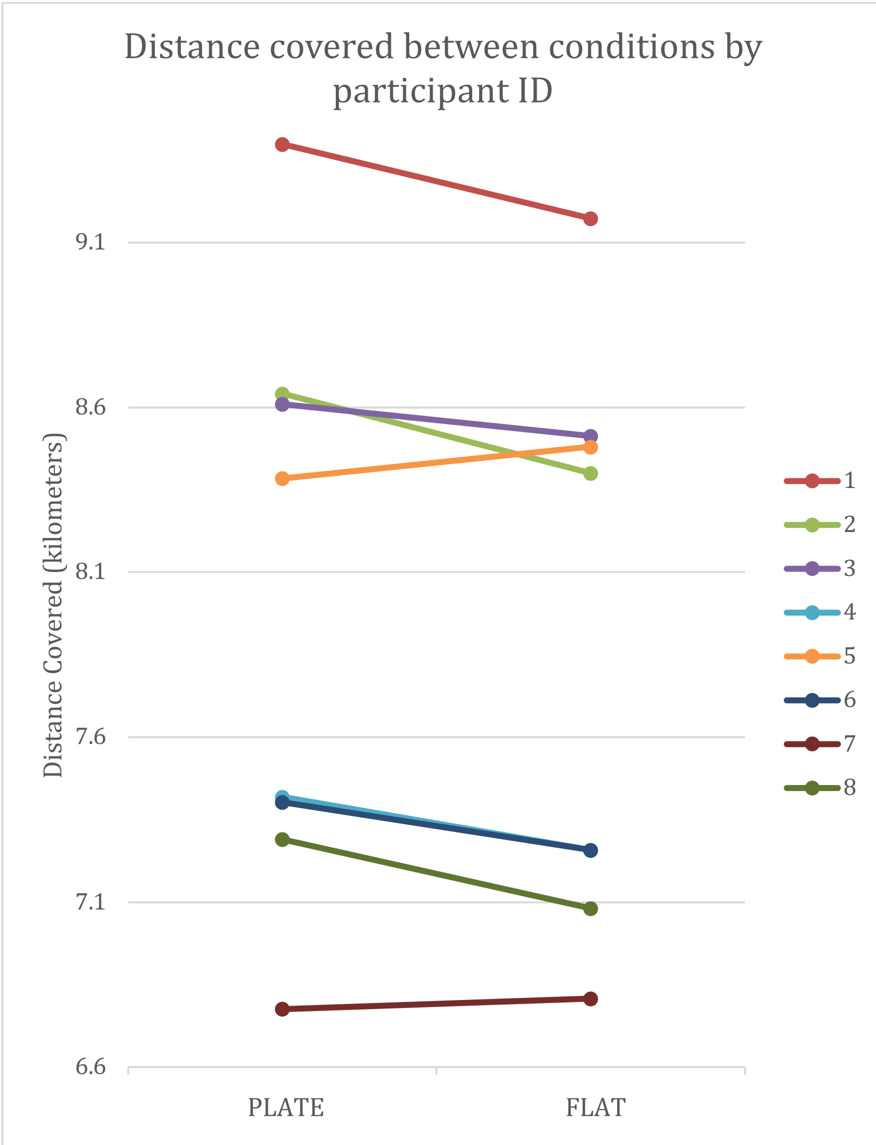
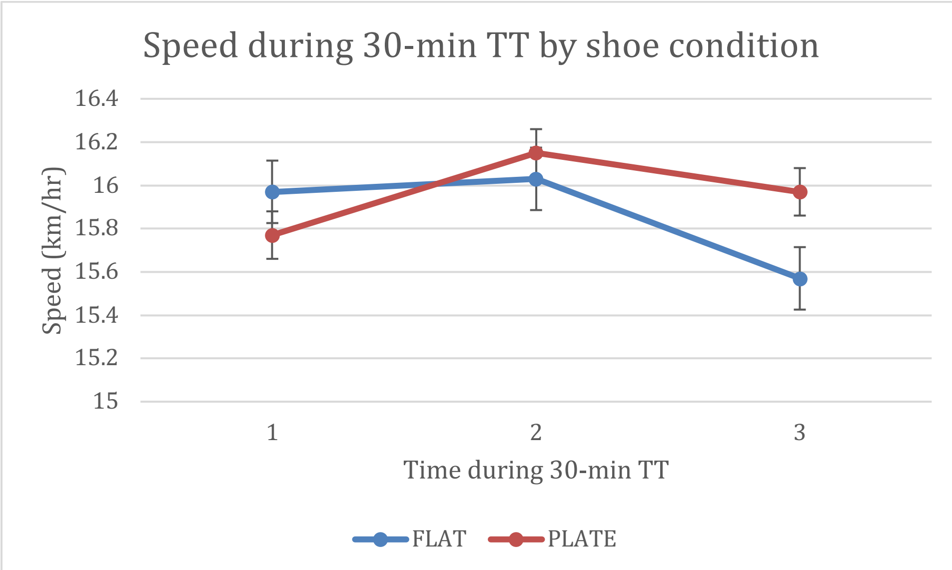


Figure 3. Changes in speed throughout the course of the 30-minute time trial for both shoe conditions.



Individual differences between trials are seen in Table 3, Table 4, and Figure 2. These illustrate the variability in response levels by individual. Standard deviations in Table 3 also provide insight into the variance in differences between FLAT and PLATE. The average improvement in speed from FLAT to PLATE was 1.50% +/- 1.54, and improvements as high as 2.95% and as low as -1.14% were observed. Figure 3 illustrates that during the PLATE trial, participants speed decreased between the last two timepoints less than in the FLAT trial.

Running Economy

Running economy saw no statistically significant improvement at any time point (10, 20, 30) of the 30-minute time trials (p = 0. 5807, 0.4333, 0.8228), or during the submaximal warmup (p = 0.1755). There were, however, small effect sizes associated with higher RE at the 10 (d = 0.226) and 20 min (d = 0.417) time points during the FLAT time trial as seen in Table 2a/b. This indicates better economy in the PLATE condition. The RE improvement observed at the 10 and 20-minute time points show 3.32% and 4.85% better economy in the PLATE group, respectively. Differences in RE during the 10-minute submaximal warmup, at 70% v $VO_{2\ max}$, were associated with a small effect size indicating better economy in the PLATE group (*d* = 0.372). The RE improvement observed in the submaximal warmup shows improved economy by 3.17% in the PLATE group.

Table 5. Oxygen cost (ml O_2*kg^{-1}*min^{1}) between conditions during warmup & time trial.

Group	Warmup (mean, sd)	10 min (mean, sd)	20 min (mean, sd)	30 min (mean, sd)
FLAT	43.78, 5.47	65.16, 9.22	63.39, 7.92	63.16, 8.79
PLATE	42.39, 4.56	63.68, 9.40	61.99, 10.15	63.69, 10.28
Mean Difference	1.388	1.489	1.402	-0.54
p	0.1755	0.5807	0.4333	0.8228
d	0.276	0.160	0.154	-0.056

Table 6. Running economy (ml O_2*kg^{-1}*km^{-1}) by individual during warmup and time trial for both conditions.

ID	Warmup PLATE	Warmup FLAT	10 min PLATE	20 min PLATE	30 min PLATE	10 min FLAT	20 min FLAT	30 min FLAT
1	185.17	199.67	227.62	233.43	251.31	222.72	230.34	244.35
2	202.57	198.84	195.12	190.04	202.67	236.24	232.21	206.40
3	183.02	211.41	259.49	285.53	294.27	227.02	276.74	287.71
4	208.20	210.62	301.05	247.97	227.38	336.15	283.43	229.58
5	167.57	176.17	207.27	195.66	207.27	232.91	203.50	223.79
6	213.48	212.97	230.33	243.25	241.71	234.43	243.54	264.96
7	182.52	180.29	240.88	236.74	226.05	262.52	261.85	235.39
8	209.35	207.92	237.81	234.80	265.21	212.75	230.94	234.88
mean	193.98	199.74	237.44	233.43	239.49	245.59	245.32	240.88
sd	16.56	14.30	32.50	30.11	30.54	39.29	26.91	25.24

Figure 4. Oxygen Cost throughout the 30 min time trial in FLAT and PLATE conditions.

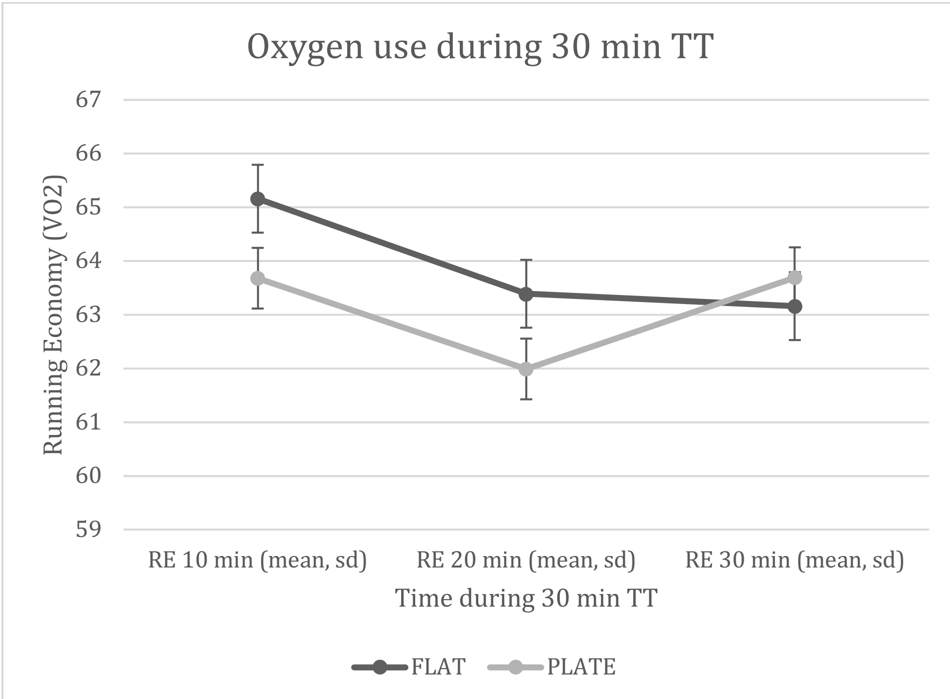


Figure 4 illustrates the average oxygen cost changes between conditions and time points. No differences were statistically significant, which indicates consistent effort by participants between time trials.

Figure 5. Running economy (ml O_2*kg^{-1}*km^{-1}) by condition throughout the 30-minute time trial.

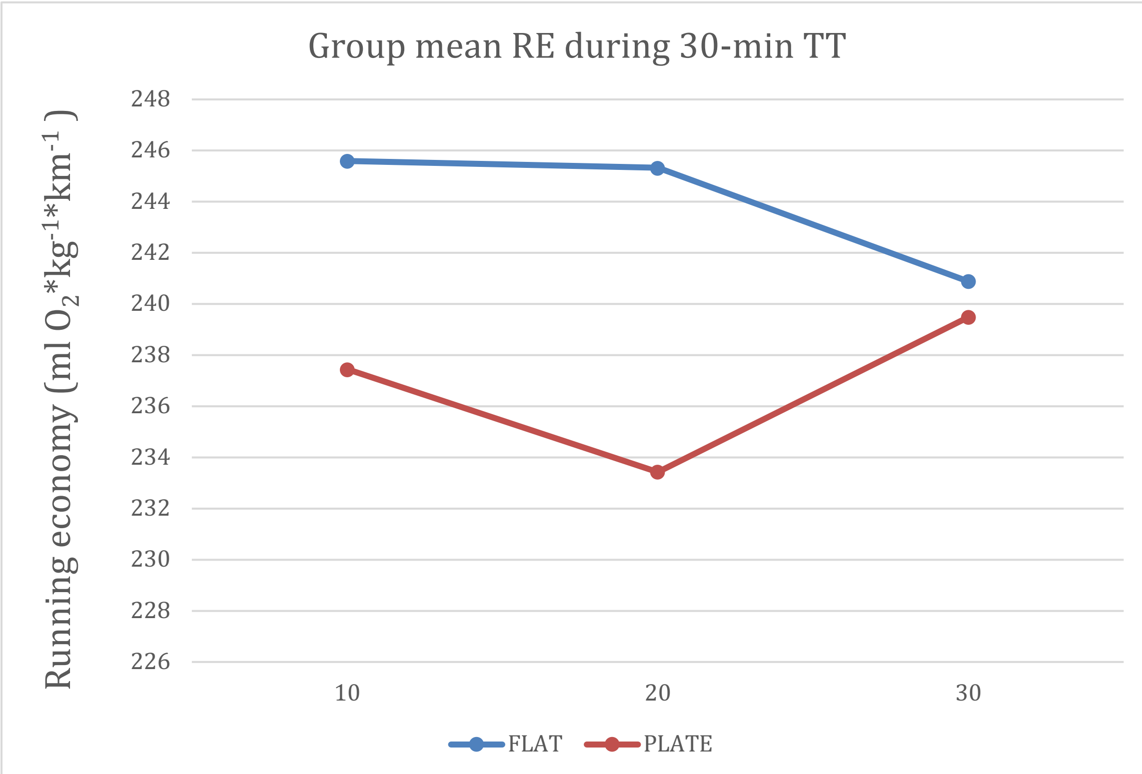


Figure 5 depicts the running economy for the three different time points during each 30-minute time trial. None of these differences were statistically significant ($p>0.05$), but differences observed at 10 and 20-minutes were associated with a small effect size. These running economy data indicate increased efficiency at the 10 and 20-minute timepoints in the carbon plated shoe.

Figure 6. Running economy by participant ID throughout the 30-minute FLAT time trial.

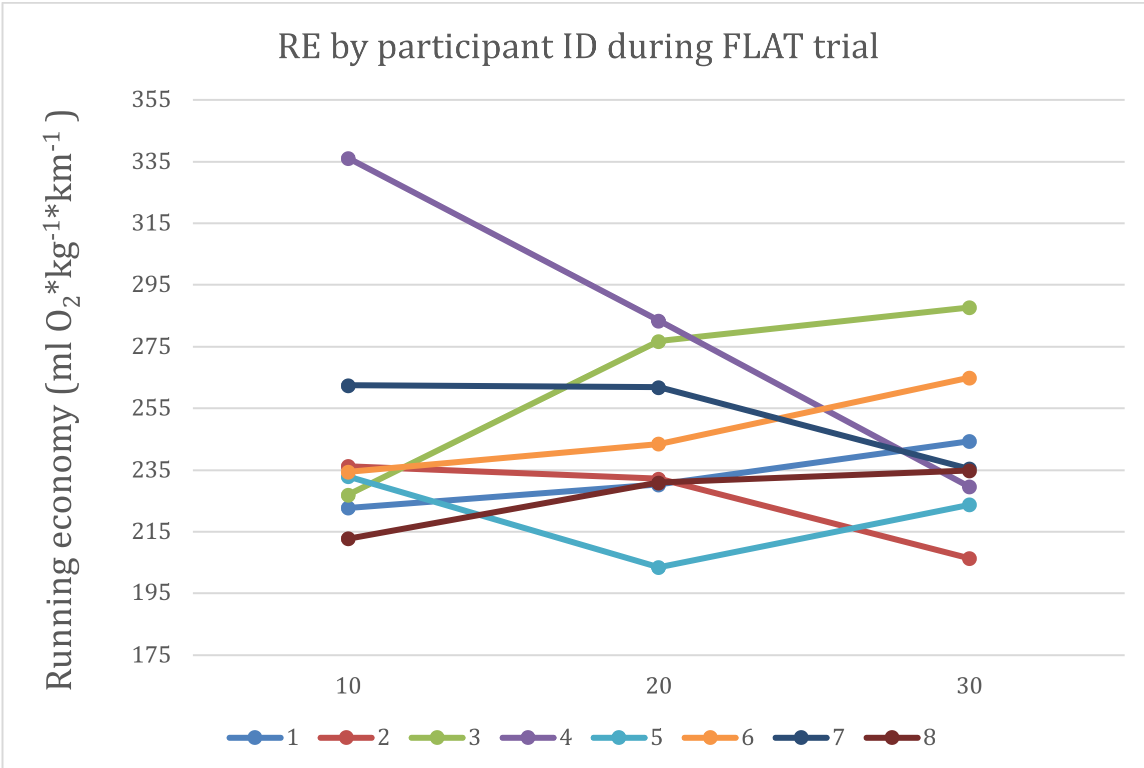


Figure 7. Running economy by participant ID throughout the 30-minute PLATE time trial.

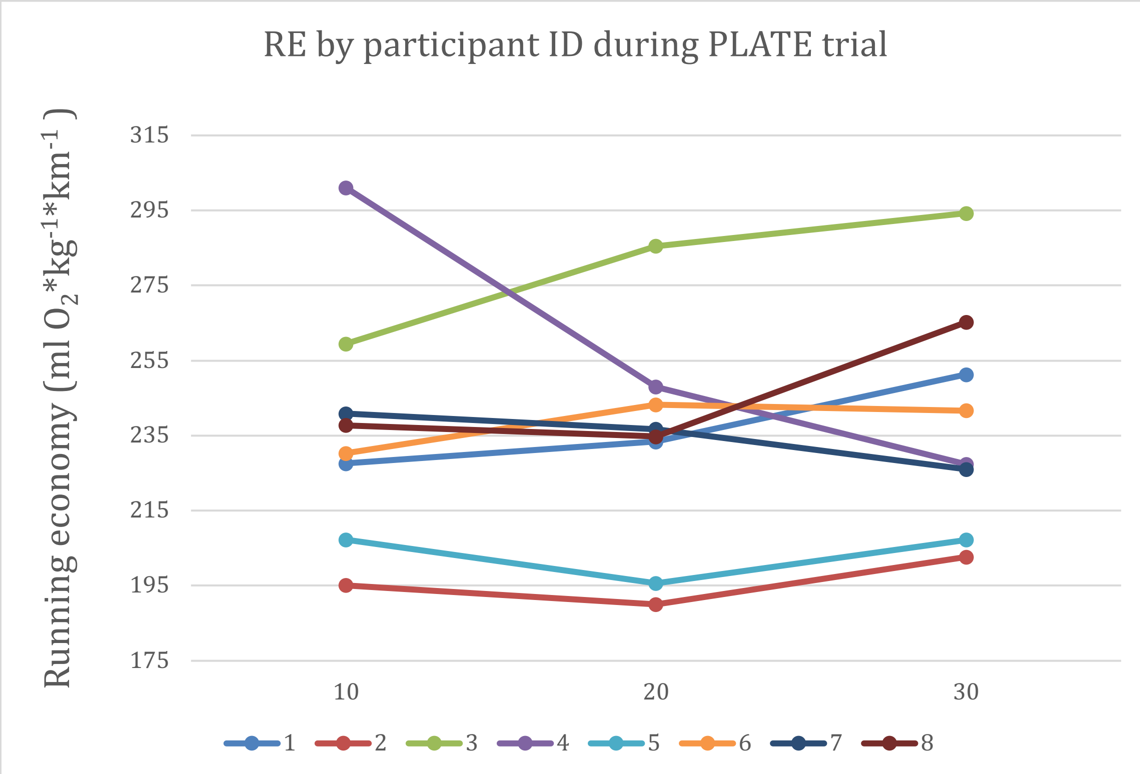
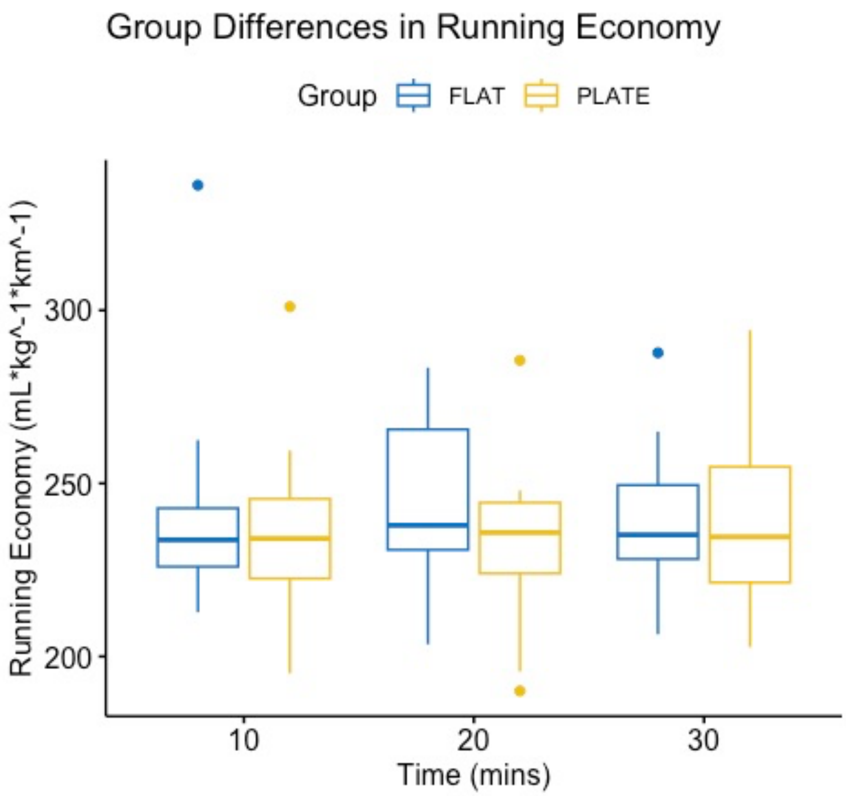


Figure 8. Group differences in running economy during the 30-minute time trials by shoe condition.



Figures 6 and 7 illustrate individual responses in terms of running economy for both shoe conditions throughout the 30-minute time trial. A wide variance is apparent, indicating response levels to carbon plated shoes are varied by individual. Figure 8 depicts group means and variance for running economy data during the 30-minute time trial in both shoe conditions.

Table 7. Repeated measures ANOVA examining differences in running economy between and within group, and time.

	Effect	**DFn**	**DFd**	***F***	***p***	**ges**
1	Group	1.00	7.00	1.191	0.311	0.015000
2	Time	1.12	7.87	0.02	0.914	0.000924
3	Group * Time	2.00	14.00	1.197	0.331	0.006000

Table 7 shows no significant effects between or within the groups (FLAT/PLATE) or time during the 30-minute time trial (p = 0.311, 0.914, 0.331). This indicates no significant differences in running economy between time points. The shoe condition also had no effect on whether running economy differed throughout the 30-minute time trial.

Chapter 5: Discussion

Distance Covered and Speed

Identifying the differences in distance covered and speed was the main goal of this study. The current research on performance outcomes such as speed has targeted time trial efforts of two miles or 3,000m (Nielsen et. al, 2022; Hébert-Losier et. al, 2022). Neilsen et. al (2022) found an improvement in time trial performance (3,000m) by a mean of 9 seconds in the Nike Vaporfly compared to a non-plated racing flat. Hébert-Losier et. al (2022) observed an improvement in 3,000m time trial performance of 16.6 seconds (2.4%) in a Nike Vaporfly compared to a non-plated racing flat. Both results were statistically significant, but differ from this study in the time trial distance tested. In distance running performance contexts, these distances are mostly raced in spikes, not carbon plated road racing shoes. This study was also designed to be more specific to the performance contexts in which carbon plated road racing shoes are typically used. Hence a 30-minute time trial was used to better estimate their effects on race distances of 10,000m and perhaps further. Table 3 illustrates group and individual differences in distance covered, speed, and kilometer pace. These variables all describe a change in the same thing, speed over a given amount of time. The observed improvement by 3.5 seconds per kilometer (p = 0.02979) is perhaps the most practically relevant finding of the study. This average speed improvement in carbon plated shoes corresponds to a 1.5% speed increase. This is lower than estimates given by Hoogkamer et. al (2017), but Hoogkamer's speed improvement estimates were given for world record marathon pace, which is approximately 55 seconds per kilometer faster than the group mean in this study. While there are certainly many other factors at play in this study, 3.5 seconds per kilometer and 1.5% speed improvement are some of the first evidence-based estimates for the performance benefits gained from carbon plated shoes in terms of speed for a long-distance running event. The speed and percent improvements likely change slightly with a change in pace, which is a future area of study that needs to be explored. Additionally, participants covered 0.1188 kilometers more during the 30-minute time trial while wearing a carbon plate. This translates to 118m which is a large difference in high performance contexts. To contextualize the magnitude of observed improvements, in most World Championship and Olympic 10,000m races since 2008, the top 10 finishers are within 100m of each other, with the medals often being decided by less than 5m (Renfree et. al, 2020). In less elite contexts, these differences are certainly practically relevant as well. A common benchmark for age group runners is to qualify for the Boston Marathon. With an improvement by 3.5 seconds per kilometer, this could potentially change a long-distance race finish by minutes.

Running Economy

Research investigating the effect carbon plated shoes have on running economy is much more plentiful than the effect on speed. This partially is why this study focused on speed and distance instead of running economy. Even as a secondary metric however, some insights were gleaned into the interplay between carbon plated shoes and running economy. First, during the standardized warmup at 70% of $vVO_{2\ max}$, the speed was not changed between the two trials. A 3.17% improvement in running economy was observed during the carbon plated trial which had a small effect size (d = 0.276). Though this was not statistically significant, these findings are fairly consistent with other studies examining the effect of carbon plated shoes on RE per a systematic review (Knopp et. al, 2023). These savings further bolster a growing body of evidence indicating 2-6% improved economy in carbon plated shoes compared to traditional road racing flats. Evidence showing improved economy at submaximal paces is extremely relevant for longer distance races such as marathons, and long-distance triathlons in which intensities are much lower than shorter races.

Running economy during the 30-minute time trials was calculated using an equation by di Prampero & Ferretti (1999) due to the non-zero anaerobic contribution. This allowed for oxygen cost to remain in terms of ml O_2*kg^{-1}*min^{-1} and were estimated based on lactate concentrations for each time point during the 30-minute time trial. Running economy was calculated factoring in speed and expressed as ml O_2*kg^{-1}*km^{-1}. Table 5, Figure 4, and Figure 5 illustrate running economy between groups during the two 30-minute time trials, by shoe condition. No statistically significant changes were seen, and only trivial to small effect sizes were associated with running economy at each time point during the 30-minute time trials. This indicates a similar effort between the two trials, which bolsters the validity of the speed improvement findings. The small effect size changes between the groups occurred at both the 10 and 20-minute time points. Running economy was improved by 3.32% and 4.85% in the plated condition for these time points. These findings are also consistent with economy improvements cited in current literature (Knopp et. al, 2023). The lack of statistically significant differences in running economy between groups could also be affected by findings that illustrate running economy expressed in terms of oxygen (as ml O_2*kg^{-1}*km^{-1}) tends to be lower at faster speeds (Fletcher et. al, 2009). Thus, the higher average running speeds in the plated condition in this study could have mitigated any potential improvements in running economy gained from the shoes.

When examining running economy trends from the data in this study, perhaps the economy savings from a carbon plated shoe during the early stages of a time trial or race allow for greater anaerobic contribution later in a race. This could explain the data provided in this study that shows a small effect size associated with an increase in efficiency (a decrease in RE) in carbon plated shoes at the 10 and 20-minute time points. A higher anaerobic contribution is observed at the 30-minute time point and is associated with a small effect size for increased RER in the carbon plated shoe condition, which will be discussed more later. These findings certainly bear further investigation, but may provide a hypothesis behind the mechanisms for speed improvements in long distance events when wearing carbon plated shoes.

Furthermore, with a small effect size seen for the 10 and 20-minute time points, and a trivial effect size observed at the 30-minute time point for changes between shoe condition, it is possible the lack of statistical significant differences in economy are due to a small sample size. It is also possible that the carbon plated shoes result in higher efficiency when an athlete is fresher, for example during the first 20 minutes of the time trial. Perhaps when the athlete reaches exhaustion towards the end of a race, or in this case time trial, the difference in ability to use oxygen is negligible as the anaerobic contribution and other factors play an increasingly important role in the athlete's ability to increase speed and 'kick' in races. It is also possible that improved running economy early in the trial allowed for greater increases in speed later in the trial.

Heart Rate

During the two 30-minute time trials, there was a small effect size associated with lower heart rates in the non-plated shoe trial. This finding was not statistically significant, but a small effect size in addition to a directional change at both the 20 and 30-minute timepoints of the trial are worth noting. While intuitively, lower heart rate may make more sense in the carbon plated trial due to the increased efficiency, this data may give insight into some mechanisms behind the improvement in performance by carbon plated shoes. The traditional racing flats used in the FLAT trial typically have far less cushioning compared to the shoes used in the PLATE trial (Burns & Tam, 2020). Perhaps the breakdown in performance in the FLAT trial came from a mechanical breakdown due to having less shock absorbance in the shoes. This could potentially limit the amount of cardiovascular or metabolic work that could be done if the stress is shifted more onto the bones, muscles, and joints of the body. The limiting factor in a non-plated shoe may be weighted towards the mechanical stress rather than the metabolic or cardiovascular stress. In a plated shoe, it is possible that the higher cushion allows for lower mechanical stress on the body, and the limiting factor becomes weighted further towards the heart and metabolic pathways and their ability to do work.

Another hypothesis is that the energy savings seen in the early portion of the trial allowed the runners to continue to increase intensity later in the trial, whereas the higher metabolic cost of running in the FLAT condition resulted in fatigue that limited the runners' ability to maintain a maximal effort later in the time trial. Figure 3 illustrates an increased ability to maintain speed during between the 20 and 30-minute timepoints of the time trial for the PLATE condition. While the speed wasn't increased between the two timepoints, the decrement in speed was less than in the FLAT condition. These hypotheses certainly need to be studied, but the heart rate data in this study may provide a hint into some mechanism behind performance improvement in carbon plated shoes.

RPE and RER

RPE and RER were also measured throughout each 30-minute time trial, with no significant changes seen. This is to be expected especially for RPE, as the participants effort should have been near maximal for both time trial conditions. This further validates any speed difference findings as it indicates that the participants' perception of effort was the same for both the FLAT and PLATE trial. RER values were slightly lower in at the 20 and 30-minute time points during the FLAT trial, but slightly higher at the 10-minute time point. A small effect size was associated with these findings, but due to the multidirectional nature of the differences, this is likely due to the small sample size. There is a small possibility that by reducing the mechanical stress on participants legs, during the PLATE trial, they were able to remain fresh enough to finish at a higher speed and intensity resulting in higher CO_2 values, which ultimately raises the RER. A higher RER illustrates higher anaerobic contribution during the later stages of the PLATE time trial, which could be another mechanism for improvements seen in carbon plated shoes, although more research would be necessary.

Limitations and future directions

This study was limited in sample size, and funding, which lends itself to being improved by researchers in the future. The small sample size provided statistical challenges such as assigning power and statistical significance in particular for our secondary variables. It also makes this study at higher risk to being skewed by outliers. As previously mentioned, many factors are at play in endurance performance, so the chances of one, or multiple, of non-biomechanical or metabolic factors having an effect on participants' time trial performance is more likely. Increased funding, providing shoes for participants, and a longer time frame would likely increase the number of participants in potential future studies. Another potential limitation is that the time trials were completed on a treadmill. While this mimics running on the roads fairly accurately, the specificity of completing a time trial on a road course simulates what these shoes are practically used for more, although this would come with challenges of its own. If a portable metabolic measuring device could be used, this would be a good option. This would also allow for various distances to be tested.

Further research can certainly build off frameworks and insights provided by this study. The framework and methodology in this study focused on speeds accessed by runners in long distance races, but could be translated into a study focusing on shorter distance events. As previously discussed, some of the current research including time trials has included shorter distance time trials, so perhaps longer time trials are necessary to be completed going forward. Longer time trials are also more applicable to the purpose of carbon plated road racing shoes as they are marketed and designed to optimize long distance running performance, especially the marathon. The framework can also be applied to studies examining different specific carbon-plated shoes, and perhaps even performance differences within the carbon-plated shoe genre. Additionally, more research is needed to draw strong conclusions about the effectiveness of carbon plated shoes in different populations. Trained runners were used in this study, but the implications on elites and novice runners can provide insight into who gleans more benefit, and ultimately who may wish to invest in carbon plated shoes. As seen in this study, and shown by others (Knopp et. al, 2023), the variability in response levels to carbon plated shoes is substantial. The mechanisms behind the variability demonstrated are unclear and require further investigation. If we are able to identify biomechanical archetypes that respond better to certain carbon-plated shoe models, this could optimize benefit for the athletes, and further development of the shoes.

Chapter 6: Conclusion

Overall, this study furthers the ever-growing body of evidence of the efficacy of carbon plated shoes. It also adds to the limited body of research examining performance differences in terms of speed provided by carbon plated technology. There has been an on-going debate about how much these shoes actually impact performance by coaches, athletes, and officials. This study provides a starting point for estimates when referencing longer distance races, 10,000m and potentially up to the marathon. This can be used to contextualize performances and to assist in rule/regulation formation.

The purpose of this study was to provide an estimate of the performance benefits provided by the energetic cost savings of a carbon plated shoe compared to a traditional, non-plated racing flat. The findings indicate improved performance in terms of speed, which is no surprise considering multiple previous studies have shown their efficacy in terms of metabolic savings, and some that have demonstrated improvements in time trial performance. While the findings in this study aren't a definitive answer to the question 'how much faster do carbon plated shoes make runners,' it is one of the first studies to provide an estimate based on a scientific rationale.

Chapter 7: References

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