Does plantarflexion fatigue influence running economy response to advanced footwear technology?

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Abstract

Since the introduction of shoes with advanced footwear technology (AFT), all world records from the 5 km to the marathon have been broken by runners wearing AFT shoes. Previous research reports an average 4.0% improvement in running economy (RE) measures in runners wearing AFT shoes; however, there is large inter-individual variability in RE responses. It is speculated that plantarflexion strength may contribute to this variability. Therefore, this thesis investigated the effects of plantarflexion fatigue on RE response to AFT shoes. It also explored correlations between baseline plantarflexion function and RE response in AFT shoes, as well as the relationship between the changes in plantarflexion function and changes in RE response from pre-plantarflexion fatigue (PRE) to post-plantarflexion fatigue (POST).

Chapter one includes a summary of literature on AFT shoes and the triceps surae muscles as these are the main contributors to plantarflexion. In summary, AFT shoes contain an embedded rigid element, larger stack height than traditional running shoes to accommodate a responsive and compliant midsole material, and a curved forefoot geometry, while remaining lightweight. Each of these AFT shoe elements appear to interact with each other to improve RE by an average of 4.0%, rather than the elements providing benefits individually that are summative. The triceps surae, comprising the soleus, gastrocnemius medialis, and gastrocnemius lateralis, meaningfully contribute to RE and performance. Previous studies have speculated that runners need a certain amount of plantarflexion strength to fully benefit from AFT shoes. Therefore, fatigue of the plantarflexion muscles may diminish the RE benefits from wearing AFT shoes.

Chapter two presents the main experimental study. Sixty-four participants (age, 33.5 ± 15.6 y; sex, 32 male, 32 female; VO_{2peak}, 49.4 ± 8.3 mL/kg/min) completed two experimental sessions. Session one collected demographic information, familiarised participants to the plantarflexion power test, and finished with an incremental VO_{2peak} treadmill test. Session two started with a baseline plantarflexion power test, leading into four six-minute RE tests using the Salomon Areo Glide 2 (Control shoe) and Salomon Phantasm S/Lab 2 (AFT shoe) in a counterbalanced mirrored crossover design. These data defined the PRE RE tests. These RE tests were followed by two rounds of a plantarflexion fatigue protocol, including pre-plantarflexion (PRE) and post-plantarflexion (POST) power tests. Each fatigue protocol was followed with a calf muscle fatigue and soreness visual analogue scales, along with a RE test in a counterbalanced shoe condition. Repeated measures RM ANOVA revealed that RE improved by 4.0 to 4.3% in the AFT shoe compared to the Control shoe, while overall RE declined 1.6 to 2.4% after plantarflexion fatigue. There was no significant interaction between shoe condition and time (PRE and POST) on oxygen consumption, energy cost, and energetic cost of transport (all, $P \geq 0.691$). Furthermore, baseline plantarflexion power did not significantly correlate to AFT shoe response (all, $P \geq 0.132$), nor did the changes in plantarflexion power from PRE to POST with the change in AFT shoe response (PRE to POST) ($P \geq 0.930$).

Chapter three summarises the experimental study results, along with practical implications and suggestions for feature research direction. This thesis provides further evidence that AFT shoes improve RE by an average of 4.0% and shows plantarflexion fatigue from repetitive calf raises worsens RE by 1.6 to 2.4%. However, contradicting our hypothesis and previous speculations, plantarflexion fatigue did not significantly influence AFT shoe response. These findings suggest runners may still respond favourably to AFT shoes with plantarflexion fatigue, which is seen during long-distance running. Furthermore, runners, coaches, retailers, and manufacturers may not need to consider plantarflexion strength when recommending AFT shoes for improving RE, although additional research on this specific topic is warranted for confirmation.

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Abbreviations

3D – three dimensional

AFT – advanced footwear technology

BW – body weight

bpm – beats per minute

CI – confidence interval

CV – coefficient of variation

ICC – intraclass correlation coefficient

max – maximum

min – minimum

MVIC – maximal voluntary isometric contraction

NZ – New Zealand

PRE – pre-plantarflexion fatigue

POST – post-plantarflexion fatigue

RE – running economy

RM ANOVA – repeated measures analysis of variance

RPE – rate of perceived exertion

RUN-CAT – running shoe comfort assessment tool

SD – standard deviation

US – United States

VAS – visual analogue scale

VCO_2 – volume of carbon dioxide

VO_2 – volume of oxygen

VO_{2peak} – peak oxygen uptake

*v*VO2peak – velocity at peak oxygen uptake

Thesis Overview

The main objective of this thesis was to identify whether plantarflexion fatigue influences running economy response to an advanced footwear technology shoe (Salomon Phantasm S/Lab 2) compared to a control shoe (Salomon Aero Glide 2). A secondary aim was to explore whether baseline plantarflexion function was linked to running economy responses, and whether changes in running economy responses to advanced footwear technology shoes with fatigue were linked to changes in plantarflexion function with fatigue.

This thesis comprises of three chapters (Figure 1). Chapter one includes a literature review on advanced footwear technology shoes, the triceps surae muscles, and the contribution of these shoes and the triceps surae muscles to running economy and performance. Chapter two encompasses an experimental study investigating running economy changes in an advanced footwear technology shoe and a control shoe before and after plantarflexion fatigue.

Chapter three provides a summary of the thesis, while highlighting the strength, limitations, and implications found from the results of the experimental study, and suggesting potential future research topics.

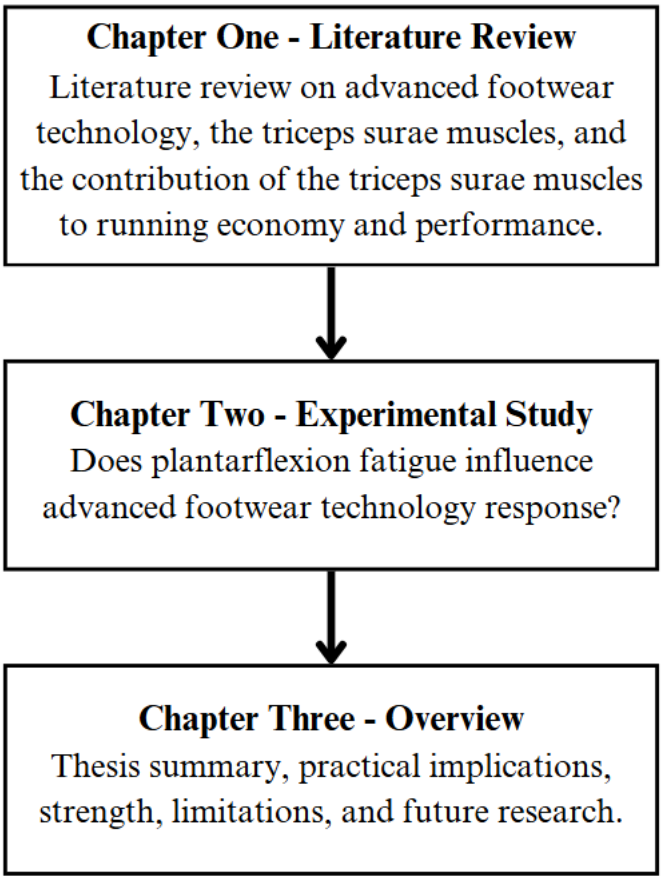


Figure 1. Thesis flow diagram.

Chapter One - Literature Review

Literature review on advanced footwear technology, the triceps surae muscles, and the contribution of the triceps surae muscles to running economy and performance.

Background

The history of running shoes dates back over 10,000 years ago, a time when shoes were made from woven sagebrush and had the main purpose of protecting the foot from the external environment (Altman & Davis, 2012). Between 1920 and 1940, rivalling brands Puma and Adidas were made by brothers Rudolph and Adi Dassler, who specialized in track and field footwear (Lund & Little, 2021) which consisted of a flexible upper and thin outsole (Alger, n.d.). Then in the 1960s, Onitsuka Tiger (later renamed to Asics) developed a shoe consisting of a multi-layer outsole to provide more cushioning (Bermon et al., 2022), along with Blue Ribbon Sports (later renamed to Nike) inventing the waffle cone patterned outsole (Morris, 2018). To this point, running footwear were relatively minimalistic in design, with low stack height, minimal heel-to-toe drop, and sparse technological features (Lieberman et al., 2010). However, in 1974, Brooks introduced and popularised pronation control technologies in shoes, as pronation was thought to increase injury risk (Bermon et al., 2022). Up until the 1960s, running was deemed as an activity only competitive athletes did or as part of extracurricular schooling (Bale, 2004). Now moving forward to the 2000s, running has become increasingly popular with millions of recreational runners around the world (Coetzee et al., 2018; Dellwing, 2022). With this increased popularity, running shoes evolved to include features like a large stack height, heel-to-toe drop, and include more motion control technologies (Coetzee et al., 2018; Pollard et al., 2018). In 2017, Nike introduced advanced footwear technology (AFT) through the breaking 2:00 attempt (Hébert-Losier & Pamment, 2023), which has substantially changed the shoe market and the competitive running scene (Bermon et al., 2022).

Since the introduction of AFT shoes, all world records from the 5 km to the marathon have been broken (Muniz-Pardos et al., 2021). Furthermore, analysis from a group of runners who switched from shoes without AFT to shoes with AFT revealed an average marathon time improvement of 1.4% (~1:42 minutes) in males, and 2.1% (~3:01 minutes) in females (Bermon et al., 2021). Initial studies involving AFT shoes indicated an average 4.0% improvement in running economy (RE) measures in runners from recreational to elite (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023), which is believed to be a key contributor to enhanced running performance in AFT (Hoogkamer et al., 2016). Shoes with AFT, also known as 'super shoes', have an embedded rigid element, larger stack height to accommodate a responsive and compliant midsole material, and a curved forefoot geometry, while remaining lightweight (Burns & Tam, 2020; Hébert-Losier & Pamment, 2023). How each element contributes to RE and performance improvements is challenging to parse, as it seems individual elements of AFT shoes interact with each other (Ghanbari et al., 2025; Healey & Hoogkamer, 2022; Hébert-Losier & Pamment, 2023).

Although studies typically show an average improvement in RE measures when wearing AFT shoes, these average improvements demonstrate inter-individual variability (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Knopp et al., 2023). Some runners experience large RE benefits, while others may see limited-to-no improvement or even be negatively affected (Hébert-Losier et al., 2022a)**.** In world-class Kenyan and amateur European male runners, AFT shoes benefited oxygen consumption measures up to 11.4 and 9.7% in comparison to traditional lightweight racing shoes, respectively. However, some runners experienced detriments of 11.3 and 1.1%, respectively (Knopp et al., 2023). Alongside RE variability is performance variability. In 3 km time trials performed on a treadmill, 61% of participating male recreational runners ran their fastest times in an AFT shoe, while the remaining 39% performed their best time in a traditional road racing flat (22%) or their own (17%) shoes (Hébert-Losier et al., 2022a). It is unclear what factors are responsible for this inter-individual variability in AFT shoe response.

The triceps surae muscles are the main plantarflexors at the ankle, and comprise of the medial and lateral gastrocnemius, soleus, and plantaris muscles (Spina, 2007). The soleus and both gastrocnemius muscles share a common distal tendon, the Achilles tendon, which is the longest and one of the strongest tendons in the human body (Maffulli, 1999). The triceps surae also has a role in running performance, as greater stiffness (Nguyen et al., 2025) and strength of the triceps surae are associated with improved RE measures (Arampatzis et al., 2006; Bohm et al., 2021). Masters runners (over 35 years of age) typically show a decline in triceps surae muscle mass, Achilles tendon stiffness, and maximal voluntary isometric contraction (MVIC) of plantarflexion strength (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012). These declines result in lowered concentric ankle power, which itself is associated with reduced propulsion (Pandy et al., 2021), shortened stride length, and slower running velocity (DeVita et al., 2016; Dorn et al., 2012). This lowered ankle power could also result in reduced RE benefit to AFT shoes, as it is speculated runners need a certain amount of plantarflexion strength to positively respond to AFT shoes (Ortega et al., 2021). Therefore, the RE benefit runners' gain from AFT shoes may vary throughout a long-distance race with plantarflexion fatigue, as MVIC of plantarflexion strength has also been shown to decline by 9 to 29% with prolonged running (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008).

Given this background, this chapter summarises key literature on AFT shoes, addressing their components and benefits towards running. Additionally, this chapter addresses literature relating to the triceps surae, specifically in relation to running, running with fatigue, and AFT shoes.

AFT Shoe Components

Rigid Elements

Shoes with AFT, also known as ‘super shoes’, have an embedded rigid element, larger stack height to accommodate a responsive and compliant midsole material, and a curved forefoot geometry, while remaining lightweight (Burns & Tam, 2020; Hébert-Losier & Pamment, 2023).

Rigid elements are implemented into AFT shoes in various ways; commonly through a rigid plate that is full-length or partial-length, top-loaded or bottom-loaded, and curved or straight (Farina et al., 2019; Ortega et al., 2021). However, some shoe companies use rigid rods instead of plates. Initial studies using embedded carbon fibre plates within running shoes showed 1.0% improvements to RE measures (Roy & Stefanyshyn, 2006), speculated to be from less energy loss at the metatarsophalangeal joint (Stefanyshyn & Nigg, 2000). However, more recent studies cut the carbon fibre plate in AFT shoes which lowered the longitudinal bending stiffness without compromising the RE benefit (Chollet et al., 2023; Healey & Hoogkamer, 2022), with very little biomechanical changes to the metatarsophalangeal joint (Healey & Hoogkamer, 2022). More recently, a shoe without a carbon fibre plate was compared against two shoes with a carbon fibre plate of differing stiffness levels (35.5 N/mm and 43.1 N/mm). The AFT shoe with the moderate level of stiffness (35.5 N/mm) showed superior RE measures (2.0 to 2.7%), with no significant difference between the stiffest AFT shoe (43.1 N/mm) and the one without a carbon fibre plate (Rodrigo-Carranza et al., 2024), suggesting there is an universal optimal bending stiffness of which runners could benefit from longitudinal bending stiffness. However, other research suggest runners may require individualised amounts of stiffness to benefit from an embedded rigid element (Day & Hahn, 2020; McLeod et al., 2020; Oh & Park, 2017). Furthermore, it is speculated this individualised optimal bending stiffness may differ between running speed (Day & Hahn, 2020).

Midsole

Midsole foams within AFT shoes are made of materials similar to polyether block amide, early research on AFT shoes demonstrated polyether block amide returned 87.0% of the energy stored, compared to only 65.5% with a traditional lightweight ethylene vinyl acetate foam (Hoogkamer et al., 2018). These midsoles are usually thicker, resulting in a larger stack height in comparison to traditional running shoes (Hébert-Losier & Pamment, 2023; Hoogkamer, 2020). The stack height is the maximal vertical thickness of a midsole at the heel of a shoe (Frederick, 2020). Larger stack heights are essentially extending leg lengths, where an 8 mm increase to a runners leg length is thought to account for ~25% of the benefit in energetic costs of transport from AFT shoes (Burns & Tam, 2020). Despite the increased amount of midsole material from the larger stack height, these midsole materials of AFT shoes have a low density meaning the shoe can remain lightweight. Having a lightweight shoe is beneficial for RE, as there is a 0.7 to 1.1% increase in oxygen consumption (mL/kg/min) for every 100 g of added mass to a running shoe (Franz et al., 2012).

Component Interactions

Implementing a rigid plate makes the point of rotation further away, creating a longer lever at the ankle. With this increased lever length, runners tend to adopt one of two strategies; either keeping a consistent push-off time while increasing torque at the ankle, or increasing push-off time while lowering torque at the ankle (Willwacher et al., 2014). With the increased push-off time, muscle contraction speed is slowed and is accompanied with less gastrocnemius activity (Hata et al., 2024), which could be less metabolically demanding (Barclay et al., 1993; Bottinelli et al., 1994; He et al., 2000; Hill, 1938). However, a more recent study found that AFT shoes reduced metabolic cost without altering soleus or gastrocnemius activity, compared to shoes with either a carbon fibre plate and ethylene vinyl acetate foam or without a carbon fibre plate and with polyether block amide foam (Ghanbari et al., 2025). While these results show that AFT shoe components interact to provide RE benefits, further studies are still needed to quantify whether lower metabolic costs associated with running in AFT shoes compared to more traditional shoes are accompanied with lowered activity with the soleus and gastrocnemius muscles.

Some suggest a curved geometry of the rigid element and midsole foam of an AFT shoe creates a ‘teeter-totter’ effect, which is thought to make it easier to plantarflexion (Nigg et al., 2021; Subramanium et al., 2024). However, a study proving this concept was comparing running mechanics between an AFT shoe and a traditional basketball shoe (Subramanium et al., 2024). Additionally, when the teeter-totter effect is reduced, changes in RE are not observed (Healey & Hoogkamer, 2022). Furthermore, a rigid plate is speculated to distribute pressure more evenly across the midsole foam, which creates more of an area-elastic foam instead of a point-elastic foam (e.g., acting more like a diving board rather than a pillow) (Kram, 2022). However, under controlled conditions using a cylindrical stamp pressing at 350 kPa to reflect a heel strike, there was little change in shoe foam behaviour in a shoe with and without a rigid plate (Burns & Joubert, 2024). Although this experiment does not necessarily reflect how the shoe elements interact under actual running conditions, it does highlight the limited understanding of how AFT shoe components interact to improve RE and running performance (Ghanbari et al., 2025; Healey & Hoogkamer, 2022; Hébert-Losier & Pamment, 2023).

AFT Shoes and Performance

Since the introduction of AFT shoes in 2017, every world record from the 5 km to the marathon have been broken by runners wearing an AFT shoe (Muniz-Pardos et al., 2021). Research involving AFT shoes identify an average 4.0% improvements in RE measures from recreational to elite runners (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023), which is believed to be a major contributor to enhancing running performance (Hoogkamer et al., 2016) since running at a given speed is less metabolically demanding when RE is improved (Di Prampero et al., 1986; Joyner, 1991).

Although average improvements of approximately 4.0% in RE are reported, large amounts of inter-individual variability exist. In a study involving male recreational runners (Hébert-Losier et al., 2022a), AFT shoes had up to 9.7% positive and 9.6% negative effect on oxygen consumption (mL/kg/min) between individuals. Similar inter-individual variability has been reported for world-class Kenyan and amateur European male runners (Knopp et al., 2023). AFT shoes benefited oxygen consumption measures up to 11.4 and 9.7% in comparison to traditional lightweight racing shoes, respectively. However, some runners experienced detriments of 11.3 and 1.1%, respectively. Alongside RE measures, treadmill 3 km time trial performances also showed large inter-individual variability, with 61% of participants running their fastest time in an AFT shoe, while the remaining 39% performed their best time in a traditional road racing flat (22%) or their own shoe (17%). Methodological variations in protocols can explain some of the reported variability, such as averaging short windows during metabolic testing, assessing one trial only in each experimental shoe (Hébert-Losier et al., 2022a; Knopp et al., 2023), or conducting testing on different days (Hébert-Losier et al., 2022a). Furthermore, these studies reporting larger individual variation in RE used traditional racing flats as the shoe comparator to an AFT shoe (Hébert-Losier et al., 2022a; Knopp et al., 2023), while studies which report less individual variation used a leading non-AFT marathon racing shoes at the time (Hoogkamer et al., 2018; Hunter et al., 2019). Further studies comparing the effects in AFT shoes and AFT spikes also demonstrate how responses charge with the shoe comparators (Joubert et al., 2024). However, several other factors have been speculated to potentially underpin the reported variability in RE responses to AFT shoes, including running speed, habituation, placebo, and plantarflexion strength.

In terms of running speed, RE benefits from wearing AFT shoes appear greater when running at faster speeds (Day & Hahn, 2020; Joubert et al., 2023; McLeod et al., 2020; Paradisis et al., 2023). An average 3.9% benefit in oxygen consumption to AFT shoes are shown at 65% velocity at VO_{2peak} (vVO_{2peak}), while an average 5.0% benefit at 80% vVO_{2peak} (Paradisis et al., 2023). However, despite males running faster than females, female world best racing times are progressing faster than male world best racing times with the inclusion of AFT shoes (Mason et al., 2024; Willwacher et al., 2024), suggesting that higher relative speeds may inflect better RE response to AFT shoes in comparison to absolute running speeds. Moving onto habituation of AFT shoes, a pilot study including eight runners showed more favourable responses to AFT shoes after an eight-week habituation period (Matties & Rowley, 2023). However, a more recent study involving sixteen trained long-distance runners found no significant difference in RE measures between runners who had not run in AFT shoes against those who had run 20 to 522 km in AFT shoes (Schwalm et al., 2024). The potential for a placebo effect contributing to the benefits of running in AFT was proposed (Hébert-Losier et al., 2022a; Hoogkamer et al., 2019; Hunter et al., 2019), but recent findings suggest no significant placebo effect on RE measures (Hébert-Losier et al., 2025). Finally, researchers have suggested a lack of plantarflexion strength may limit the RE benefits of wearing shoes with carbon plates or other similar stiff elements (Madden et al., 2016; Ortega et al., 2021), with applications towards AFT shoe responses. Highlighting the importance of considering muscular contributions, particularly those of the triceps surae, when evaluating biomechanical and metabolic responses to AFT shoes.

Triceps Surae and Performance

The triceps surae muscles are the main plantarflexors at the ankle, and comprise of the medial and lateral gastrocnemius, soleus, and plantaris muscles (Spina, 2007). The soleus and both gastrocnemius muscles share a common distal tendon inserting at the calcaneus, the Achilles tendon, which is the longest and one of the strongest tendons in the human body (Maffulli, 1999). The plantaris muscle has its own tendon that also inserts at the calcaneus (Spina, 2007). The triceps surae muscles contribute up to 80% of plantarflexion torque (Murray et al., 1976), primarily driven by the soleus and gastrocnemius. The soleus is monoarticular, originating from below the knee joint, whereas the gastrocnemius muscles are bi-articular and originate from above the knee joint. Hence, these muscles primarily act to plantarflexion the ankle, with the gastrocnemius also contributing to knee flexion. The plantaris muscle is also bi-articular, but contributes very little towards plantarflexion and knee flexion, and rather helps with proprioception due to a higher density of muscle spindles (Spina, 2007). For the remainder of this thesis, the triceps surae will refer to the soleus and gastrocnemius muscles.

The triceps surae muscle-tendon unit is a key contributor to distance running (DeVita et al., 2016; Dorn et al., 2012). The triceps surae contributes the most toward propulsion and support throughout the second half of the stance phase, in comparison to other lower extremity muscles (Hamner et al., 2010). Additionally, the soleus generates approximately double a runners body weight in ground reaction forces (Hamner & Delp, 2013), while the Achilles tendon can experience from 4.4 to 7.7 body weights of load during running (Baxter et al., 2021; Demangeot et al., 2023). During the stance phase of running, the Achilles tendon stretches and stores elastic potential energy. When an Achilles tendon is stiffer (Nguyen et al., 2025), longer, and has a larger cross-sectional area; it can store and release more elastic energy, proving beneficial for RE (Machado et al., 2022; Stenroth et al., 2016). Furthermore, runners with shorter triceps surae muscle fibres will have a larger proportion of shank mass distributed more proximally to the knee joint, resulting in a more energy efficient swing phase during running (Machado et al., 2022). The importance of the triceps surae is reflected through the age-related declines in muscle mass, Achilles tendon stiffness, and MVIC of plantarflexion strength with masters runners (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012), which all contribute to reduced running performance (Willy & Paquette, 2019). Concentric ankle power, which is strongly correlated with propulsion (Pandy et al., 2021) and stride length (DeVita et al., 2016; Dorn et al., 2012), also decreases with age, often leading to shorter stride lengths and reduced velocity (Willy & Paquette, 2019). The importance of the triceps surae also extends to sprinting, as greater plantarflexion power and strength endurance in Rugby Union players show a *large* relationship with 10 m sprint times (Hébert-Losier et al., 2023), while a heavier one-repetition maximum calf raise is associated with faster 30 m sprint times in university students (Möck et al., 2018).

Fatigued Triceps Surae

Muscular fatigue is defined as a reduction in maximal force output and greater task difficulty for prolonged or repetitive efforts (Enoka & Stuart, 1992). Muscle fatigue can be split into two categories: central and peripheral (González-Izal et al., 2012; Maclaren et al., 1989). Central fatigue is the reduced ability to voluntarily produce force due to a reduction in motor unit recruitment (González-Izal et al., 2012). Peripheral fatigue is reduced force generation due to altered neuromuscular transition and action potential propagation at the neuromuscular junction (Carroll et al., 2017; González-Izal et al., 2012; Maclaren et al., 1989).

The triceps surae is suspectable to fatigue during prolonged running, resulting in large declines (9 to 29%) in MVIC of plantarflexion strength measures (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). It is clear why the triceps surae is prone to fatigue when considering it accounts for ~25% of the total metabolic cost of running in highly trained individuals, and up to ~40% in untrained individuals (Fletcher & MacIntosh, 2015). Additionally, the ankle produces the most amount of positive work during running compared to the hip and knee (Schache et al., 2019), while contributing the most towards vertical support and stride length while running at speeds less than 7 m/s (25.2 km/h) (Dorn et al., 2012). However, when the triceps surae is fatigued, positive work shifts away from the ankle joint to the knee joint (Sanno et al., 2018). This fatigue is accompanied with lowered elastic tension within the Achilles tendon, resulting in less elastic potential energy being stored and released during running (Liu et al., 2022; Machado et al., 2022). Additionally, a fatigued muscle recruits larger type II muscle fibres to a greater extent (Conwit et al., 2000; Stock et al., 2012), which could require more contractile energy (Barclay et al., 1993; Bottinelli et al., 1994; He et al., 2000; Stienen et al., 1996), suggesting a fatigued triceps surae will result in declined RE. Previous research has shown that prolonged running not only impairs RE but also induces plantarflexion fatigue. Whereby RE declines approximately 13.6% following a marathon (Kyröläinen et al., 2000) and 3.0 to 6.6% after 60 minutes of steady-state running (Sproule, 1998). While a 29.8 N reduction in plantarflexion strength is observed through MVIC after 2 hours of running (Avela et al., 1999), and a 25.9 Nm reduction following a marathon (Saldanha et al., 2008).

AFT Shoes and Triceps Surae

There are a limited number of studies which look at the interaction between the triceps surae and AFT shoes. Previous research suggests that metabolic rate and ground contact time during running are inversely related, meaning shorter contact times are associated with increased metabolic rate through quicker muscle contractions (Kram & Taylor, 1990). Although, as mentioned before, a rigid element creates a longer lever at the ankle, which could either slow the muscle contraction velocity or require greater plantarflexion strength (greater torque) (Willwacher et al., 2014; Willwacher et al., 2016), positively or negatively affecting RE respectively (Hill, 1938). Those runners who show increased push-off time from slower muscle contractions typically responded better to shoes with a stiff element compared to those who increase torque at the ankle joint (Madden et al., 2016). These findings led to speculations that runners need a ‘strong enough’ triceps surae to benefit from AFT shoes (Ortega et al., 2021), and stiffer shoes may reduce the rate of triceps surae fatigue due to slower contractile velocities of the triceps surae (Cigoja et al., 2021). However, it remains unknown how plantarflexion fatigue influences RE responses to AFT shoes or what constitutes of a ‘strong enough’ triceps surae to benefit from AFT shoes.

Summary

The running shoe industry has grown dramatically over the past century, particularly in the last decade with the emergence of AFT shoes. These lightweight AFT shoes incorporate an embedded rigid element, larger stack height alongside more responsive and compliant midsole material, and a curved forefoot geometry. Together, these elements contribute to improving RE on average by approximately 4.0%. While AFT shoes benefit RE on average, this benefit varies considerably between individuals. One area worth investigating is whether plantarflexion fatigue influences RE response to AFT shoes, as it is speculated a certain amount of plantarflexion strength is needed to benefit from AFT shoes, of which may change throughout a long-distance race.

Chapter Two - Experimental Study

Does plantarflexion fatigue influence advanced footwear technology response?

Abstract

Background: Previous research found an average 4.0% increase in running economy (RE) with runners wearing shoes with advanced footwear technology (AFT), however there is large inter-individual variability. Serval speculations have arisen to explain this variability, one being runners needing strong enough plantarflexion strength to fully benefit from AFT shoes. Therefore, this study will investigate the effects of plantarflexion fatigue on RE response to AFT shoes. **Methods:** Sixty-four participants (age, 33.5 ± 15.6 y; sex, 32 male, 32 female; VO_{2peak}, 49.4 ± 8.3 mL/kg/min) completed two sessions. Session one collected demographic information and conducted an incremental VO_{2peak} test on a treadmill. Session two included a plantarflexion power test and four RE tests in the Control and AFT shoe in a counterbalanced mirrored crossover design. These RE tests were followed by two rounds of a plantarflexion fatigue protocol, including pre-plantarflexion (PRE) and post-plantarflexion (POST) power tests. Each fatigue protocol was followed with a calf muscle fatigue and soreness visual analogue scales, along with a RE test in a counterbalanced shoe condition. **Results:** RE improved 4.0 to 4.3% in the AFT compared to the Control shoe. Plantarflexion fatigue induced 1.6 to 2.4% decline in RE. There were no significant interaction between shoe conditions and time ($P > 0.691$). Baseline plantarflexion power did not significantly correlate to AFT response ($P > 0.132$), nor did the change in plantarflexion power (PRE to POST) to the change in AFT response (PRE to POST) ($P > 0.930$). **Conclusion:** Overall, AFT improved RE while plantarflexion fatigue negatively affected RE. Isolated plantarflexion fatigue did not alter AFT response and plantarflexion power was not linked to AFT response, refuting speculations that runners need strong enough plantarflexion strength to fully benefit from AFT. Since isolated plantarflexion fatigue is not generalisable to running induced fatigue, investigating the effects of running induced fatigue on RE response to AFT is recommended.

Introduction

Advancements in running shoe technology have considerably altered the distance running landscape and meaningfully improved performances (Bermon et al., 2021; Muniz-Pardos et al., 2021). For example, runners between 2016 and 2019 who switched from shoes without advanced footwear technology (AFT) to shoes with AFT had their average marathon times improve by 1.4% (~1:43 minutes) for males and 2.1% (~3:01 minutes) for females (Bermon et al., 2021). Furthermore, all world records from the 5 km to the marathon have been broken by runners wearing an AFT shoe (Muniz-Pardos et al., 2021). The initial studies involving shoes with AFT, indicate an 4.0% average improvement in running economy (RE) in runners from recreational to elite (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023). These RE improvements generally reported in runners wearing AFT shoes are believed to be a key contributor to enhancing running performance (Hoogkamer et al., 2016), as running is less metabolically demanding at a given speed when RE is improved (Di Prampero et al., 1986; Joyner, 1991).

Initially, road racing shoes had minimal cushioning and lacked AFT to maintain low shoe mass (Esculier et al., 2015; Lieberman et al., 2010), as an 100 g increase in shoe mass raises oxygen consumption (mL/kg/min) by approximately 0.7 to 1.1% (Franz et al., 2012). In contrast, AFT shoes typically have considerably more cushioning and a stiff element embedded within the midsole. The cushioning in the midsole is more responsive and compliant than traditional foam, while remaining lightweight due to its low foam density (Burns & Tam, 2020; Hébert-Losier & Pamment, 2023). Early research on AFT shoes demonstrated the prototype foam of polyether block amide used in some AFT shoes returned 87.0% of the energy stored, compared to only 65.5% with a traditional lightweight ethylene vinyl acetate foam (Hoogkamer et al., 2018). Studies which investigated the use of carbon fibre plates as a means to increase longitudinal bending stiffness within running shoes showed a 1% improvement in RE compared to no plate (Roy & Stefanyshyn, 2006), speculatively due to reduced energy loss at the metatarsophalangeal joint (Stefanyshyn & Nigg, 2000). However, there is debate about whether increasing the longitudinal bending stiffness of shoes improves RE and how much the metatarsophalangeal joint mechanics contribute to the change in RE. In AFT shoes, cutting the carbon fibre plate element decreased the longitudinal bending stiffness of the shoes without compromising RE (Healey & Hoogkamer, 2022). Alternatively, some studies propose an optimal bending stiffness exists to improve RE that may be individual and speed specific (Day & Hahn, 2020; Joubert et al., 2023; McLeod et al., 2020; Paradisis et al., 2023), suggesting that the benefits of a rigid plate are not universal, but instead vary between runners and running speeds (Day & Hahn, 2020; McLeod et al., 2020). How each AFT shoe elements contribute to RE and performance improvements is challenging to parse, as it seems individual elements interact with each other to result in the reported improvements (Ghanbari et al., 2025; Healey & Hoogkamer, 2022; Hébert-Losier & Pamment, 2023).

Although studies typically show an average 4.0% improvement in RE when wearing AFT (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023), these average improvements demonstrate inter-individual variability. Some runners experience large benefits, while others may see limited-to-no improvement or be negatively affected (Hébert-Losier et al., 2022a). In world-class Kenyan and amateur European male runners, AFT benefited oxygen consumption measures up to 11.4 and 9.7% compared to a traditional lightweight racing shoe, respectively (Knopp et al., 2023). However, some runners experienced detriments of 11.3 and 1.1%. Alongside RE variability to AFT shoes is also variability in running performance measures. In a 3 km time trial performed on a treadmill, 61% of participating male recreational runners ran their fastest times in an AFT shoe, while the remaining 39% performed their best in a traditional road racing flat (22%) or their own (17%) shoes (Hébert-Losier et al., 2022a). Methodological variations in protocols can explain some of the reported variability, such as averaging short windows during metabolic testing, assessing one trial only in each experimental shoe (Hébert-Losier et al., 2022a; Knopp et al., 2023), or conducting testing on different days (Hébert-Losier et al., 2022a). Other factors speculatively underpinning the variability include running speed where faster running speeds are linked with greater benefits (Day & Hahn, 2020; Joubert et al., 2023; McLeod et al., 2020; Paradisis et al., 2023); a potential placebo effect (Hébert-Losier et al., 2022a; Hoogkamer et al., 2019; Hunter et al., 2019), although recent findings suggest no significant placebo effect on RE measures (Hébert-Losier et al.); finally, researchers have suggested a lack of plantarflexion strength may limit the RE benefits of wearing shoes with carbon plates or other similar stiff elements (Madden et al., 2016; Ortega et al., 2021), with applications towards AFT shoe responses. The potential for plantarflexion strength to mitigate RE response to AFT highlights the importance of considering muscular contributions, particularly those of the triceps surae, when evaluating biomechanical and metabolic responses to AFT shoes.

The triceps surae muscles are the main plantarflexors and are important contributors to RE and performance, as greater Achilles tendon stiffness (Nguyen et al., 2025) and plantarflexion strength are associated with improved RE (Arampatzis et al., 2006; Bohm et al., 2021). Additionally, the triceps surae is thought to account for ~25% of the total metabolic cost during running in highly trained individuals, and up to ~40% in untrained individuals (Fletcher & MacIntosh, 2015). AFT shoes are typically designed for racing, with more pronounced performance benefits for longer running distances (e.g., half-marathons and marathons) than shorter distances (Willwacher et al., 2024). It remains unknown whether the benefits of AFT on RE and performance reduce over the course of a race as the triceps surae fatigues.

Therefore, we aimed to investigate the influence of plantarflexion fatigue on the RE response of runners to AFT in a heterogeneous cohort. We hypothesised that the RE benefits from running in AFT would be superior before plantarflexion fatigue. A secondary aim was to explore whether baseline plantarflexion power was linked to RE responses, and changes in RE responses to AFT shoes (from PRE to POST fatigue) were investigated against changes in plantarflexion power (from PRE to POST fatigue).

Methods

Study Design

This study was experimental with a counterbalanced cross-over study design, requiring participants to attend two laboratory sessions. The study was conducted according to the principles of the University of Waikato Human Research Ethics Regulations 2008, the Declaration of Helsinki, and UNICEF's principles for guiding ethical research involving children (Graham et al., 2013). Prior to participants' involvement, participants were provided with an information sheet that described the risks (e.g., delayed onset muscle soreness), benefits (e.g., individualised report), and aims of the study. All participants provided their written informed consent before participating, with approval also sought from legal guardians of participants younger than 16 years of age, in line with New Zealand's Health Research Guidelines (Health Research Council, 2007). The Human Research Ethics Committee granted ethical approval [HREC(Health)2020#83] and the trial was registered in the Australian New Zealand Trials Registry (ACTRN12624000753550) prior to study commencement.

Participants

A priori sample size calculations was conducted using G*Power 3.1.9.7. To detect a *moderate* two-tailed effect size difference (d = 0.50) between paired means with 80% power (β = 0.20) and 5% statistical significance (α = 0.05), 34 participants were required. This study was part of a larger project targeting 66 participants. Ultimately, 64 participants completed the study, resulting in an ability to identify an effect size difference of $d = 0.36$ given the same sample size parameters.

To be eligible, participants were required to have been running at least once a week for at least six months prior to participation and be able to run for at least 30 minutes. Participants were excluded if they were currently or recently (within the last month) injured following the consensus definition of running-related injury (Yamato et al., 2015), had a history of an Achilles tendon rupture, or did not fit the shoe sizes available (men US5 to men US13). The broad inclusion criteria of participants was to increase the generalisation of results. Participants were recruited through word-of-mouth, posters, running clubs, and social media advertisement, and tested within a four month period. Following completion of the two experimental studies, participants received a NZ$30 petrol voucher and went in a draw to receive one of the experimental shoes.

Session One

Participants attended two sessions of 90 to 120 minutes in duration (Figure 2). These sessions were separated by 5.3 ± 4.6 days (*Mean* ± *SD*). All participants were asked to refrain from training before testing.

Session one started with informed consent and the collection of individual characteristics, including height using a AnthroFlex Wall Mounted Stadiometer (Seca), mass using a Kistler 9260AA6 multicomponent force plate (Kistler Group, Winterthur, Switzerland), sex, age, and running experience. Following similar methods reported elsewhere (Hébert-Losier et al., 2023; Hébert-Losier et al., 2022b; Silbernagel et al., 2006), participants were familiarised to the eccentric-concentric plantarflexion power test, which would be used during session two. Participants stood barefoot on a specifically constructed steel step, placed within a steel frame, with their metatarsophalangeal joint aligned with the edge of the step and heels off the edge. Participants were permitted index and middle fingertip support from both hands on the steel frame at shoulder height for balance and asked to maintain the knee of their tested leg straight during testing. Participants then lifted both heels as high as possible, raised the non-tested foot off the step, and went ‘down and up’ as quickly and strongly as possible, returning their heel to the initial position. Participants first did the test without additional weight as a familiarisation, followed by three repetitions with ~1 s between each, while wearing a weighted vest set to 30% of their bodyweight (Figure 3). At the end of session one, participants completed a peak oxygen uptake test (VO_{2peak}), running on a motorised treadmill (HP Cosmos Pulsar 3p, Germany). Participants ran using their own shoes with a 0% incline and speed increasing by 0.5 km/h every minute until volitional cessation (Van Hooren & Lepers, 2023). The starting speeds were individualised based on personal best 10 km times within the last six months (8 km/h when 10 km $\geq$ 50 min, 10 km/h when between 40 to 49 min, and 12 km/h when between 35 to 39 min, and 14 km/h when < 35 min), aiming to have the VO_{2peak} tests last between 8 to 15 minutes. Expired gas were measured via a calibrated metabolic cart (True One 2400; Parvo Medics, Salt Lake City, UT) to determine oxygen consumption (VO_2) and respiratory exchange ratio, which was averaged every 15 s interval. The metabolic cart was calibrated with a 3 L syringe and a known mixture of oxygen (16.00%) and carbon dioxide (4.002%). Throughout the test, participants were verbally encouraged, and at the conclusion of the VO_{2peak} test the final treadmill speed (vVO_{2peak}) was recorded. After five minutes recovery, participants were fitted and familiarised to running in the two experimental shoes that would be used in session two, running two minutes at a self-selected speed in both shoes.

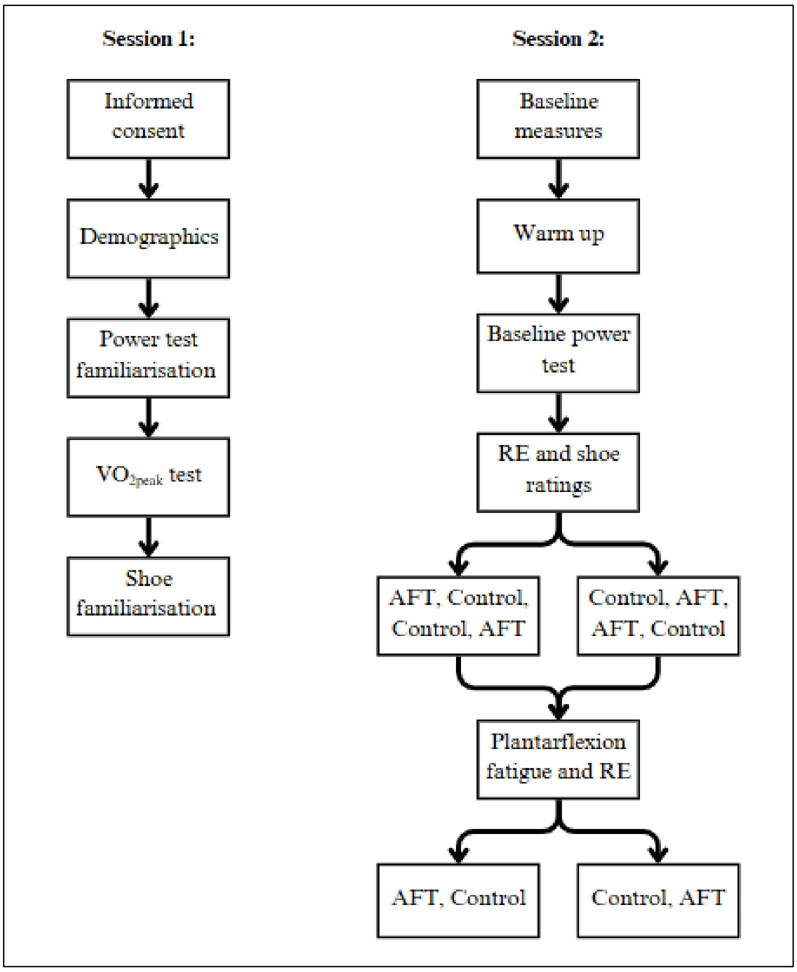
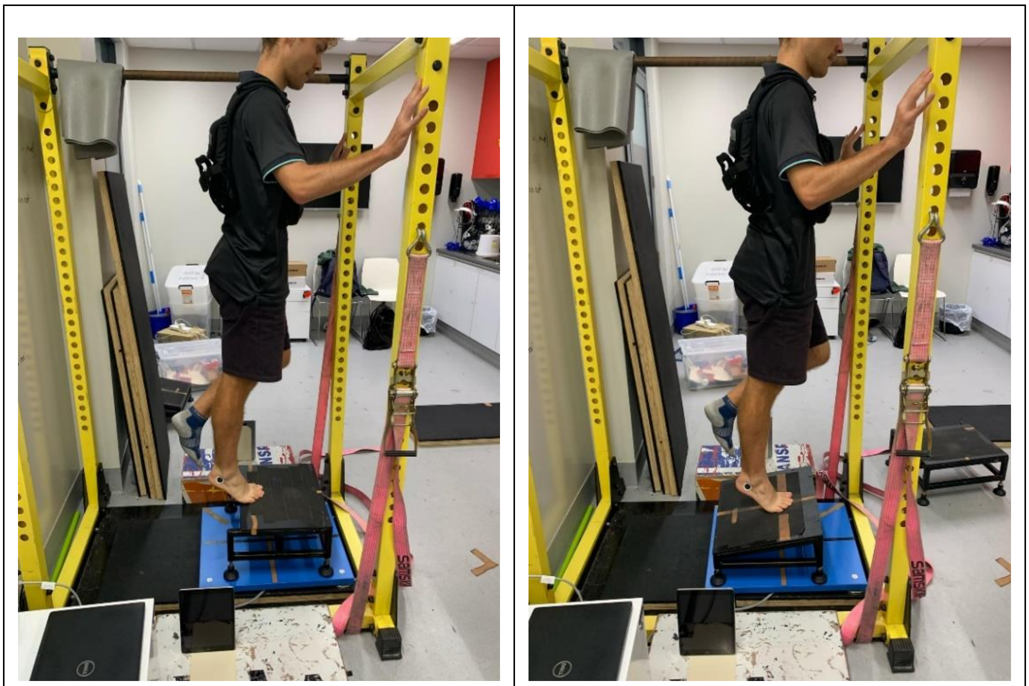


Figure 2. Experimental flow diagram. *Abbreviations*: AFT, Salomon Phantasm S/Lab 2; Control, Salomon Aero Glide 2; RE, running economy; VO_{2peak}, peak oxygen uptake.



Plantarflexion power test

Repetitive calf raise test

Figure 3. Plantarflexion power and calf raise test setup. (**a.**) Plantarflexion power test has a flat steel platform, where participants perform plantarflexion power on the edge of the platform. (**b.**) Repetitive calf raises has a 10° inclined steel platform, where participant perform as many single-leg calf raises as possible.

Session Two

Pre-Plantarflexion Fatigue. Session two consisted of RE tests being performed in an AFT shoe (Salomon S/Lab Phantasm 2) and a control shoe (Salomon Aero Glide 2) (Table 1 and Figure 4). Participants body mass was recorded and then participants rated their baseline levels of calf muscle fatigue and soreness separately, with a 100 mm visual analogue scale (VAS), using Qualtrics online survey application (Qualtrics$^{©}$, Provo, UT (17.1.7)) (Delgado et al., 2018). The VAS scale for calf muscle fatigue was anchored with ‘not fatigued’ (0 mm left anchor) and ‘very very fatigued’ (100 mm right anchor), whereas calf muscle soreness was anchored with ‘not sore’ (0 mm left anchor) and ‘very very sore’ (100 mm right anchor) (Kasahara et al., 2022). Participants were then fitted with the metabolic analyser gear. To warm-up, participants ran for three minutes on the treadmill with 0% incline, in their own running shoes, at a self-selected speed not exceeding 70% of $v\text{VO}_{2\text{peak}}$, followed by a further three minutes at 70% $v\text{VO}_{2\text{peak}}$. After the warm-up, a baseline eccentric-concentric plantarflexion power test, with the weighted vest, was then completed with only the right leg. An iPad (6th generation) running iOS 17.5.1 was used to record the motion of a 24 mm in diameter black circular sticker placed in the middle of a 32 mm in diameter white circular sticker, which were positioned on a flat area just below the lateral malleolus of the right leg. The motion was recorded at 60 Hz using the Calf Raise App v.1.5.1, with an iPad placed 50 cm perpendicular to the participants’ right foot. The Calf Raise App has been shown to be valid and reliable for assessing weighted ankle power, with *CV*s of 6.6% and 4.7%, and *ICC*s of 0.84 and 0.90 when compared to force plate and 3D motion capture data respectively (Hébert-Losier et al., 2022b).

Table 1. Experimental shoe details.

Shoe	**Mass**	**Price**	**Stack height**	**Minimalist Index**†	**Foam**	**Stiff plate**
AFT	219 g	NZ$459.99	37.5 mm	24%	Polyether block amide	Yes
Control	254 g	NZ$210.00	37.4 mm	16%	Ethylene vinyl acetate	No

Note: Shoe comparison is with a US men’s size 9.

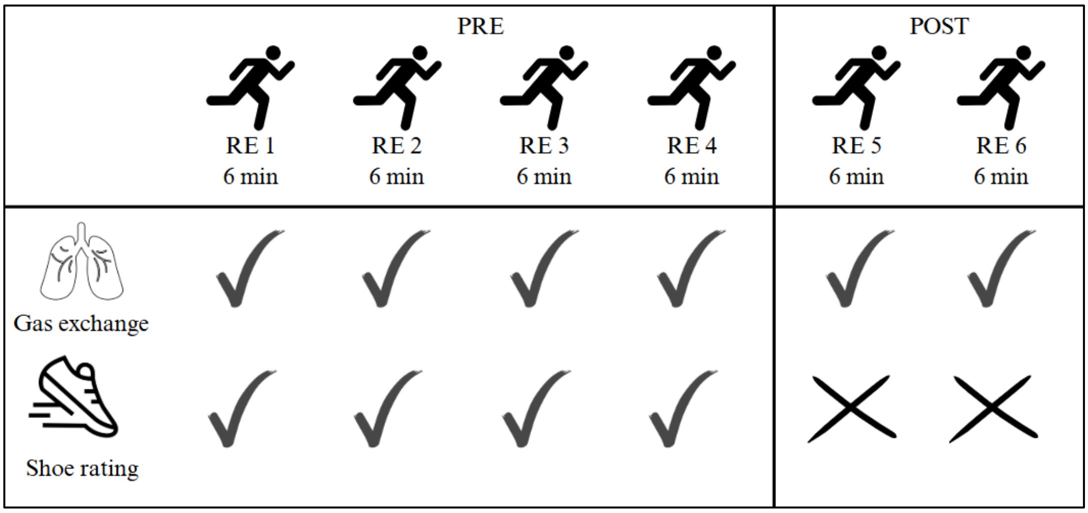
†Minimalist index range: 0% (lowest) to 100% (highest) degree of minimalism.

Abbreviations: AFT, Salomon Phantasm S/Lab 2; Control, Salomon Aero Glide 2; NZ, New Zealand.

	
Salomon Aero Glide 2 (Control)	Salomon S/Lab Phantasm 2 (AFT)

Figure 4. Experimental shoes. *Abbreviations*: AFT, advanced footwear technology.

RE was then assessed using a counterbalanced mirrored crossover design, collecting two pre-plantarflexion fatigue (PRE) RE tests per shoe. Specifically, participants ran four six-minute tests at 70% of $v\text{VO}_{2\text{peak}}$, with five-minutes seated rest between tests. Tests were completed in one of two shoe orders: AFT-Control-Control-AFT or Control-AFT-AFT-Control. Completely two RE tests in each shoe condition is recommended to reduce intra-individual variability (Barrons et al., 2024). During each RE test, VO_2 consumption, volume of carbon dioxide (VCO_2), and respiratory exchange ratio were continuously averaged and recorded every 15 s. During the rest periods after every RE test, participants remained seated with their footwear removed and completed questionnaires displayed in Qualtrics. These questionnaires included VAS relating to the Running Shoe Comfort Assessment Tool (RUN-CAT), alongside perceived overall comfort, pleasure/displeasure, ease (easier/harder), performance, and injury risk running in allocated shoes. The RUN-CAT is a four-question 100 mm VAS questionnaire assessing heel cushioning, forefoot cushioning, forefoot flexibility, and shoe stability on a goldilocks scale (Bishop et al., 2020). Where the middle (50 mm) represents ideal, the left anchor (0 mm) represents too little and right anchor (100 mm) represents too much. Using a weighted averaging system of all four questions, the RUN-CAT is converted to a single 0 mm (least ideal) to 100 mm (most ideal) VAS (Bishop et al., 2020). A summary of the recorded measures for each RE test is presented in Figure 5.



	PRE				POST	
	RE 1 6 min	RE 2 6 min	RE 3 6 min	RE 4 6 min	RE 5 6 min	RE 6 6 min
Gas exchange	✓	✓	✓	✓	✓	✓
Shoe rating	✓	✓	✓	✓	✗	✗

Figure 5. Summary of data collected during running economy tests. *Note*: Tick mark represents data collected, a cross represents data not collected. PRE are the RE tests before the plantarflexion fatigue protocol. POST is the RE tests following plantarflexion fatigue. *Abbreviations*: POST, post-plantarflexion fatigue; PRE, pre-plantarflexion fatigue; RE, running economy.

Plantarflexion Fatigue. Prior to the plantarflexion fatigue protocol, a PRE weighted plantarflexion power test was completed on the right foot. To develop plantarflexion fatigue, participants completed one set of body-weight calf raise repetitions to failure (Sara et al., 2021) on a 10° steel inclined step in time to a metronome set to 60 bpm (Hébert-Losier et al., 2022b), starting with the left leg, then the right leg. Participants were instructed to keep their knee straight and lift their heels as high as possible during testing, going up on one beat and down on one beat (i.e., 30 repetitions per minute). Single-leg calf raises were then repeated with the additional 30% body weighted vest, first with the left leg and then the right leg. The second bout of calf raises with the 30% body weight vest was implemented to increase the muscle activity in the triceps surae (Pincheira et al., 2023), as pilot testing ($n = 3$) indicated that a single bout of body-weighted calf raises was insufficient in reducing plantarflexion power. As soon as the right leg reached failure on the second bout of calf raises, post-plantarflexion fatigue

(POST) weighted plantarflexion power test was completed on the right foot. All weighted plantarflexion power tests and calf raises to failure were monitored using the Calf Raise App. Following the POST weighted power test, participants filled out a calf muscle fatigue and calf muscle soreness VAS before completing another six-minute RE test in one of the counterbalanced shoe conditions to collect physiological measures. Participants then repeated the process, collecting a new PRE weighted power measure, completing the plantarflexion fatigue protocol, collection a POST weighted power, answering the calf muscle fatigue and soreness VAS questions, and undergoing a RE test in the alternate counterbalanced shoe.

Data Processing

Participants VO_{2peak} (mL/kg/min) was calculated using an average of two adjacent 15 s values that provide the highest average, representing 30 s of data. For the RE tests, data from VO_2 (mL/kg/min) and respiratory exchange ratio were averaged over the last 2 minutes and extracted. Energetic cost (W/kg) and energetic cost of transport (J/kg/m) were also calculated. All PRE RE data were averaged together to result in one PRE and one POST measure.

The Calf Raise App tracked the 24 mm black circular marker on participants' foot following a validated tracking algorithm (Fernandez et al., 2023). Measures obtained from the Calf Raise App include the number of repetitions, total positive work (J), and peak power (W) according to the entered mass. For the weighted calf raise and plantarflexion power tests, the additional 30% body weight was added for computations of work and power. Only the repetition with the greatest peak concentric power during the weighted power tests was used for analysis.

Statistical Analysis

R (version 4.4.2) was used to explore the data. Descriptive statistics were reported as mean and standard deviations (*mean* ± *SD*). Paired *t*-tests were used to identify significant differences (*P*-value < 0.050) between shoe conditions in RUN-CAT scores and shoe ratings. The effect size for these variables were found using Cohens *d* with 95% confidence intervals (*CI*), where *small*, *medium*, and *large* effect sizes are reached with 0.2, 0.5, and 0.8 respectively. While a *trivial* effect size is found with a Cohens *d* less than 0.2 (Cohen, 1988).

Paired *t*-tests were conducted to ensure there was no significant order effect of shoe condition on plantarflexion power tests, VAS calf muscle fatigue and soreness scores, and RE outcomes. Multiple two-way repeated measures analysis of variance (RM ANOVA) was used to identify significant differences in plantarflexion power, VAS calf muscle fatigue, VAS calf muscle soreness, oxygen consumption, energy costs, and energetic cost of transport between shoe conditions (AFT, Control) and time (PRE, POST), accounting for a potential interaction effect (shoe x time). Participant ID was set as the between-subject error term, with shoe and time as the repeated variables. Effect sizes of the ANOVA were determined by partial eta-squared (ηp^2) with 95% *CI* and were defined as *small*, *moderate*, and *large* when reaching 0.01, 0.06, and 0.14, respectively (Cohen, 1988).

Pearson correlations were run with 95% *CI* using the percentage difference of oxygen consumption, energy cost, and energetic cost of transport between shoe conditions against the max value from the baseline plantarflexion power test, for both PRE and POST RE measures (therefore six total correlation). Furthermore, Pearson correlations were also run with 95% *CI* using the difference in the two POST plantarflexion power tests (expressed as a percentage of baseline plantarflexion power prior to equating the difference) against the difference in PRE and POST percent RE responses. Pearson correlations were considered *small*, *moderate*, and *large* when the *r*-value reached 0.10, 0.30, and 0.50, respectively (Cohen, 1992). *Trivial* correlations are when the *r*-value is less than 0.10.

Results

Participants

Ultimately, 64 participants completed both sessions and were included in the analysis (Table 2). However, a total of 82 participants took part in this study. Eight participants completed the first session, but not the second and, data from ten participants were removed from analysis due to a change of equipment impacting data comparability. These eighteen participants were removed from all analysis. Runners were of varied performance levels: 52% recreational, 42% experienced, and 6% national level. Along with varied running types: 14% sprinter, 19% middle distance, 62% long distance, and 5% ultra distance. A total of 25 participants (39%) were 35 years or more, classifying them as masters runners. Only one participant exceeded the pre-determined respiratory exchange ratio threshold of 1.00, which was their second RE test in the Control shoe during PRE. Hence, the PRE data for this participant were from a single trial only.

In terms of subjective perceptions of the experimental shoes, the RUN-CAT scores were not significantly different between AFT and Control shoes ($P = 0.972$). However, participants rated VAS scores significantly higher (more favourable) in the AFT shoe, *small* effect of comfort ($P = 0.007$, $d = 0.35$), *moderate* effect of pleasure ($P < 0.001$, $d = 0.67$), *moderate* effect of running ease ($P < 0.001$, $d = 0.77$), and *large* effect of performance ($P < 0.001$, $d = 1.17$); however, they were rated worse with perceived injury risk with a *small* effect ($P = 0.043$, $d = 0.26$) (Table 3).

Table 2. Baseline characteristics and fatigue protocol metrics from participants (n = 64). Data are means ± standard deviations with ranges.

	All (*n* = 64)			**Male (*n* = 32)**			**Female (*n* = 32)**		
	Mean ± SD	*Min*	*Max*	*Mean ± SD*	*Min*	*Max*	*Mean ± SD*	*Min*	*Max*
Baseline characteristics									
Age (y)	33.5 ± 15.6	14.6	72.2	38.4 ± 18.2	15.1	72.2	28.7 ± 10.7	14.6	49.2
Mass (kg)	69.5 ± 11.9	46.8	102.7	77.5 ± 8.6	61.9	102.7	61.4 ± 9.1	46.8	88.6
Height (cm)	172.3 ± 7.9	158.0	191.5	178.0 ± 5.9	165.5	191.5	166.6 ± 5.0	158.0	178.0
Milage (km)	33.6 ± 24.8	2.0	90.0	36.8 ± 26.2	3.0	90.0	30.5 ± 23.3	2.0	90.0
Years running (y)	8.3 ± 8.3	0.5	45.0	9.9 ± 9.8	0.5	45.0	6.7 ± 6.4	0.5	25.0
Baseline plantarflexion power (W)	464.2 ± 169.1	191.8	874.8	546.3 ± 174.8	191.8	874.8	384.7 ± 119.9	207.4	738.9
VO$_{2\text{peak}}$ (mL/kg/min)	49.4 ± 8.3	33.1	72.3	53.4 ± 8.8	36.9	72.3	45.4 ± 5.3	33.1	56.7
vVO$_{2\text{peak}}$ (km/h)	10.8 ± 1.5	8.4	14.7	11.4 ± 1.7	8.4	14.7	10.2 ± 1.0	8.4	11.9
Fatigue protocol									
BW calf raises (count)	40.3 ± 23.2	11	213	40.6 ± 21.6	19	153	40.0 ± 24.8	11	213
Weighted calf raise (count)	20.0 ± 7.6	7	71	21.3 ± 8.7	8	71	18.8 ± 6.0	7	45
BW calf raise work (J)	2138.9 ± 1084.3	110.2	8474.2	2327.4 ± 994.0	110.2	6193.0	1953.4 ± 1140.2	876.2	8474.2
Weighted calf raise work (J)	1255.1 ± 464.7	118.5	3214.6	1457.5 ± 480.1	603.4	3214.6	1060.6 ± 354.8	118.5	2062.9

Abbreviations: BW, body weight; Max, maximum value; Min, minimum value; SD, standard deviation; VO$_{2\text{peak}}$, peak oxygen uptake; vVO$_{2\text{peak}}$, velocity at peak oxygen uptake.

Table 3. Shoe visual analogue scale scores from participants (*n* = 64). Data are means ± standard deviations.

Shoe ratings	**Control**	**AFT**	**Difference**	**P-value**	**Cohens *d* [95% *CI*]**
RUN-CAT	82.7 ± 13.5	82.6 ± 13.2	-0.1 ± 13.6	0.972	0.00 [-0.25, 0.25]
Comfort	61.6 ± 19.5	68.5 ± 19.0	6.9 ± 19.9	**0.007***	0.35 [0.09, 0.61]
Pleasure	63.0 ± 18.8	74.4 ± 18.1	11.4 ± 17.0	**<0.001***	0.67 [0.39, 0.95]
Ease	62.2 ± 16.7	74.8 ± 17.4	12.6 ± 16.3	**<0.001***	0.77 [0.49, 1.06]
Performance	58.1 ± 16.7	77.5 ± 16.3	19.4 ± 16.6	**<0.001***	1.17 [0.85, 1.49]
Injury risk	62.2 ± 16.7	56.9 ± 22.0	-5.3 ± 20.6	**0.043***	-0.26 [-0.512, -0.005]

Note: Visual analogue scale scores range from 0 to 100, where higher values indicate more favourable outcomes.

* Significant effect ($P < 0.05$)

Abbreviations: AFT, Salomon Phantasm S/Lab 2; Control, Salomon Aero Glide 2; SD, standard deviation; RUN-CAT, Running Shoe Comfort Assessment Tool.

Plantarflexion Fatigue

On average, participants completed 40 bodyweight calf raises and 2163.5 J of work, and 20 weighted calf raises and 1259.2 J of work during the fatigue protocol. There was considerable inter-individual variability, as reported in Table 2.

Two participants plantarflexion power footage was lost prior to analysis, resulting in plantarflexion power tests only including 62 participants. A paired *t*-test exploring the effect on shoe order on POST plantarflexion power tests showed no significant results ($P = 0.247$). Average plantarflexion power measures PRE and POST are shown in Table 4 for each shoe condition. Further RM ANOVA indicated there were no significant interaction effect ($F = 0.4$, $P = 0.503$) or main effect of shoe ($F = 0.0$, $P = 0.929$) of power measures, but a significant main effect of time ($F = 19.0$, $P < 0.001$, $\eta p^2 = 0.09$ [0.03, 0.18]) (Table 5). Participants' average PRE plantarflexion power was 459.6 ± 168.0 W, while POST was 429.6 ± 155.2 W, resulting in a *moderate* effect size difference of -30.0 ± 61.5 W (6.5 ± 13.17%). Change in power PRE to POST ranged from -282.0 W (52.1%) to +114.9 W (18.2%).

Another paired *t*-test was used to explore the effect on shoe order on subjective VAS scores for calf muscle fatigue and soreness, which did show a significant effect ($P = 0.004$ and 0.008, respectively). Fatigue and soreness scores on average were rated 78.5 and 65.0 mm after the first plantarflexion fatigue, then 83.7 and 72.6 mm after the second plantarflexion fatigue, respectively. However, due to the counterbalanced design, the effects of order should cancel each other out between shoe conditions. VAS scores following plantarflexion fatigue had no significant interaction effect ($F = 0.3$ and 0.8, $P = 0.575$ and 0.383, respectively) or main effect between shoes ($F = 0.3$ and 0.8, $P = 0.575$ and 0.383, respectively). However, there is a *large* main effect of time ($F = 1172.9$ and 464.9, $P = 0.000$ and 0.000, $\eta p^2 = 0.86$ and 0.71, respectively) (Table 5).

Table 4. Running economy descriptive data from participants (*n* = 64). Data are means ± standard deviations.

	Control		**AFT**	
	PRE	**POST**	**PRE**	**POST**
Plantarflexion power (W)[†]	460.6 ± 174.0	425.7 ± 158.9	457.4 ± 163.3	432.2 ± 152.5
VAS calf muscle fatigue (mm)	16.8 ± 20.5[‡]	80.0 ± 19.7	16.8 ± 20.5[‡]	82.2 ± 20.2
VAS calf muscle soreness (mm)	15.9 ± 21.5[‡]	66.6 ± 28.1	15.9 ± 21.5[‡]	70.9 ± 27.3
Oxygen consumption (mL/kg/min)	36.5 ± 5.1	37.3 ± 5.4	35.0 ± 5.0	35.9 ± 5.1
Energy cost (W/kg)	13.0 ± 1.8	13.2 ± 1.9	12.4 ± 1.8	12.7 ± 1.8
Energetic cost of transport (J/kg/m)	4.35 ± 0.39	4.41 ± 0.43	4.16 ± 0.39	4.23 ± 0.41

Notes: VAS scores range from 0 to 100, where higher values indicate more calf muscle soreness or fatigue.

[†] Data missing from two participants.

[‡] PRE data for VAS collected before running economy tests.

Abbreviations: AFT, Salomon Phantasm S/Lab 2; Control, Salomon Aero Glide 2; POST, post-plantarflexion fatigue; PRE, pre-plantarflexion fatigue; VAS, visual analogue scale.

Table 5. Repeated measures analysis of variance results from participants data (*n* = 64). Differences reported as means ± standard deviations.

	Raw difference	Difference (%)	*F*-value	*P*-value	*ηp²* [95% *CI*]
Power (W)†					
Shoe	-0.62 ± 52.10	-1.88 ± 13.85	0.0	0.929	0.00 [0.00, 0.01]
Time	-30.00 ± 61.50	5.46 ± 13.17	19.0	**<0.001***	0.09 [0.03, 0.18]
Shoe x Time	-	-	0.4	0.503	0.00 [0.00, 0.04]
VAS calf muscle fatigue (mm) ‡					
Shoe	-1.1 ± 10.6	-2.8 ± 27.3	0.3	0.575	0.00 [0.00, 0.03]
Time	-64.3 ± 24.9	-79.6 ± 23.9	1172.9	**<0.001***	0.86 [0.83, 0.89]
Shoe x Time	-	-	0.3	0.575	0.00 [0.00, 0.03]
VAS calf muscle soreness (mm) ‡					
Shoe	-2.1 ± 16.3	-14.7 ± 82.0	0.8	0.383	0.00 [0.00, 0.04]
Time	-52.9 ± 32.0	-70.8 ± 55.1	464.9	**<0.001***	0.71 [0.65, 0.76]
Shoe x Time	-	-	0.8	0.383	0.00 [0.00, 0.04]
Oxygen consumption (mL/kg/min)					
Shoe	1.5 ± 0.6	4.0 ± 1.6	223.9	**<0.001***	0.54 [0.45, 0.62]
Time	-0.9 ± 1.1	-2.4 ± 3.1	80.4	**<0.001***	0.30 [0.20. 0.40]
Shoe x Time	-	-	0.2	0.691	0.00 [0.00, 0.03]
Energy cost (W/kg)					
Shoe	0.6 ± 0.2	4.3 ± 1.6	284.3	**<0.001***	0.60 [0.52, 0.67]
Time	-0.2 ± 0.4	-1.6 ± 3.0	35.5	**<0.001***	0.16 [0.07, 0.25]

Shoe x Time	-	-	0.1	0.743	0.00 [0.00, 0.02]
Energetic cost of transport (J/kg/m)					
Shoe	0.2 ± 0.1	4.3 ± 1.6	267.9	**<0.001***	0.59 [0.50, 0.65]
Time	-0.1 ± 0.1	-1.6 ± 3.0	34.8	**<0.001***	0.16 [0.07, 0.25]
Shoe x Time	-	-	0.1	0.775	0.00 [0.00, 0.02]

Note: Larger values indicate more favourable outcome towards the advanced footwear technology shoe (shoe) or pre-plantarflexion fatigue (time). VAS scores range from 0 to 100, where higher values indicate more calf muscle soreness or fatigue.

[†] Data missing from two participants.

[‡] PRE data is collected before running economy tests and are the same in both shoe conditions.

* Significant effect ($P < 0.05$)

Abbreviations: ηp^2, partial eta-squared; shoe, shoe condition; PRE, pre-plantarflexion fatigue; time, pre-plantarflexion fatigue and post-plantarflexion fatigue; VAS, visual analogue scale.

Running Economy

Average oxygen consumption, energy cost, and energetic cost of transport are reported in Table 4 for each shoe condition and time point. Using a paired *t*-test found no significant effect of shoe order in both PRE and POST RE conditions on oxygen consumption ($P = 0.992$ and 0.453, respectively), energy cost ($P = 0.978$ and 0.281, respectively), and energetic cost of transport ($P = 0.905$ and 0.392, respectively).

Three separate RM ANOVAs revealed no significant interaction effect across RE variables ($P \geq 0.691$), but significant *large* main effects of shoe ($P < 0.001$, $\eta^2 \geq 0.54$) and time ($P < 0.001$, $\eta^2 \geq 0.16$) (Table 5). RE measures were on average 4.0 to 4.3% better in AFT than Control when averaging both time points, ranging from 0.5 to 9.1%. RE measures were on average 1.6 to 2.4% worse POST than PRE when averaging both shoe conditions, ranging from -11.8 to 5.2%.

There were no significant correlations identified between baseline plantarflexion power and RE response to AFT shoes in PRE and POST ($P \geq 0.132$, Table 6). Furthermore, there were no significant correlations found in percent change in POST plantarflexion power from baseline power and the change in RE response PRE to POST ($P \geq 0.930$, Table 6).

Table 6. Running economy and power correlations.

	r [95% *CI*]	*P*-value
Baseline power (W) vs PRE responses (%) (*n* = 63)		
Oxygen consumption (mL/kg/min)	0.18 [-0.07, 0.41]	0.156
Energy cost (W/kg)	0.19 [-0.06, 0.42]	0.132
Energetic cost of transport (J/kg/m)	0.06 [-0.19, 0.30]	0.653
Baseline power (W) vs POST responses (%) (*n* = 62)		
Oxygen consumption (mL/kg/min)	0.16 [-0.09, 0.39]	0.216
Energy cost (W/kg)	0.15 [-0.10, 0.38]	0.247
Energetic cost of transport (J/kg/m)	0.05 [-0.20, 0.30]	0.680
Change in power (%) vs change in response (%) (*n* = 62)		
Oxygen consumption (mL/kg/min)	-0.01 [-0.26, 0.24]	0.930
Energy cost (W/kg)	-0.01 [-0.26, 0.24]	0.953
Energetic cost of transport (J/kg/m)	0.00 [-0.25, 0.25]	1.000

Abbreviations: POST, post-plantarflexion fatigue; PRE, pre-plantarflexion fatigue.

Discussion

Summary

We investigated the influence of plantarflexion fatigue on AFT shoe response. Running in AFT versus Control shoes resulted in an average 4.0 to 4.3% improvement in RE measures (individual responses ranged from 0.5 to 9.1%). This overall 4.0 to 4.3% improvement in RE measures with AFT shoes aligns with previous research using other AFT shoe models (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023). There was no significant difference in RE response to AFT shoes before and after plantarflexion fatigue, despite the overall average 1.6 to 2.4% detriment in RE with plantarflexion fatigue. Previous research using the same metabolic analyser found the smallest worthwhile change in oxygen consumption, energetic cost, and energetic cost of transport to be 1.6, 1.7, and 1.4% respectively (Hébert-Losier et al., 2022a), the observed 1.6 to 2.4%

determent to RE measures with plantarflexion fatigue surpass this threshold. Therefore, changes in RE measures are not only statistically significant but also practically meaningful, highlighting the importance of the triceps surae muscle tendon unit on RE measures and potentially running performance. Muscle fatigue and RE can be linked from previous research, whereby RE shows impairments of 13.6% after a marathon (Kyröläinen et al., 2000) and 3.0 to 6.6% after 60 minutes of steady running (Sproule, 1998), along with plantarflexion fatigue of 29.8 N difference in MVIC before and following two hours of running (Avela et al., 1999) and 25.9 Nm difference in MVIC before and after a marathon (Saldanha et al., 2008). Furthermore, larger type II muscle fibres contribute more to movement with fatigue (Conwit et al., 2000; Stock et al., 2012), which could require more energy to contract than smaller type I muscle fibres (Barclay et al., 1993; Bottinelli et al., 1994; He et al., 2000). We also explored the relationship between baseline plantarflexion power and RE response to AFT shoes, identifying no significant correlations to RE responses PRE and POST. These findings oppose the speculations from authors that suggest runners need a certain level of plantarflexion strength to fully benefit from AFT shoes (Madden et al., 2016; Ortega et al., 2021). Altogether, these findings suggest RE response to AFT shoes may not change throughout a long-distance race with the accumulation of plantarflexion fatigue from prolonged running.

Running Economy Response

The inter-individual variation we observed in the RE response of runners to AFT shoes (0.5 to 9.1%) is less than variations reported elsewhere, but similar inter-individual variation exists. For instance, the RE response to AFT shoes was reported to range from -9.6 to +9.7% in recreational runners (Hébert-Losier et al., 2022a), -11.3 to +11.4% in elite Kenyan runners, and -1.1 to +9.7% in amateur European runners (Knopp et al., 2023). However, variations in RE response to AFT shoes of a similar or lesser extent than the current study also exist, ranging from 0.0 to +6.4% (Hunter et al., 2019) and +1.59 to +6.26% (Hoogkamer et al., 2018) in runners who have ran 10 km under 32 minutes. Differences in study design likely contribute to these differing ranges in RE response to AFT shoes. The average RE response for this study includes three RE tests in each examined shoe, potentially leading to lesser variability in RE response, as those studies with larger variability only examine RE measures from a single test per shoe (Hébert-Losier et al., 2022a; Knopp et al., 2023). Although one test is deemed sufficiently reliable for RE testing, it is still recommended to use at least two RE tests per shoe to limit variability in RE measures (Barrons et al., 2024; Oehlert et al., 2025). Furthermore, this study completed all RE tests for each participant in a single session, whereas other studies used multiple days to complete all RE tests (Hébert-Losier et al., 2022a). Although between-day RE measures are deemed reliable within 2.4% (Saunders et al., 2004), single-day assessment are preferred to reduce intra-individual variability (Barrons et al., 2024). Additionally, the runners who volunteered to participate in our study may have simply not encompassed the range of potential responses to AFT shoes by chance, with no negative responders taking part.

Furthermore, differences in AFT models and shoes used as a comparator also need consideration. This study used Salomon Phantasm S/Lab 2 (AFT) and Salomon Aero Glide 2 (Control) shoes. The Control shoe was selected to reflect the design of the AFT shoe, although the match was not perfect. The Control shoe was 35 g heavier and had an 8% lower minimalist index than the AFT shoe. It is debatable whether a 35 g difference in shoe mass would meaningfully influence response, given that 100 g difference equates to roughly 0.7 to 1.1% change in RE measures (Franz et al., 2012) and previous research indicating a negligeable correlation between shoe mass and metabolic cost when footwear mass was within 30 g (r^2 = 0.0118) (Joubert & Jones, 2022). As such, the 35 g difference would equate to an approximate 0.2 to 0.4% change in RE. To ensure a more ecologically valid setting for runners, the experimental shoes were not weight matched. Furthermore, the difference in minimalist index of 8% is not meaningful and should not significantly affect running mechanics, as a 70% minimalist index score or more is deemed to represent a more minimal shoe (Fuller et al., 2017) that could potentially mimic barefoot and alter running biomechanics (Squadrone et al., 2015) compared to more traditionally constructed shoes. Therefore, the meaningful differences in footwear properties between the Control and AFT shoe are the types of foam (Control used a combination of ethylene vinyl acetate and Olefin, AFT used a polyether block amide based foam) and the absence or presence of a carbon fibre plate, suggesting the average 4.0 to 4.3% improvement to RE in the AFT shoes appears to be driven by these footwear technologies. Studies reporting larger variations in RE response were comparing shoes that differed to a greater extent, more specifically, AFT shoes against traditional lightweight racing flats (Hébert-Losier et al., 2022a; Knopp et al., 2023). In contrast, studies reporting smaller variation in RE response were comparing AFT shoes to leading non-AFT marathon racing shoes at the time (Hoogkamer et al., 2018; Hunter et al., 2019). Therefore, comparing the variability in AFT shoe response between studies using different AFT shoe models and comparator shoes may not be suitable, especially as it is poorly understood how components within AFT shoes interact with each other (Ghanbari et al., 2025; Healey & Hoogkamer, 2022; Hébert-Losier & Pamment, 2023).

Despite differences in shoe models, most studies report an average 4.0% improvement to RE in AFT shoes (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023). The associated individual variability in RE responses are likely in part due to alterations in running mechanics and how individuals interact with the shoes. When increasing longitudinal bending stiffness in a shoe, runners were found to adopt one of two running strategies; either keeping a consistent push-off time while increasing torque at the ankle, or increasing push-off time while lowering torque at the ankle (Willwacher et al., 2014). Furthermore, an optimal bending stiffness appears to be individual specific (Day & Hahn, 2020; McLeod et al., 2020; Oh & Park, 2017), as well as speed dependent (Day & Hahn, 2020; Joubert et al., 2023; McLeod et al., 2020; Paradisis et al., 2023). Therefore, individual runners may not only respond to the same AFT model differently from other runners, but also at different running speeds. These factors could help explain some of the variability in RE response to AFT shoes reported in the literature.

Study Hypothesis

We hypothesised that plantarflexion fatigue would limit the RE benefits of AFT shoes, however our findings reject this hypothesis as runners benefited to a similar extent from wearing AFT shoes with or without plantarflexion fatigue. This beneficial response was observed despite plantarflexion fatigue worsening the overall RE of runners. In this study, plantarflexion fatigue was induced via repetitive body-weighted and weighted calf raises, resulting in an average 6.5% decline in plantarflexion power. However, prolonged running results in larger declines (9 to 29%) in plantarflexion strength when assessed using MVIC (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). It may be with greater plantarflexion fatigue or more specific running-induced fatigue, altered RE response to AFT shoes may have surfaced. The neuromuscular plantarflexion fatigue induced by our protocol may have partially recovered between the end of the plantarflexion fatigue protocol and the start of the plantarflexion power test, and more so before the RE test, given that partial recovery from repetitive knee extensions are seen within eight minutes (Husmann et al., 2018). Additionally, individuals in this study may have recovered at different rates following plantarflexion fatigue, as muscle fibre typology seems to influence recovery rate after Wingate tests (Lievens et al., 2020). Nonetheless, the difference we observed between PRE and POST plantarflexion power tests was of a *moderate* effect size ($F = 19.0$, $P < 0.001$, $\eta p^2 = 0.09$ [0.03, 0.18]), indicative of plantarflexion fatigue, in addition to being a more dynamic assessment of plantarflexion function than what is typically used to assess plantarflexion fatigue (i.e., MVIC) in the prolonged running studies (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). Additionally, participants reported *large* amounts of perceptual calf muscle fatigue and soreness ($F = 1172.9$ and 464.9, $P = 0.000$ and 0.000, $\eta p^2 = 0.86$ and 0.71, respectively), corroborating plantarflexion fatigue.

The weighted plantarflexion power test was selected over a MVIC test as an indicator of plantarflexion fatigue, as plantarflexion power was more sensitive to detecting plantarflexion fatigue during pilot testing than MVIC. In agreement, repetitive calf raises failed to show changes in MVIC responses in previous studies (Leabeater et al., 2024). Additionally, MVICs are static and do not involve a stretch-shortening cycle, which consists of concentric and eccentric dynamic movements (Komi, 2000), therefore MVICs are not functionally similar to running. Furthermore, James et al. (2024) suggests isometric and dynamic strength measures lack in agreement and these two measures represent two separate neuromuscular domains. The dynamic testing of plantarflexion power appears more appropriate in the context of running, with our study suggesting fatigue from a 6.5% decline in plantarflexion power. However, the plantarflexion power task likely relies more on type II muscle fibre recruitment (Schiaffino & Reggiani, 2011), whereas MVICs use both type I and II muscle fibres (Beltman et al., 2004). Considering type II muscle fibres are more susceptible to fatigue compared to type I muscle fibres (Lievens et al., 2020; Schiaffino & Reggiani, 2011), these type II muscle fibres were likely successfully fatigued, as our pilot testing found no meaningful difference in MVIC while the plantarflexion power test showed meaningful declines from the fatigue protocol, suggesting type II muscle fibre fatigue may not influence different RE responses to AFT shoes. Therefore, future studies should examine whether a running induced fatigue would change RE response to AFT rather than isolated plantarflexion muscle fatigue, as both type I and II muscle fibres would likely fatigue. This plantarflexion fatigue from prolonged running could provide further insight into how people respond to AFT shoes throughout a long-distance race such as a marathon.

Another factor to consider in interpreting our results is the average age of participants (males: 38.4 ± 18.2 y , females: 28.7 ± 10.7 y), with a large proportion (39%) of runners being masters runners (over 35 years of age) who are potentially affected by age-related declines in plantarflexion strength (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012). If a lack of plantarflexion strength limits runners RE response to AFT shoes (Madden et al., 2016; Ortega et al., 2021), the pre-existing decline in plantarflexion strength of masters runners may limit the amount of plantarflexion power decline and influence POST RE test results. The project was specifically designed to target heterogenous runners for broader generalisation of findings. A more targeted study in younger and trained runners with developed plantarflexion strength may yield different findings.

Strengths

A strength of our study is the broad generalisation of findings to runners given the even distribution of male and female participants, along with a broad range of performance levels, running types (i.e., sprinter, middle distance runner, long distance runner, and ultra distance runner), and age. Females in sport and exercise are generally underrepresented (Cowley et al., 2021; Martínez-Rosales et al., 2021), and more specifically in AFT shoe research (Mason et al., 2024). Our inclusion of half female and half male participants helps to address this gap. However, this variability in participating runners could introduce variables that were not accounted for in our analysis.

Another strength of this study is the large sample size. This study required 34 participants to identify a *moderate* two-tails effect size difference; however, we have data from 64 participants. Therefore, this larger sample size alongside the diversity of our participants will enhance the generalisation of our results. Other AFT shoe research includes 9 to 18 participants (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023) and other plantarflexion fatigue research include 7 to 24 participants (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008), highlighting how large our sample size is.

Finally, we used a mirrored counterbalanced crossover design for PRE RE testing, with counterbalanced POST testing conditions. This approach helps minimise the risk of order effects on RE measures (Bradley, 1958). Furthermore, all RE tests were completed on the same day, which will reduce intra-individual variability and is recommended when comparing the RE measures in different footwear (Barrons et al., 2024).

Limitations

The main limitation of this study surrounds the plantarflexion fatigue protocol. Although the protocol induced significant plantarflexion fatigue based on objective and subjective measures, how it relates to specific running-induced plantarflexion fatigue is unknown. An alternative approach to inducing plantarflexion fatigue could have involved participants completing a prolonged run, which typically results in 9 to 29% decline in plantarflexion strength (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). This method would likely produce a more ecologically valid running-specific plantarflexion fatigue. However, this protocol would require a larger time commitment from participants, potentially completing RE tests on different days, and difficulty in limiting plantarflexion recovery before RE testing.

Another limitation of the plantarflexion fatigue protocol was the variability in the number of calf raises completed (e.g., body weighted calf raise: 7 to 213 repetitions), suggestive of differing physiological and neuromuscular responses, as participants who completed more repetitions may experience larger neuromuscular fatigue (Varela-Olalla et al., 2024). The use of surface electromyography and twitch interpolation techniques, for instance, would be needed to further explore centrally versus peripherally mediated fatigue. Nonetheless, participants all experienced increased levels of subjective calf muscle fatigue, and the change in RE response to AFT was not correlated to the change in plantarflexion power from PRE to POST fatigue.

Although recommended that two or more RE tests be collected when assessing footwear responses (Barrons et al., 2024), only a single RE test was collected POST for each shoe condition rather than two (as done PRE). The collection of a single test was purposeful to avoid the plantarflexors from recovering from fatigue and to limit the amount of plantarflexion fatigue protocols, as the two plantarflexion fatigue protocols used in this study are already physically demanding. As a result, we only collected one plantarflexion fatigued RE measurement in each experimental shoe. Consequently, we compared a single RE test with plantarflexion fatigue against an average of two RE tests without plantarflexion fatigue.

Conclusion

Aligning with previous research, AFT shoes improved RE by 4.0 to 4.3% compared to the Control shoe, while plantarflexion fatigue resulted in an overall detriment to RE of 1.6 to 2.4%. Contradictory to our hypothesis and previous speculations, RE response to AFT shoes did not change with plantarflexion fatigue. Furthermore, plantarflexion power did not correlate AFT shoe response. Altogether, these findings suggest there is not a required level of plantarflexion strength to benefit from AFT shoes. Furthermore, runners response to AFT shoes may not change throughout a long-distance race with accumulated plantarflexion fatigue, although further research on this topic is required.

Chapter Three - Overview

Thesis summary, practical implications, strength, limitations, and future research.

Summary

Shoes are rapidly evolving, with initial shoes serving as a way to protect our feet from the external environment (Altman & Davis, 2012). Nowadays, running shoes are designed with AFT features aimed to improve RE (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023). Since the introduction of AFT shoes, every world record from the 5 km to the marathon have been broken by runners wearing an AFT shoe (Muniz-Pardos et al., 2021). These AFT shoes incorporate elements such as an embedded rigid element, larger stack height than traditional running shoes to accommodate a responsive and compliant midsole material, and a curved forefoot geometry, while remaining lightweight (Burns & Tam, 2020; Hébert-Losier & Pamment, 2023); all of which seem to interact with each other to create these observed RE improvements rather than individually (Ghanbari et al., 2025; Healey & Hoogkamer, 2022; Hébert-Losier & Pamment, 2023). However, this average improvement in RE varies considerably between individuals (Hébert-Losier et al., 2022a; Knopp et al., 2023). Several explanations have arisen to suggest why there might be variability in AFT response between runners. Some of these explanations include running speed, where faster running speeds are linked with greater benefits (Day & Hahn, 2020; Joubert et al., 2023; McLeod et al., 2020; Paradisis et al., 2023); habituation to AFT shoes (Matties & Rowley, 2023), although a recent study found no significant difference in RE when running in a non-habituated AFT shoe compared to an habituated AFT shoe (Schwalm et al., 2024); a placebo effect (Hébert-Losier et al., 2022a; Hoogkamer et al., 2019; Hunter et al., 2019), although recent findings suggest no significant placebo effect of running in AFT shoes on RE measures (Hébert-Losier et al., 2025); and a lack of plantarflexion strength limiting RE benefits (Madden et al., 2016; Ortega et al., 2021), despite limited research on this specific topic.

The main purpose of this thesis was to identify whether plantarflexion fatigue influences RE response to AFT shoes. It was hypothesised that the RE benefits from running in AFT would decrease post plantarflexion fatigue. A secondary aim was to explore whether baseline plantarflexion function was linked to RE responses to AFT shoes, and whether changes in RE responses to AFT shoes with plantarflexion fatigue were linked to changes in plantarflexion function with plantarflexion fatigue. This study involved two experimental sessions with 64 participants. Session one collected demographic information and an incremental VO_{2peak} test on a motorised treadmill. Session two started with a baseline plantarflexion power test, leading into four six-minute RE tests using a Control and AFT shoe in a counterbalanced mirrored crossover design. These RE tests were followed by two rounds of PRE power tests, plantarflexion fatigue, POST power tests, calf muscle fatigue and soreness VAS questionnaires, and a RE test in either the Control or AFT shoe allocated in a counterbalanced order. Running in AFT shoes resulted in a 4.0 to 4.3% average improvement in RE (individual responses ranged from 0.5 to 9.1%) compared to the Control. Plantarflexion fatigue resulted in an average 1.6 to 2.4% detriment in RE; however, RE response to AFT shoes was not significantly altered by plantarflexion fatigue. Previous research using the same metabolic analyser found the smallest worthwhile change in oxygen consumption, energetic cost, and energetic cost of transport to be 1.6, 1.7, and 1.4% respectively (Hébert-Losier et al., 2022a). Therefore, the observed 1.6 to 2.4% determent to RE measures surpass this threshold, showing these changes in RE measures are not only statistically significant but also practically meaningful.

Several reasons can help explain why our hypothesis was rejected. Firstly, the magnitude of plantarflexion fatigue induced may not have been sufficient to result in RE response changes to AFT, acknowledging that MVIC of plantarflexion strength has been reported to decline by 9 to 29% after prolonged running (Avela et al., 1999; Finni et al., 2003;

Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). Furthermore, it may be the induced plantarflexion fatigue from repeated calf raises does not reflect plantarflexion fatigue induced from actual running or plantarflexion muscles may have partially recovered between the end of the plantarflexion fatigue protocol and the start of the plantarflexion power test and subsequent RE test, given that partial recovery from repetitive knee extensions is seen within eight minutes (Husmann et al., 2018). There is also potential for muscle fibre typology differences between individuals to influence our plantarflexion fatigue observation, as type II muscle fibres are more prone to fatigue compared to type I (Lievens et al., 2020; Schiaffino & Reggiani, 2011) and recover at different rates (Lievens et al., 2020). Nonetheless, our plantarflexion fatigue protocol successfully induced both physical and subjective fatigue, reflected by the corresponding 6.5% decline in plantarflexion power and the increased VAS for calf muscle fatigue and soreness questionnaires. Finally, age related declines in plantarflexion strength (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012) may also contribute to our results given a large proportion of the sample were above 35 years of age (i.e., masters runners). If previous speculations are accurate about plantarflexion strength influencing runners' RE response to AFT shoes (Madden et al., 2016; Ortega et al., 2021), the pre-existing decline in plantarflexion strength of masters runners may limit the amount of plantarflexion power decline and influence POST RE test results. However, baseline plantarflexion power did not significantly correlate to AFT shoe response in our study, nor did the change in plantarflexion power PRE to POST with the change in AFT shoe response (PRE to POST). These findings refute claims that a certain amount of plantarflexion strength is needed for beneficial AFT shoe response.

Practical Implications

This thesis shows an average RE improvement of 4.0 to 4.3% when running in AFT compared to Control shoes, aligning with previous literature which reported similar improvements (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023), additionally supporting that the plantarflexion muscle-tendon unit is important for RE (Arampatzis et al., 2006; Bohm et al., 2021; Nguyen et al., 2025). Furthermore, this thesis goes against previous speculations that a lack in plantarflexion strength might limit AFT shoe response (Madden et al., 2016; Ortega et al., 2021). Therefore, runners, coaches, retailers, and manufacturers may not need to consider the baseline plantarflexion strength when recommending AFT shoes for improving RE. In addition, these findings could suggest runners will still benefit from AFT shoes even with the presence plantarflexion fatigue from prolonged running (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008), although a specific study on this topic is recommended. Nonetheless, going into a race with plantarflexion fatigue is not recommended due to the overall detriment to RE with plantarflexion fatigue, irrespective of shoes worn. Finally, this thesis adds to the current literature on individual RE variability with AFT shoes, showing that plantarflexion power is not a limiting factor on AFT shoe response, which could extrapolate to plantarflexion strength. Overall, this thesis adds to our current understanding on the reported RE variability between people running in AFT shoes, indicating plantarflexion power and fatigue are not key mediators, with future studies needed to confirm which factors are.

Strengths

One notable strength of this thesis is the relatively large sample size. While a minimum of 34 participants was required to detect a *moderate* two-tailed effect size difference between paired means, our study included data from 64 participants and thus was powered to detect a *small* effect size difference (*d* = 0.36). This sample size is noteworthy given previous AFT research typically includes 9 to 18 participants (Hébert-Losier et al., 2022a; Hoogkamer et al., 2018; Hunter et al., 2019; Joubert et al., 2024; Knopp et al., 2023), while plantarflexion fatigue research often includes 7 to 24 participants (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008).

Another strength of this thesis is the broad generalisability of our findings to the running population, reflected by the even distribution of male and female participants, as well as the range of performance levels, running distances (sprinters, middle-distance, long-distance, and ultra-distance runners), and ages of the included runners. This variability of runners was purposeful to represent the demographics of runners using AFT shoes. Females are often underrepresented in sport and exercise research (Cowley et al., 2021; Martínez-Rosales et al., 2021), and AFT shoe research (Mason et al., 2024). Our inclusion of half female and half male participants helps to address this gap. However, this diverse population may also introduce confounding variables that were not controlled for in our analysis, along with increased inter-individual variability (increased standard deviation) meaning a large sample size is required to identify differences between groups (Williams & Williams, 2020), suggesting recruiting a more homogenous population of runners might led to more evident differences in AFT shoe response PRE and POST.

This study used Salomon Phantasm S/Lab 2 (AFT) and Salomon Aero Glide 2 (Control) shoes. These two shoes were selected in attempts to match shoe characteristics other than inclusion or exclusion of AFT shoe elements (i.e., midsole foam and the presence of a carbon fibre plate). Based on a US9 shoe size, the Control shoe was 35 g heavier and had an 8% lower minimalist shoe index than the AFT shoe. However, these differences in mass and minimalist shoe index are not likely to meaningfully change RE or biomechanics. Therefore, any change in RE observed between shoes are linked to the presence or absence of AFT features.

Finally, we used a mirrored counterbalanced crossover design for PRE RE testing, with counterbalanced POST testing conditions. This approach helps minimise the risk of order effects on RE measures. Furthermore, all RE tests were completed on the same day, which will reduce intra-individual variability and is recommended when comparing the RE measures in different footwear (Barrons et al., 2024).

Limitations

The primary limitation of this thesis relates to the plantarflexion fatigue protocol. While the protocol effectively induced significant plantarflexion fatigue, it remains unclear how specific this calf raise-induced plantarflexion fatigue is to running-induced plantarflexion fatigue. An alternative approach to inducing fatigue could have involved prolonged running, which has been associated to a 9 to 29% decline in plantarflexion strength (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). This method of plantarflexion fatigue would likely be more ecologically valid to running-specific fatigue. However, this method would require substantially more time, may require RE testing across multiple days, and introduces challenges in controlling the amount of plantarflexion fatigue and plantarflexion recovery during the experimental protocol. Furthermore, this method would likely induce fatigue to the whole body rather than isolated plantarflexion fatigue, of which this thesis aimed to investigate the influence of solely plantarflexion fatigue.

A second limitation of the plantarflexion fatigue protocol was the large variation in completed calf raise repetitions between participants (i.e., bodyweight calf raises ranged from 7 to 213 repetitions) and associated amount of total mechanical work, indicating participants may experience different physiological and neuromuscular fatigue responses. Those who performed more repetitions may have experienced greater neuromuscular fatigue (Varela-Olalla et al., 2024). Further investigation using surface electromyography or twitch interpolation could help differentiate between central and peripheral fatigue mechanisms. Nevertheless, participants reported increased levels of perceived calf muscle fatigue and soreness, and the change in RE response to AFT footwear was not associated with the change in plantarflexion power from PRE to POST fatigue.

Although it is recommended to obtain multiple RE trials when assessing footwear effects (Barrons et al., 2024), only a single POST RE test was conducted for each shoe condition, although two RE tests were performed PRE. The single POST RE test design was chosen to avoid participants needing to complete four plantarflexion fatigue protocols, and to limit plantarflexion recovery using four RE tests with only two plantarflexion fatigue protocols. Therefore, the average of two RE test PRE are compared to a single RE test POST, with the latter measurement subject to greater variability.

This thesis did not explore the differences in response between sex or age. Previous research has suggested females benefit to a greater extent from AFT shoes than males, reflected by the faster progression in world best racing times in females compared to males (Mason et al., 2024; Willwacher et al., 2024). Additionally, MVIC of plantarflexion strength tends to decline with age (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012). Consequently, masters runners may benefit from AFT shoes to a lesser extent than younger runners if plantarflexion strength is indeed important in benefiting from AFT shoes, which was not accounted for in the current thesis. Both sex and age-related differences in RE to AFT with plantarflexion fatigue were beyond the scope of this thesis, and therefore, were not investigated. The focus of this project was to identify whether plantarflexion fatigue alters AFT shoes response, which was achieved. Furthermore, despite the relatively large sample size, there were no negative responders observed within this thesis. The sample of participants therefore did not incapsulate in full range of responses to AFT shoes.

Finally, no biomechanical measures were assessed throughout this thesis. Previous research has shown people tend to adopt one of two strategies; either keeping a consistent push-off time while increasing torque at the ankle, or increasing push-off time while lowering torque at the ankle (Willwacher et al., 2014). These two running strategies in AFT shoes may induce alternative RE responses with plantarflexion fatigue. The increased torque at the ankle may require greater metabolic demands, meaning this strategy may see greater detriments to RE response to AFT shoes with plantarflexion fatigue. However, people who tend to increase their push-off time in AFT shoes, slow the muscle contractile velocity in the gastrocnemius (Hata et al., 2024), which this slowed muscle contraction could be less metabolically demanding (Barclay et al., 1993; Bottinelli et al., 1994; He et al., 2000; Hill, 1938). Further research into whether these two strategies affect RE response with plantarflexion fatigue is warranted and may provide insight into how runners biomechanics with AFT shoes affect RE towards the end of a long-distance race.

Future Research

Future studies can build upon this thesis, addressing the limitations discussed within the thesis, specifically those related to sample diversity and plantarflexion fatigue protocol. Examining only younger trained runners with developed plantarflexion strength would reduce the likelihood of age-related declines in plantarflexion strength (Karamanidis & Arampatzis, 2005; Stenroth et al., 2012), and potentially the variability in calf raise performances during the fatigue protocol. Additionally, it may be worthwhile investigation whether female runners response to AFT shoes with plantarflexion fatigue differently to male runners, as previous research suggests females tend to respond to AFT shoes more favourably than males (Mason et al., 2024; Willwacher et al., 2024). Further research could also explore whether running-induced plantarflexion fatigue alters RE response to AFT shoes, as prolonged running shows declines of 9 to 29% to MVIC of plantarflexion strength (Avela et al., 1999; Finni et al., 2003; Murray et al., 2019; Petersen et al., 2007; Play et al., 2024; Saldanha et al., 2008). Findings from running-induced fatigue may differ from isolated plantarflexion fatigue. Finally, further research should consider measuring push-off time and ankle torque variations between runners, as runners tend to increase either their push-off time or ankle torque (Willwacher et al., 2014), of which may lead to differing RE response to AFT shoes with plantarflexion fatigue. The use of electromyography, 3D motion capture, and force data may provide further insight to how running mechanics interact with AFT responses and plantarflexion fatigue.

Conclusion

Altogether, this thesis provides evidence that plantarflexion fatigue does not significantly alter RE response to AFT shoes. Furthermore, greater plantarflexion power does not correlate to greater RE response to AFT shoes. These findings go against speculations about runners needing a certain level of plantarflexion strength to fully benefit from AFT shoes. This thesis confirms an average of 4.0 to 4.3% improvement in RE with AFT shoes in a diverse population of runners, while also highlighting an overall 1.6 to 2.4% detriment in RE with plantarflexion fatigue. Although plantarflexion fatigue may hinder RE towards the end of a long-distance run or race, these findings suggest RE response to AFT shoes may remain similar despite the presence of running-induced plantarflexion fatigue, which needs confirmation in future research.

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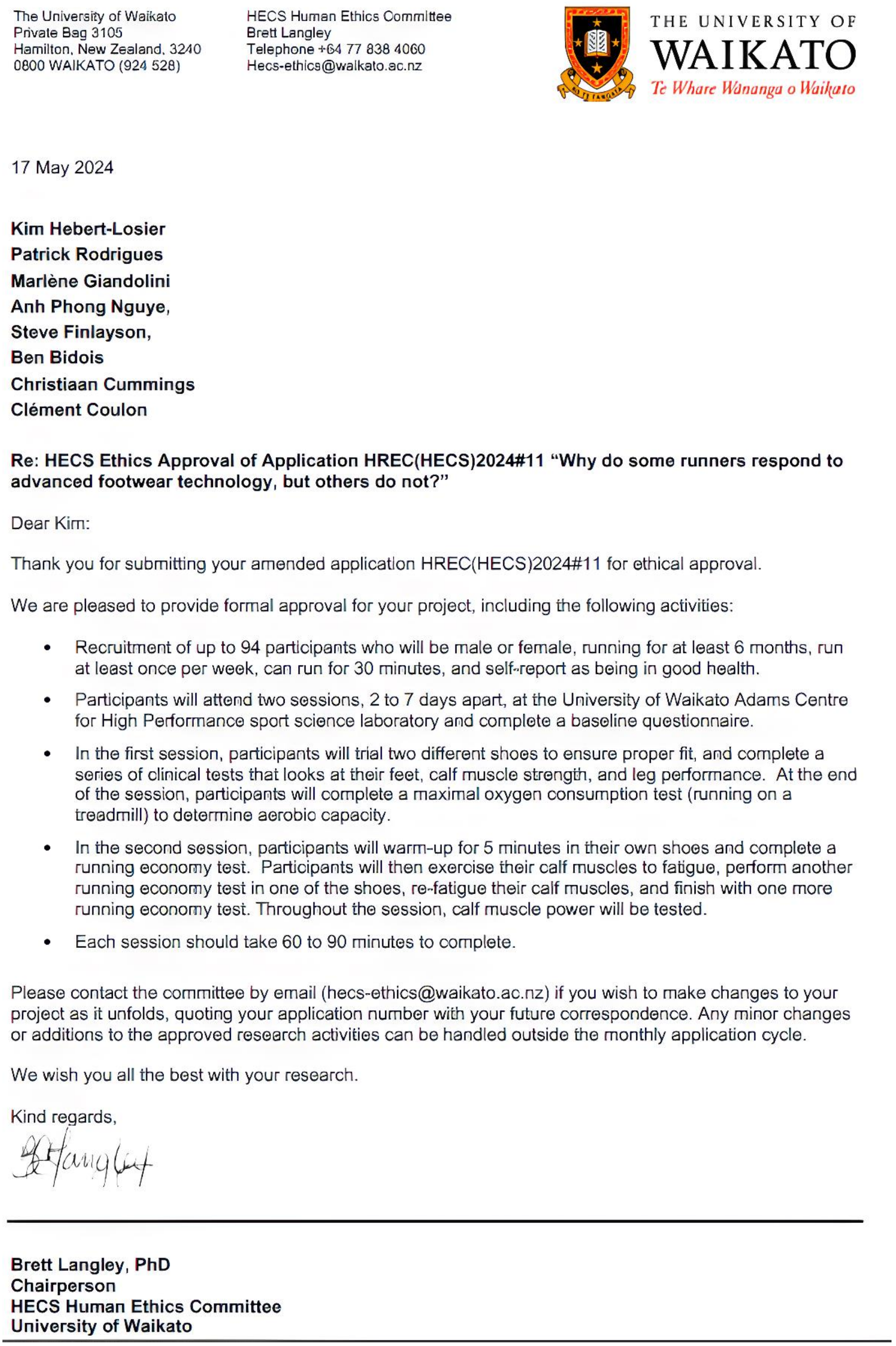
Appendices

Appendix A HECS Ethics Approval



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0800 WAIKATO (924 528)

HECS Human Ethics Committee
Brett Langley
Telephone +64 77 838 4060
Hecs-ethics@waikato.ac.nz

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

17 May 2024

Kim Hebert-Losier
Patrick Rodrigues
Marlène Giandolini
Anh Phong Nguye,
Steve Finlayson,
Ben Bidois
Christiaan Cummings
Clément Coulon

Re: HECS Ethics Approval of Application HREC(HECS)2024#11 "Why do some runners respond to advanced footwear technology, but others do not?"

Dear Kim:

Thank you for submitting your amended application HREC(HECS)2024#11 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Recruitment of up to 94 participants who will be male or female, running for at least 6 months, run at least once per week, can run for 30 minutes, and self-report as being in good health.
- Participants will attend two sessions, 2 to 7 days apart, at the University of Waikato Adams Centre for High Performance sport science laboratory and complete a baseline questionnaire.
- In the first session, participants will trial two different shoes to ensure proper fit, and complete a series of clinical tests that looks at their feet, calf muscle strength, and leg performance. At the end of the session, participants will complete a maximal oxygen consumption test (running on a treadmill) to determine aerobic capacity.
- In the second session, participants will warm-up for 5 minutes in their own shoes and complete a running economy test. Participants will then exercise their calf muscles to fatigue, perform another running economy test in one of the shoes, re-fatigue their calf muscles, and finish with one more running economy test. Throughout the session, calf muscle power will be tested.
- Each session should take 60 to 90 minutes to complete.

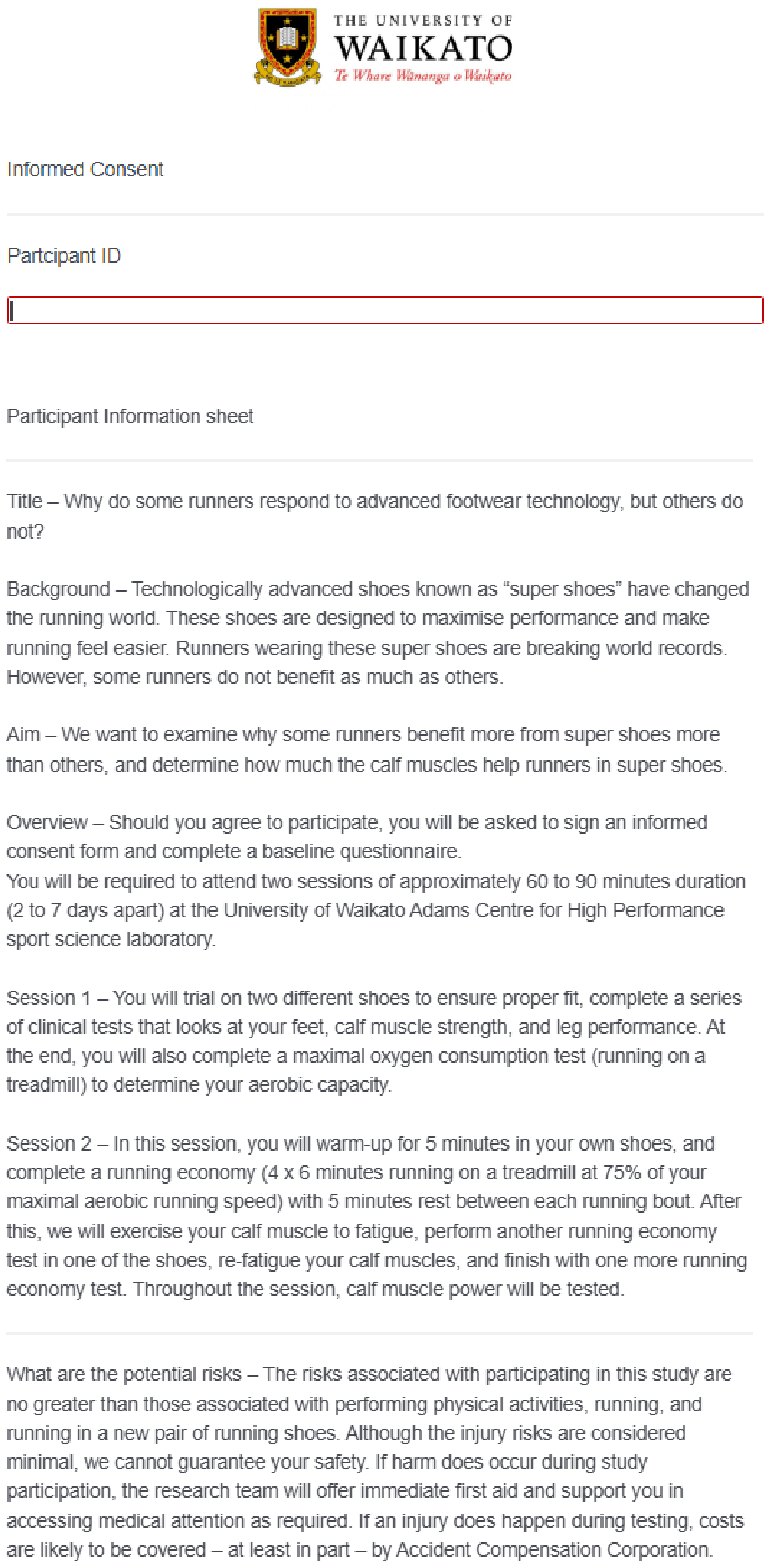
Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application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

We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato

Appendix B Participant Consent Form



THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

Informed Consent

Partcipant ID

Participant Information sheet

Title – Why do some runners respond to advanced footwear technology, but others do not?

Background – Technologically advanced shoes known as “super shoes” have changed the running world. These shoes are designed to maximise performance and make running feel easier. Runners wearing these super shoes are breaking world records. However, some runners do not benefit as much as others.

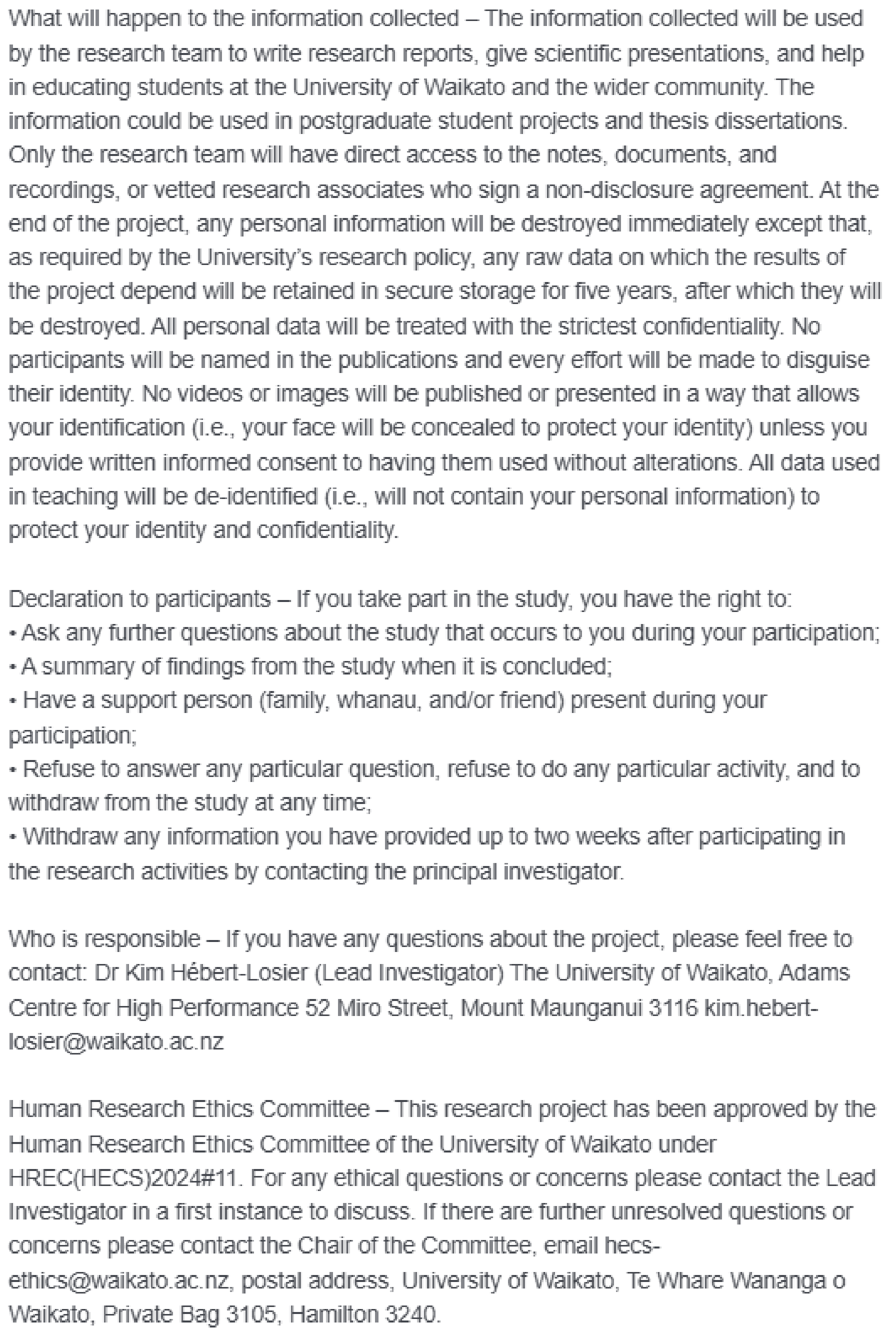
Aim – We want to examine why some runners benefit more from super shoes more than others, and determine how much the calf muscles help runners in super shoes.

Overview – Should you agree to participate, you will be asked to sign an informed consent form and complete a baseline questionnaire.
You will be required to attend two sessions of approximately 60 to 90 minutes duration (2 to 7 days apart) at the University of Waikato Adams Centre for High Performance sport science laboratory.

Session 1 – You will trial on two different shoes to ensure proper fit, complete a series of clinical tests that looks at your feet, calf muscle strength, and leg performance. At the end, you will also complete a maximal oxygen consumption test (running on a treadmill) to determine your aerobic capacity.

Session 2 – In this session, you will warm-up for 5 minutes in your own shoes, and complete a running economy (4 x 6 minutes running on a treadmill at 75% of your maximal aerobic running speed) with 5 minutes rest between each running bout. After this, we will exercise your calf muscle to fatigue, perform another running economy test in one of the shoes, re-fatigue your calf muscles, and finish with one more running economy test. Throughout the session, calf muscle power will be tested.

What are the potential risks – The risks associated with participating in this study are no greater than those associated with performing physical activities, running, and running in a new pair of running shoes. Although the injury risks are considered minimal, we cannot guarantee your safety. If harm does occur during study participation, the research team will offer immediate first aid and support you in accessing medical attention as required. If an injury does happen during testing, costs are likely to be covered – at least in part – by Accident Compensation Corporation.

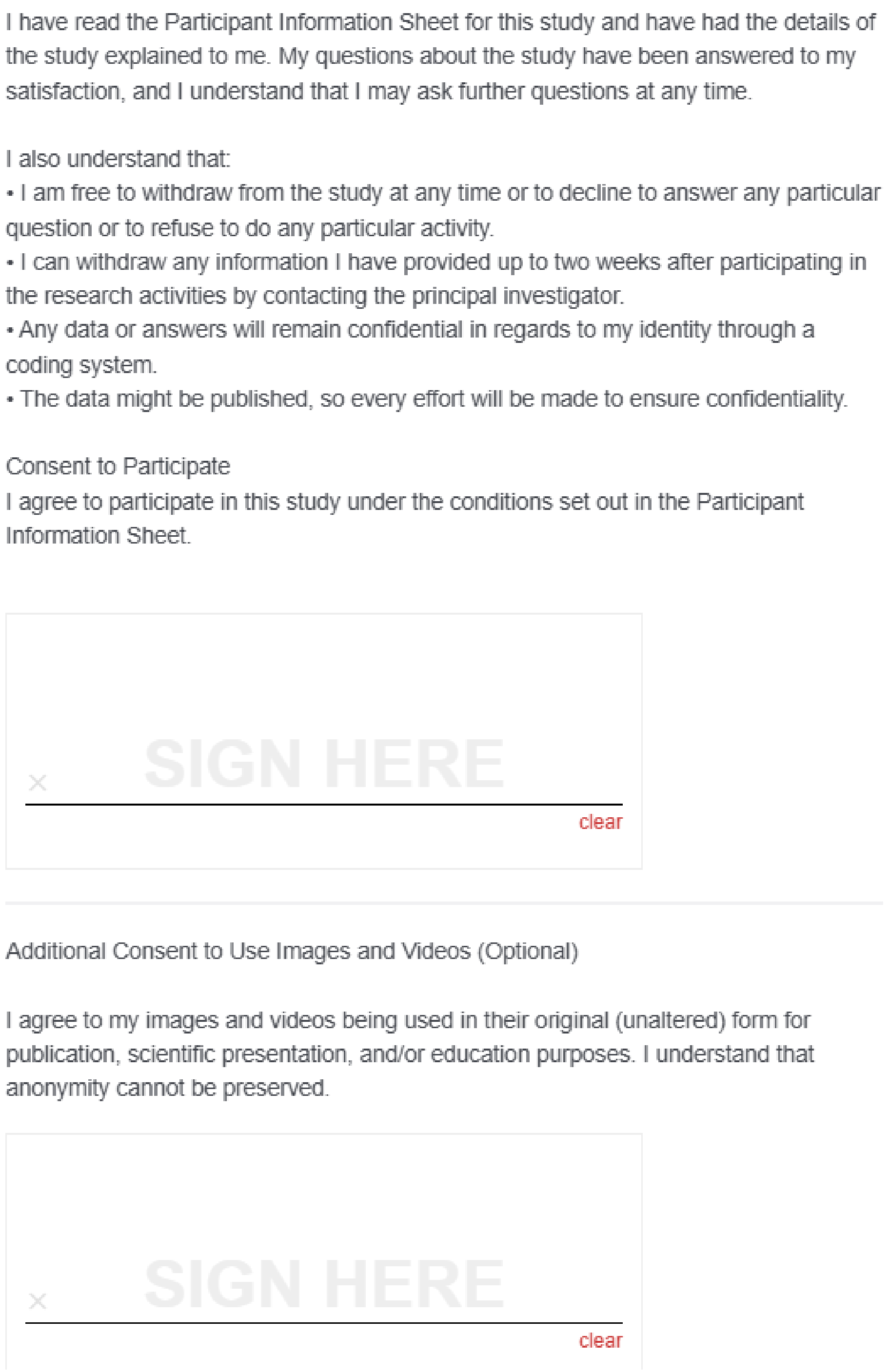


What will happen to the information collected – The information collected will be used by the research team to write research reports, give scientific presentations, and help in educating students at the University of Waikato and the wider community. The information could be used in postgraduate student projects and thesis dissertations. Only the research team will have direct access to the notes, documents, and recordings, or vetted research associates who sign a non-disclosure agreement. At the end of the project, any personal information will be destroyed immediately except that, as required by the University's research policy, any raw data on which the results of the project depend will be retained in secure storage for five years, after which they will be destroyed. All personal data will be treated with the strictest confidentiality. No participants will be named in the publications and every effort will be made to disguise their identity. No videos or images will be published or presented in a way that allows your identification (i.e., your face will be concealed to protect your identity) unless you provide written informed consent to having them used without alterations. All data used in teaching will be de-identified (i.e., will not contain your personal information) to protect your identity and confidentiality.

Declaration to participants – If you take part in the study, you have the right to:
- Ask any further questions about the study that occurs to you during your participation;
- A summary of findings from the study when it is concluded;
- Have a support person (family, whanau, and/or friend) present during your participation;
- Refuse to answer any particular question, refuse to do any particular activity, and to withdraw from the study at any time;
- Withdraw any information you have provided up to two weeks after participating in the research activities by contacting the principal investigator.

Who is responsible – If you have any questions about the project, please feel free to contact: Dr Kim Hébert-Losier (Lead Investigator) The University of Waikato, Adams Centre for High Performance 52 Miro Street, Mount Maunganui 3116 kim.hebert-losier@waikato.ac.nz

Human Research Ethics Committee – This research project has been approved by the Human Research Ethics Committee of the University of Waikato under HREC(HECS)2024#11. For any ethical questions or concerns please contact the Lead Investigator in a first instance to discuss. If there are further unresolved questions or concerns please contact the Chair of the Committee, email hecs-ethics@waikato.ac.nz, postal address, University of Waikato, Te Whare Wananga o Waikato, Private Bag 3105, Hamilton 3240.



I have read the Participant Information Sheet for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

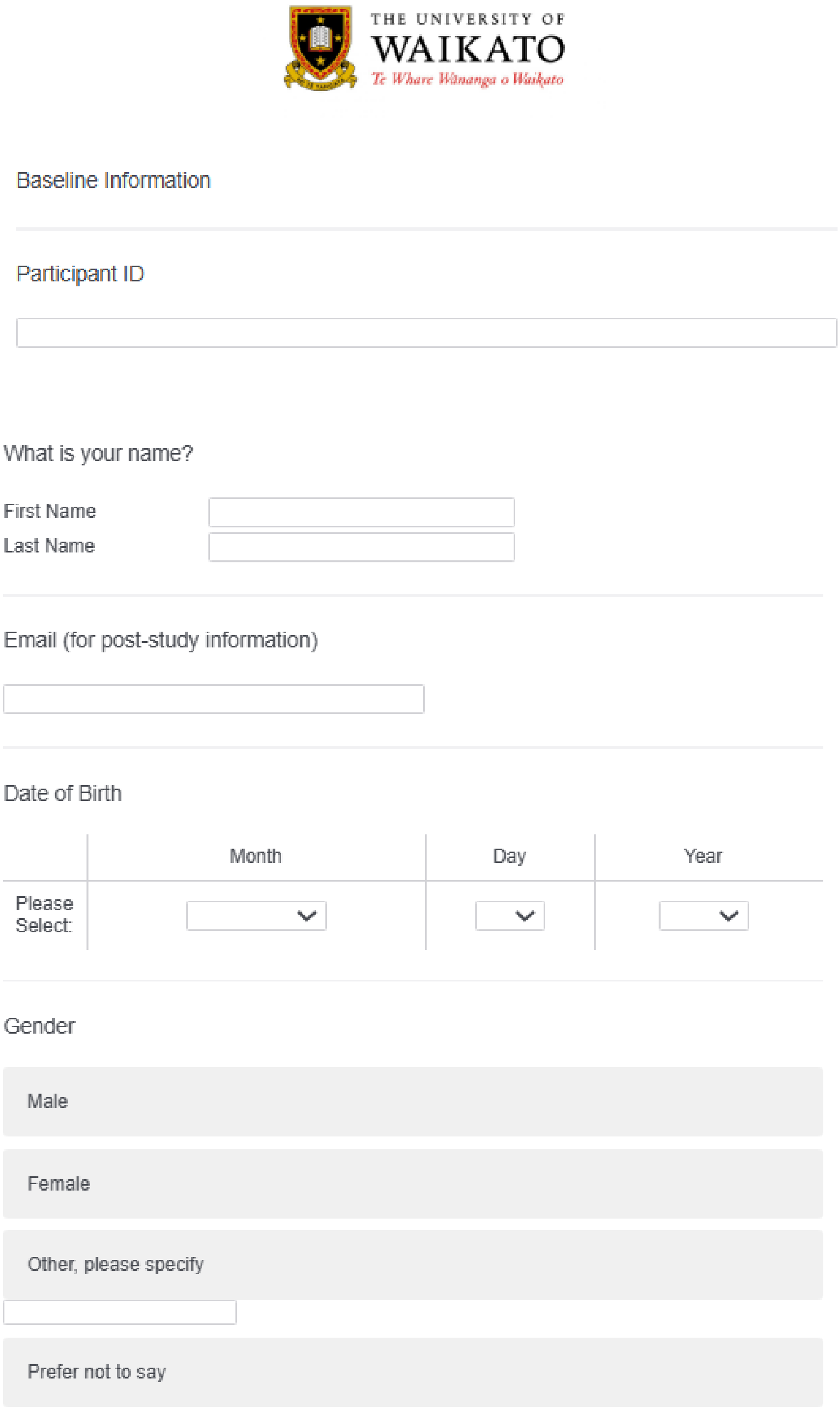
I also understand that:
- I am free to withdraw from the study at any time or to decline to answer any particular question or to refuse to do any particular activity.
- I can withdraw any information I have provided up to two weeks after participating in the research activities by contacting the principal investigator.
- Any data or answers will remain confidential in regards to my identity through a coding system.
- The data might be published, so every effort will be made to ensure confidentiality.

Consent to Participate
I agree to participate in this study under the conditions set out in the Participant Information Sheet.

Additional Consent to Use Images and Videos (Optional)

I agree to my images and videos being used in their original (unaltered) form for publication, scientific presentation, and/or education purposes. I understand that anonymity cannot be preserved.

Appendix C Qualtrics Demographic Information



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Baseline Information

Participant ID

What is your name?

First Name
Last Name

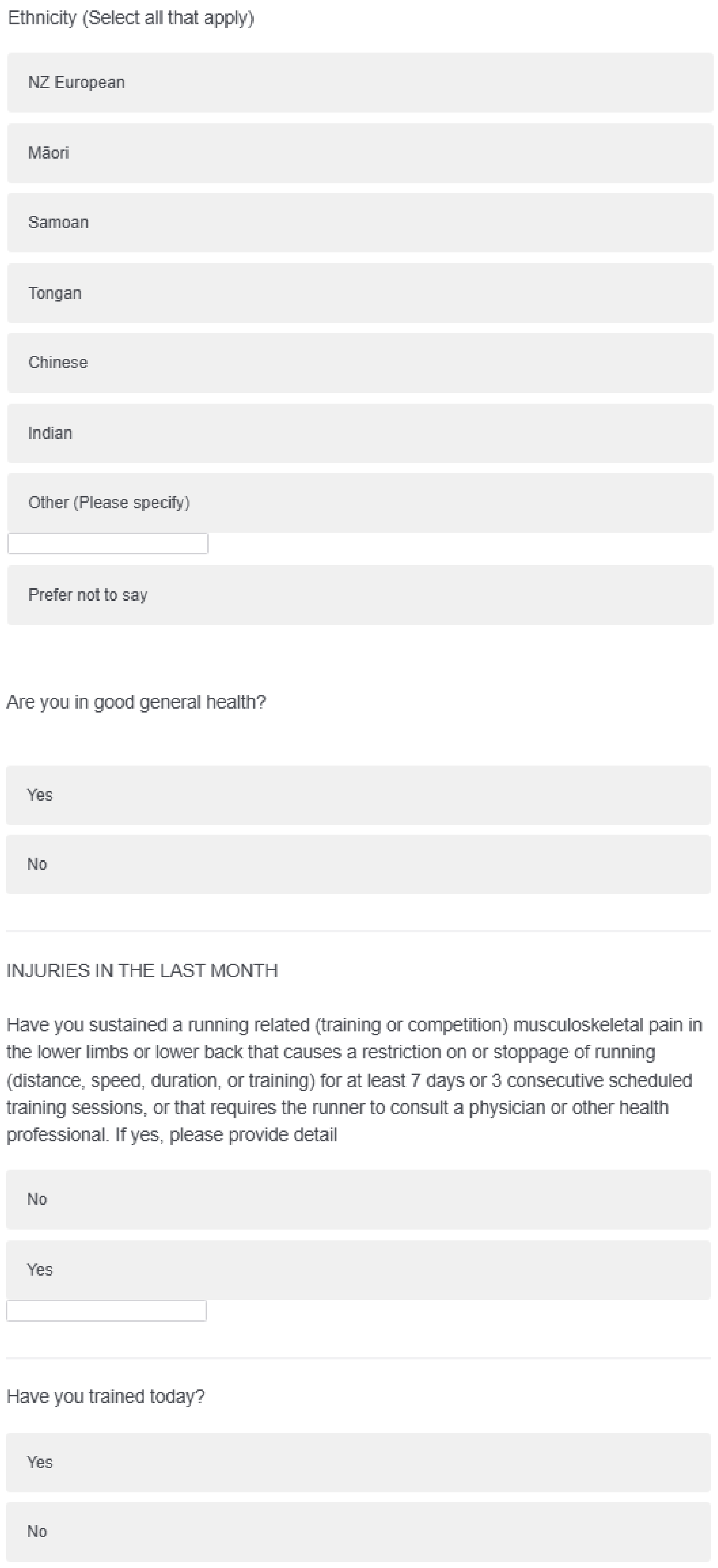
Email (for post-study information)

Date of Birth

	Month	Day	Year
Please Select:	⌄	⌄	⌄

Gender

○ Male
○ Female
○ Other, please specify
○ Prefer not to say



Ethnicity (Select all that apply)

NZ European

Māori

Samoan

Tongan

Chinese

Indian

Other (Please specify)

Prefer not to say

Are you in good general health?

Yes

No

INJURIES IN THE LAST MONTH

Have you sustained a running related (training or competition) musculoskeletal pain in the lower limbs or lower back that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional. If yes, please provide detail

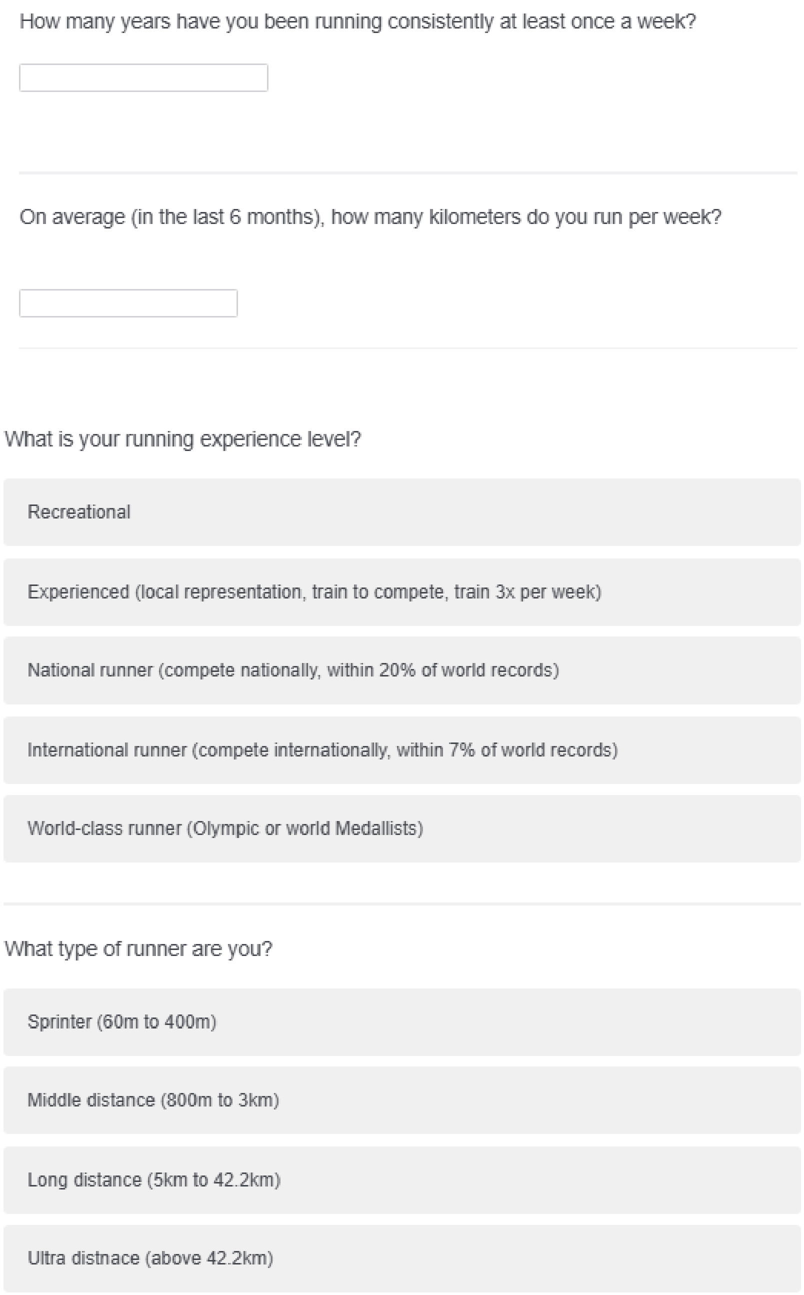
No

Yes

Have you trained today?

Yes

No



How many years have you been running consistently at least once a week?

On average (in the last 6 months), how many kilometers do you run per week?

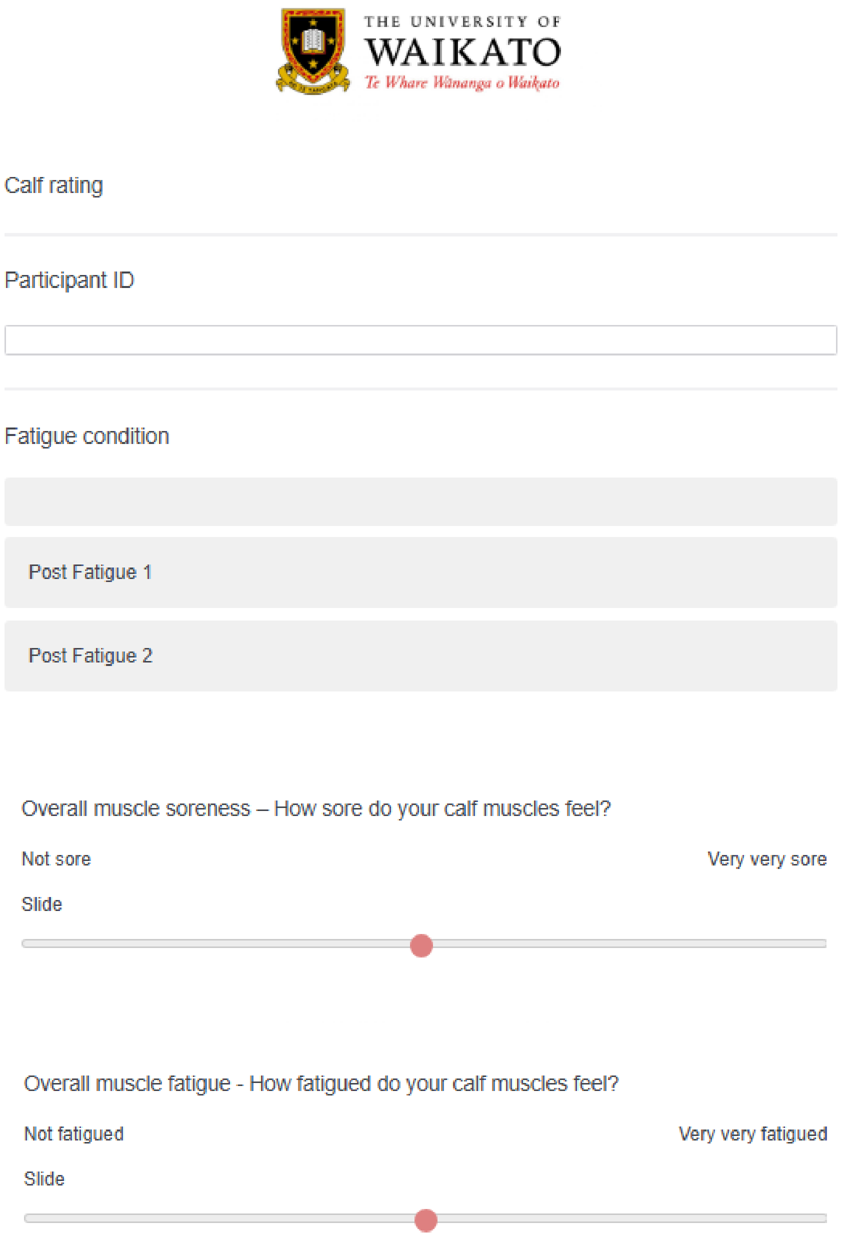
What is your running experience level?

- Recreational
- Experienced (local representation, train to compete, train 3x per week)
- National runner (compete nationally, within 20% of world records)
- International runner (compete internationally, within 7% of world records)
- World-class runner (Olympic or world Medallists)

What type of runner are you?

- Sprinter (60m to 400m)
- Middle distance (800m to 3km)
- Long distance (5km to 42.2km)
- Ultra distnace (above 42.2km)

Appendix D Calf Muscle Soreness and Fatigue VAS Questionnaire



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Calf rating

Participant ID

Fatigue condition

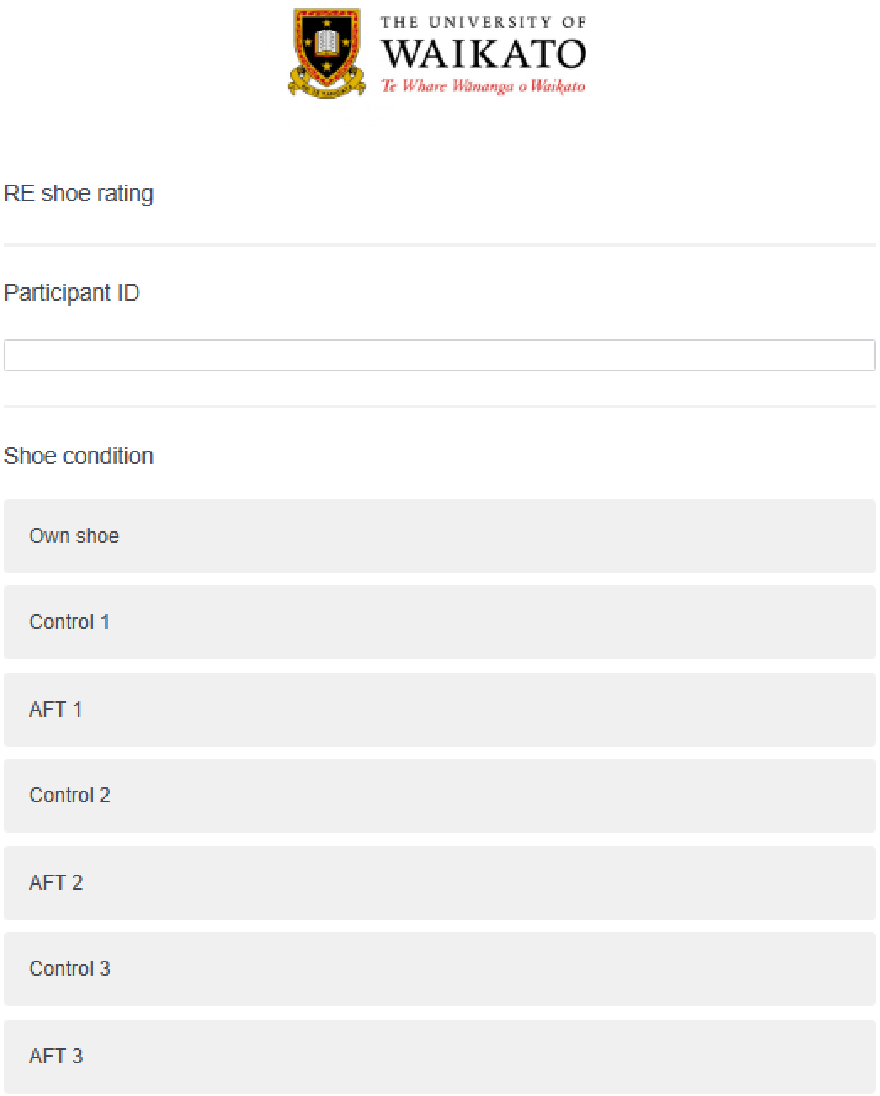
Post Fatigue 1

Post Fatigue 2

Overall muscle soreness – How sore do your calf muscles feel?

Overall muscle fatigue - How fatigued do your calf muscles feel?

Appendix E Running Shoe Comfort Assessment Questionnaire



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RE shoe rating

Participant ID

Shoe condition

- Own shoe
- Control 1
- AFT 1
- Control 2
- AFT 2
- Control 3
- AFT 3

In the following questions, the right side of the scale is better

Overall comfort – Consider your overall comfort in these shoes. How did the shoe feel?

Not comfortable at all | Most comfortable imaginable

Slide

Pleasure-displeasure – Consider overall how you felt running in these shoes (pleasure-displeasure)

Very bad | Neutral | Very good

Slide

Easier – harder - Consider overall how difficult it felt running in these shoes (easier-harder)

Very hard | Neutral | Very easy

Slide

Performance – Consider overall how you feel these shoes might influence your performance (worse-improve)

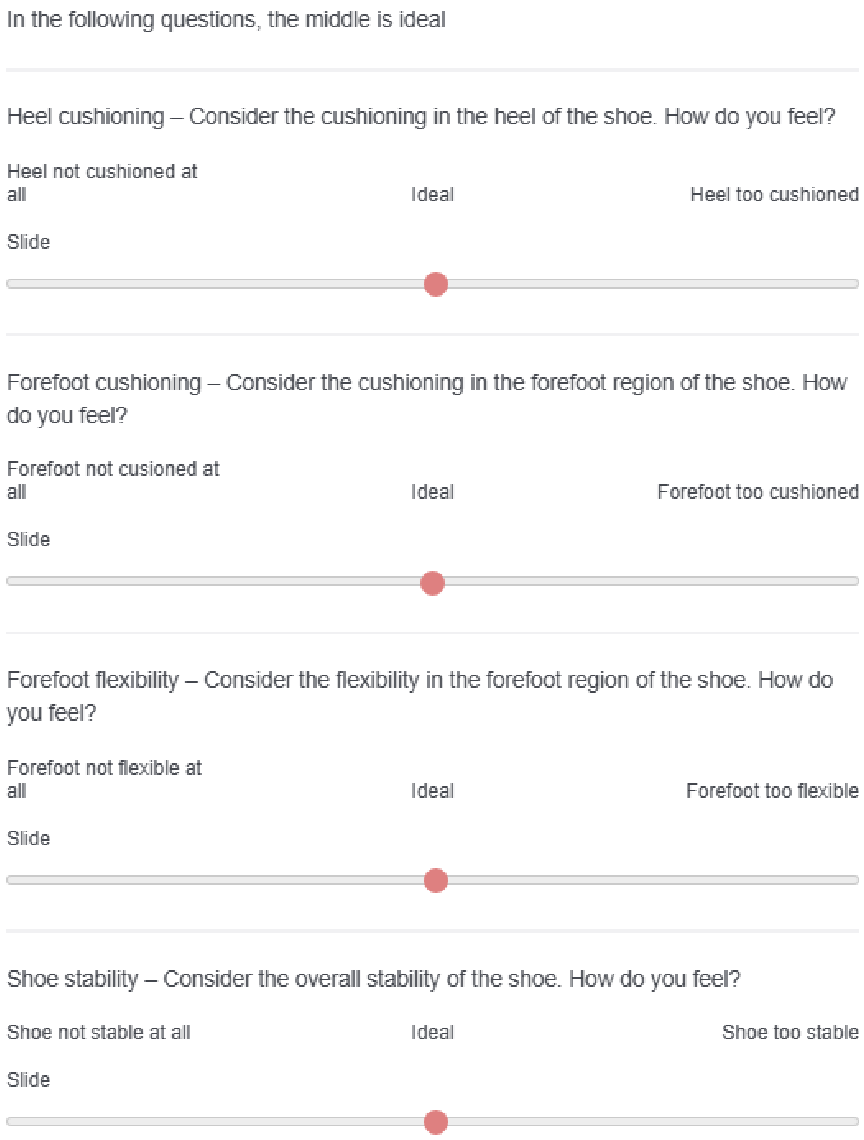
Very bad | Neutral | Very good

Slide

Injury – Consider overall how you feel these shoes might influence your risk of injury (worse-improve)

Very high risk of injury | Neutral | Very low risk of injury

Slide



In the following questions, the middle is ideal

Heel cushioning – Consider the cushioning in the heel of the shoe. How do you feel?

Heel not cushioned at all	Ideal	Heel too cushioned

Slide

Forefoot cushioning – Consider the cushioning in the forefoot region of the shoe. How do you feel?

Forefoot not cusioned at all	Ideal	Forefoot too cushioned

Slide

Forefoot flexibility – Consider the flexibility in the forefoot region of the shoe. How do you feel?

Forefoot not flexible at all	Ideal	Forefoot too flexible

Slide

Shoe stability – Consider the overall stability of the shoe. How do you feel?

Shoe not stable at all	Ideal	Shoe too stable

Slide