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**Exploring interindividual running economy responses to advanced footwear
technology shoes across a range of variables: A quantitative study**

A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Master of Health, Sport, and Human Performance
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Abstract

In the past decade, the running landscape has changed due to advanced footwear technology (AFT) being imbedded in running shoes. While AFT shoes have been shown to improve running economy (RE) on average, little is known about the factors that explain the large interindividual variability in RE response. Therefore, this study aimed to investigate the interindividual variability in RE response to AFT and identify potential predictors of this variability using quantitative methods. This thesis considered participant characteristics, anthropometric measures, neuromuscular measures, and subjective perceptions as potential factors underpinning interindividual variability.

This thesis is separated into three chapters. Chapter One is a brief review on AFT, their components, and their influence on RE and performance, as well as the observed interindividual variability in AFT shoe responses and the factors proposed to mediate this variability. AFT shoes have been designed to improve RE and include thick lightweight resilient and compliant foams, stiff elements embedded in the foam, and curved shoe geometry. Research has explored how these components may contribute to RE improvements and has proposed various factors that may explain the interindividual variability, such as running speed, training level, sex, leg length, body mass, shoe size, and plantarflexion muscle-tendon unit properties. Comparing the characteristics of responders to non-responders and exploring relationships between these characteristics and RE responses can assist in identifying runners more likely to benefit from running in AFT.

Chapter Two presents an experimental study using a cross-sectional, repeated-measures design. A heterogenous sample of sixty-four participants (32 males, 32 females) of varying running levels, experience, age, and anthropometric characteristics completed two laboratory sessions between two and seven days apart. The first included baseline information and

participant characteristics for anthropometric, neuromuscular measures, and maximal oxygen uptake. The second session served as the experimental phase, during which RE variables were evaluated in the two different shoe conditions: Salomon S/Lab Phantasm 2 (AFT) and Salomon Aero Glide 2 (CONTROL). RE was measured over four 6-minute trials in an AFT and a CONTROL shoe, allocated in a randomised, crossover order. Descriptive statistics (means \pm SD), inferential comparisons (paired samples t-tests, Chi square, and Fishers exact), and Pearson's correlation coefficients were calculated to compare between responders and non-responders to AFT shoes and explain AFT shoe response. The mean improvement in RE (expressed in terms of oxygen consumption) was $4.13 \pm 1.6\%$ when wearing AFT compared to CONTROL shoes, with individual responses ranging from -2.62% to 11.01% . From all the variables collected, only gastrocnemius medialis (GM) stiffness normalised to leg length was significantly different ($p = 0.046$) between groups, with responders exhibiting greater GM stiffness ($329.8 \pm 36.6 \text{ N/m}^2$) compared to non-responders ($296.4 \pm 47.3 \text{ N/m}^2$). No other between-group differences were statistically significant. Two variables were significantly and *moderately* correlated to RE response, where greater navicular drop ($r = 0.31, p = 0.012$) and greater GM stiffness (normalised to leg length) ($r = 0.35, p = 0.005$) were linked to greater RE benefits from running in AFT shoes. Additionally greater gear ratio ($r = 0.26, p = 0.040$) and lower standing plantarflexion isometric strength (normalised to body weight) ($r = -0.26, p = 0.041$) displayed significant and *small* correlations with improvements in RE when running in AFT shoes. A multiple linear regression including standing plantarflexion isometric strength, navicular drop, gear ratio, and GM stiffness (normalised to leg length) explained 27% of the variance in our AFT RE responses ($R^2 = 0.2731$, adjusted $R^2 = 0.223$), with GM stiffness being the most important factor ($B = 0.014, p = 0.015$).

Lastly, Chapter Three summarises the findings, strengths, limitations, and recommendations for future research. This research provides further insight into interindividual variability in

RE responses to AFT, showing not all runners benefit equally from AFT shoes. Therefore, runners should be aware that they may not improve their RE via AFT, however, individuals with greater GM stiffness, navicular drop, and static ankle gear ratio, and with lower standing plantarflexion isometric strength may benefit to a greater extent from AFT shoe wear. These factors may help guide more personalised footwear selection and prescription. Future research should investigate whether training interventions that modify these characteristics can enhance responses to AFT footwear and examine how other biomechanical variables, such as foot strike patterns or flight times, may interact with RE responses.

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List of Abbreviations

AFT - Advanced footwear technology

AT - Achilles tendon

BMI - Body mass index

bpm - Beats per minute

BW - Body weight

CI - Confidence interval

EVA - Ethylene-vinyl-acetate

Exp - Experienced

GM - Gastrocnemius medialis

MARS - Measurement, Analysis, Reporting and Software

MTP - Metatarsophalangeal

MVIC - Maximal voluntary isometric contraction

Nat - National

OR - Odds ratio

PEBA - Polyether block amide

PF – Plantarflexion

Rec - Recreational

RER - Respiratory exchange ratio

RE - Running economy

RUN-CAT - Running comfort assessment tool

SD - Standard deviation

UNICEF - United Nations Children's Fund

VAS - Visual analogue scale

VO₂ - Volume of oxygen consumption

$v\text{VO}_2$ - Velocity at maximal oxygen uptake

$\text{VO}_2 \text{ max}$ - maximal oxygen uptake

$\text{VO}_2 \text{ peak}$ - peak oxygen uptake

y - Years

Thesis Overview

This thesis contains three chapters (Figure 1). Chapter One is a literature review on advanced footwear technology (AFT), running economy, and potential factors that explain responders and non-responders. Chapter Two is an experimental study using a cross-sectional, repeated-measures design. This study involved 64 runners (50% female) of varied running experiences, two laboratory sessions, the collection of a range of potential factors explaining responses to AFT, and the assessment of running economy in two different shoe conditions: Salomon S/Lab Phantasm 2 (AFT) and Salomon Aero Glide 2 (CONTROL). Chapter Three is the final chapter that summarises the findings, strengths, limitations, and recommendations for future research based on the literature review and experimental study.

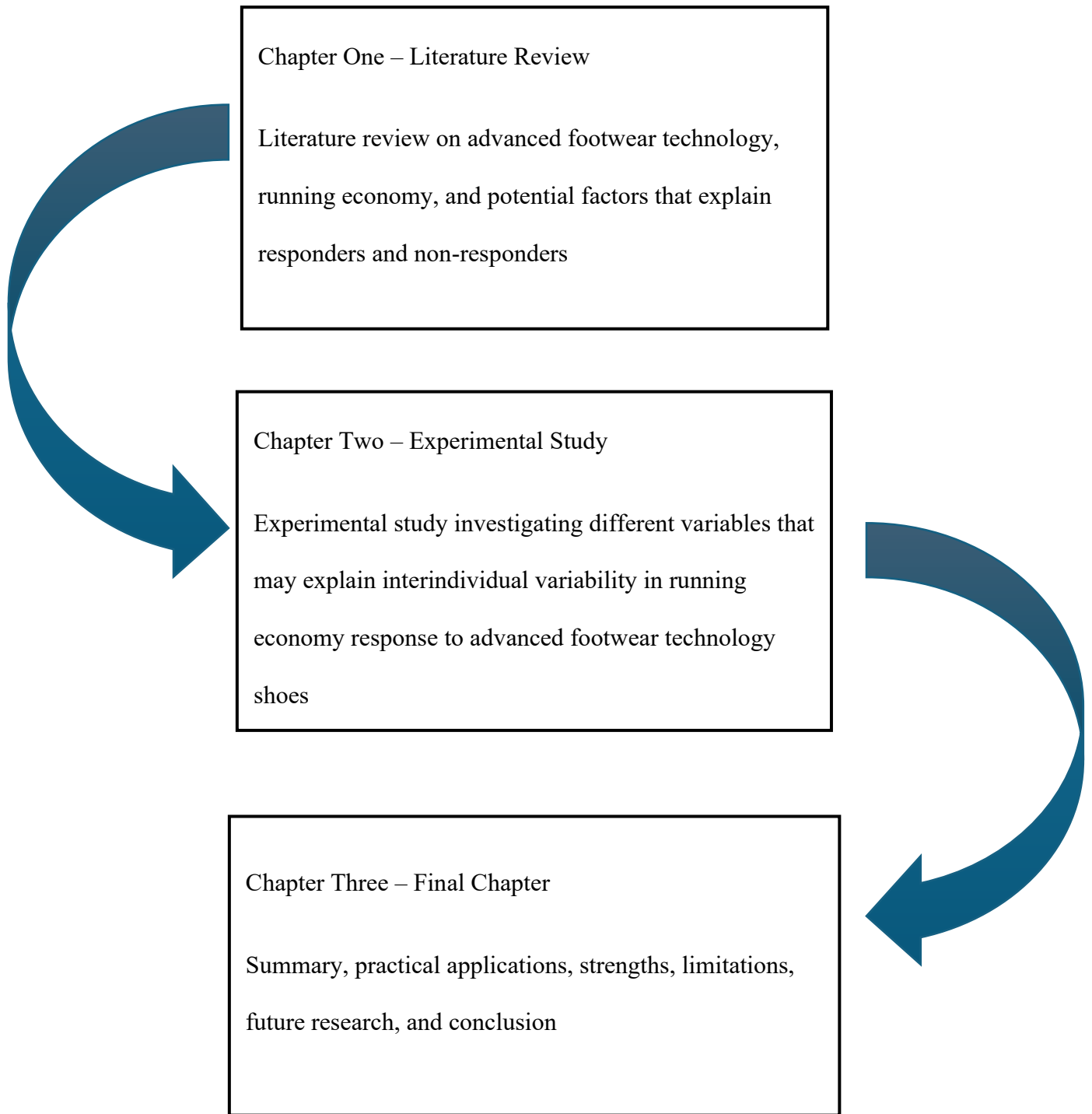


Figure 1. Thesis outline

Chapter One – Literature Review

Running shoes with advanced footwear technology, and variability in running economy responses

Introduction

Throughout the last century, athletic performance has improved and may be due to a variety of factors, such as social and environmental changes, and advances in training, technology, and equipment (Lippi et al., 2008). Specifically in running, performances and technologies have greatly advanced (Bermon et al., 2021). Manufacturers have developed footwear shown to aid running performances (Dinato et al., 2021), with improvements in running economy (RE) being a particular focus as it is one of the strongest determinants of distance running performance (Van Hooren et al., 2024).

Evolution of advanced footwear technology

Shoes have played a fundamental role in human movement, initially serving to protect the feet from the environment (Mohammadi & Nourani, 2025). However, as athletic competition evolved, so did the technology in footwear. In the context of running, shoe technology has undergone a transformative journey, transitioning from simple protective coverings to sophisticated performance-enhancing tools (Burns & Joubert, 2024). With the advancement of sports science and biomechanics research, attention shifted towards optimising RE, the efficiency with which energy is used during a submaximal running effort, often expressed as the steady state oxygen consumption (VO_2) at a given velocity (Barnes & Kilding, 2015a). Early efforts in this direction primarily focused on reducing shoe mass, based on evidence indicating that an increase in shoe mass by 100 g negatively affected metabolic rate and oxygen consumption by approximately 1% (Franz et al., 2012; Hoogkamer et al., 2016; Rodrigo-Carranza et al., 2020). A review by Nigg et al. (2020) documents how attempts to improve running performance have ventured past shoe mass modification and into specific components, such as midsole material, shoe shape, and longitudinal bending stiffness.

In the last decade, there has been an incremental step forward in running shoe technology research and use, specifically with the introduction of the Nike Vaporfly 4%. This shoe was developed for use in the Breaking 2 campaign to aid the runner, Eluid Kipchoge, in his attempt to run the marathon distance under 2 hours, a barrier previously thought impossible to break (Hoogkamer et al., 2018). The introduction of the Nike Vaporfly 4% in May of 2017 was the beginning of the advanced footwear technology (AFT) era, or more commonly known as “super shoes”. Advertised to improve RE by 4%, the key components of the Nike Vaporfly 4% were the incorporation of a light, thick, and resilient midsole foam made of polyether block amide (PEBA), integrated with a stiff curved carbon fibre plate in the midsole (Bermon et al., 2021). Although there is no consensus definition on what more broadly constitutes an AFT shoe, the elements of a lightweight, resilient, and high-energy thick midsole; a stiff element within the midsole; and a curved shoe geometry are cornerstones (Hébert-Losier & Pamment, 2023).

Since the inception of the Nike Vaporfly 4%, several shoe brands alongside Nike Inc. have continued to innovate these elements and shoes with soft high-energy returning midsoles (Joubert & Jones, 2022). As highlighted by Muniz-Pardos et al. (2021), since the introduction of AFT shoes, athletes wearing AFT shoes or spikes have broken all World Records from 5 km to the marathon, with a similar trend observed in middle-distance running (Healey et al., 2022). Rodrigo-Carranza et al. (2021) investigated the influence of AFT on top 100 marathon performances between 2015 and 2019, finding that AFT shoes were used by 90% of athletes, and marathon performances improved between 0.75 to 1.5% from 2017 to 2019. Furthermore, several experimental and observational studies have reported similar improvements in RE, time-trial performances, and races due to AFT shoe wearing in both road and track contexts (Langley & Langley, 2024; Rodrigo-Carranza et al., 2022b; Senefeld et al., 2021; Willwacher et al., 2024).

Running economy

RE results from a complex combination of metabolic, cardiorespiratory, biomechanical, and neuromuscular factors (Barnes & Kilding, 2015a, 2015b). Comparisons between individuals RE are traditionally made by expressing VO_2 relative to body mass per minute (mL/kg/min) (Barnes & Kilding, 2015a). Most commonly RE is measured while running at a range of constant speeds, each constant speed stage lasting between 3 to 15 minutes to achieve physiological steady state. This steady-state is verified by ensuring the respiratory exchange ratio (RER) remains below 1.0 and blood lactate concentration level remains similar to baseline (Barnes & Kilding, 2015a). It is also important to ensure RE is measured during submaximal effort and below 80% of maximal oxygen uptake ($\text{VO}_2 \text{ max}$) as individual differences in efficiency become too large when working anaerobically (Daniels, 1985). Additionally, some studies assess RE as the energy expended per km for a given body mass (kcal/kg/km) (Barnes & Kilding, 2015a), along with the rate of metabolic energy consumption (W/kg) (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Hunter et al., 2019; Perry et al., 2025).

Alongside RE, $\text{VO}_2 \text{ max}$ and the ability to run at a high percentage of $\text{VO}_2 \text{ max}$ (known as fractional utilisation) are the greatest factors in distance running performance. RE shows the greatest association to running performance (Van Hooren et al., 2024), where runners with better RE yet poorer $\text{VO}_2 \text{ max}$ are able to outperform runners with a superior $\text{VO}_2 \text{ max}$. $\text{VO}_2 \text{ max}$ represents the maximal rate of oxygen that an individual can use during intense exercise and is often used as a measure of aerobic capacity (Bassett & Howley, 2000). $\text{VO}_2 \text{ max}$ is typically measured with a breath-by-breath gas exchange analyser, with runners following a ramp protocol. A plateau in oxygen consumption after a peak is sought to verify that a maximum has been obtained (Green & Askew, 2018). In practical settings, particularly during ramp protocols, a clear plateau in oxygen uptake may not be observed. In such cases,

the highest oxygen uptake achieved is reported as VO_2 peak, an acceptable and commonly used estimate of cardiorespiratory fitness and aerobic capacity (Green & Askew, 2018; Wagner et al., 2020).

Gait cycle

The gait cycle describes the sequence of movement during human locomotion. The gait cycle begins when one foot strikes the ground and ends when the same foot strikes the ground again (Dugan & Bhat, 2005). The cycle can be broken into two main phases. The stance phase, which begins at the initial contact when the foot first hits the ground and ends when that foot is no longer on the ground. The swing phase begins at toe-off, where the foot swings through the air and ends when the foot strikes the ground again (Novacheck, 1998). The key distinction between running and walking is there are two periods of double support with both feet on the ground during walking (Dugan & Bhat, 2005). However, in running there is an aerial phase where both feet are in the air simultaneously (Novacheck, 1998). The stance phase is particularly relevant to RE as it includes impact absorption during early stance and propulsion during late stance. Key muscles involved include the triceps surae, anterior tibialis, hamstrings, quadriceps, and hip extensors, which are active primarily from late swing to mid-stance to prepare for and absorb ground reaction forces, and to generate forward propulsion (Novacheck, 1998; Prilutsky & Zatsiorsky, 1994).

The Achilles tendon also plays a critical role in the mechanics of running, functioning as a biological spring to store and return mechanical energy (Lichtwark & Wilson, 2006). Sasaki and Neptune (2006) estimate nearly 50% of the mechanical energy from running is stored in the Achilles tendon and foot arch complex during the stance phase. Working alongside the triceps surae and foot structure, the Achilles tendon stretches to absorb ground reaction forces

during the stance phase. This elastic energy is then released during the late stance phase and toe-off, contributing to forwards propulsion.

Advanced footwear technology components

A growing body of evidence demonstrates that AFT shoes can improve RE by around 4% (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019) and performance by 1 to 3% (Langley & Langley, 2024; Rodrigo-Carranza et al., 2022b; Willwacher et al., 2024). However, the underlying mechanisms driving these improvements remain only partially understood, suggesting further investigation is needed to better inform the running community. Mechanisms proposed to improve RE include increases in longitudinal shoe stiffness (Nigg et al., 2020; Perry et al., 2025; Rodrigo-Carranza et al., 2023) the teeter-totter effect (Nigg et al., 2020; Subramaniam et al., 2024), the high-energy returning midsole material (Hébert-Losier & Pamment, 2023; Nigg et al., 2020; Perry et al., 2025; Rodrigo-Carranza et al., 2024), and reduced shoe mass (Hébert-Losier & Pamment, 2023; Nigg et al., 2020; Rodrigo-Carranza et al., 2020). Additionally, increased stack height has been suggested to contribute to RE benefits by increasing lower-limb length relative to body mass, which may improve metabolic efficiency (Muniz-Pardos et al., 2021; Steudel-Numbers et al., 2007). However, Hoogkamer (2020) argued that increased midsole thickness might be self-limiting, as increases in midsole thickness increases shoe mass and is likely to reduce frontal plane stability, specifically when turning corners during road running. Barrons et al. (2023) similarly argued that increases in stack height often leads to decreased frontal plane ankle stability, negating any potential performance improvements from increased limb length.

Longitudinal bending stiffness

Early research found that increasing longitudinal bending stiffness of running shoes reduced the metabolic cost of running by approximately 1% (Roy & Stefanyshyn, 2006). However, results have been mixed in subsequent studies, whereby inserting flat stiff insoles to increase longitudinal bending stiffness resulted in no significant change in RE (Beck et al., 2020; Flores et al., 2019). However, Rodrigo-Carranza et al. (2023) reported average improvements in RE (W/kg) by around 3% when using a curved carbon fibre plate, with trained runners experiencing greater benefits than national-level runners. This improvement aligns with findings from Rodrigo-Carranza et al. (2022a), whose systematic review and meta-analysis on midsole bending stiffness reported an average RE enhancement of 3.15%. However, other researchers have highlighted this number may be inflated by other interventions not controlled for, such as shoe mass, running speed, and plate location or length, along with whether or not runners were responders (Hébert-Losier & Pamment, 2023).

Teeter-totter effect

Nigg et al. (2020) proposed a mechanism known as the teeter-totter effect linked to the increased longitudinal bending stiffness via the curved stiff element embedded within the midsole and the curved forefoot geometry of AFT shoes. This mechanism speculates that as ground contact progresses, the point where the resultant ground reaction force is applied shifts towards the front of the curved plate and shoe. At this moment, the ground reaction force generates an upward reaction force at the heel, perpendicular to the plate's surface. This effect has been supported by a recent proof of concept by Subramaniam et al. (2024), confirming the propulsion moment was greater in an AFT shoe compared to a control shoe, seen with a greater posterior shift of the centre of pressure during late stance (65-95%). However, this mechanism remains controversial, as previous research has not observed the

anterior to posterior shift of the centre of pressure. Hoogkamer et al. (2019) found no differences in the anterior to posterior centre of pressure at the metatarsophalangeal (MTP) joint across three shoe conditions: Nike prototype AFT, Nike Zoom Streak 6, and the Adidas Adizero Adios Boost 2 shoes. This finding rather suggests the absence of a teeter-totter mechanism in AFT. Moreover, the proof-of-concept study (Subramaniam et al., 2024) supporting this mechanism compared the Nike Vaporfly 4% (an AFT racing shoe) to the Nike Air Force 1, a casual lifestyle shoe not designed for running. This stark contrast in shoe function and design likely influenced the observed results, limiting the generalisability of the findings.

Midsole material

Midsole material foam is an integral part of AFT (Hébert-Losier & Pamment, 2023). Earlier studies before the emergence of AFT showed that running in soft and resilient midsole foam could improve RE. Specifically, Worobets et al. (2014) compared a control shoe with an ethylene-vinyl acetate (EVA) midsole foam and a softer shoe with an expanded thermoplastic polyurethane pellet-based midsole foam. Their study demonstrated an average of 1% decrease in oxygen consumption during treadmill and overground running in the softer shoe. Midsole foam in AFT shoes is often made of polyether block amide (PEBA). PEBA is both lighter and returns more energy than more traditional running shoe foams, which are typically made of EVA. A Nike AFT with PEBA foam was shown to return more mechanical energy (87% return) compared to an Adidas Boost shoe with a thermoplastic polyurethane foam midsole (75.9% return) and a Nike racing flat with an EVA foam midsole (65.5% return) (Hoogkamer et al., 2018). Rodrigo-Carranza et al. (2024) have since compared the influence of PEBA and EVA on RE in new and worn shoes, finding an 1.88% improvement in the energy cost of running (W/kg) when wearing new shoes with PEBA than new shoes with EVA midsoles. However, after 450 km of road running, the PEBA shoes showed an 2.28%

decline in the energy cost of running (W/kg) compared to the new PEBA shoes, whereas no difference in the energy cost of running was observed between the new and worn (450 km) EVA shoes. These results highlight that PEBA is more likely to breakdown and lose its beneficial energy returning properties. Though PEBA midsoles have higher energy return, this feature alone does not fully explain the improvement in RE as the energy can be returned at the wrong time, location, frequency, and direction (Flores et al., 2019; Nigg et al., 2020; Rodrigo-Carranza et al., 2024).

It is thought the improvements in RE may not come from an individual component, but rather the sum of its parts (Hébert-Losier & Pamment, 2023). In this area, Perry et al. (2025) explored the influence of both midsole foam and longitudinal bending stiffness on RE across four shoe conditions: PEBA shoes with a plate, PEBA shoes without a plate, EVA shoes with a plate, and EVA shoes without a plate. Starting with a traditional EVA foam shoe without a plate, the addition of PEBA foam or a stiff plate improved RE by 1.3 % (W/kg). Yet, the use of both technologies combined resulted in an 1.9% (W/kg) improvement, which was not significantly greater than the individual effects. The lack of significance may be due to the small sample size (14 runners). Overall, it appears that the combination effect of AFT is due to more than just midsole foam and bending stiffness.

Shoe mass

The effect of shoe mass on RE has been extensively explored, with findings of 1% detriment in RE for every 100 g of added mass (Franz et al., 2012). Similarly, Hoogkamer et al. (2016) found that changes of 100 g between shoes were needed to elicit a 1.1% change in metabolic costs (W/kg) at a speed of 3.5 m/s. More recently, Rodrigo-Carranza et al. (2020) reported that adding 100 g per shoe impaired running economy by 7.4% and 10.2% at speeds equal to 85% and 95% of each runner's second ventilatory threshold. Although the impairments by

Rodrigo-Carranza et al. (2020) are significantly greater than the previous findings, this may be due to a different RE outcome (mL/kg/km opposed to W/kg). Despite the addition of extra foam and stiff elements in the midsoles, AFT shoes remain relatively lightweight. For example, compared to the Adidas Adizero Adios Boost 2 (the World Record racing flat at the time of AFT introduction), the Nike AFT shoe was 51 grams lighter (Hoogkamer et al., 2018). This lightweight construction likely contributes to the improved RE observed in AFT shoes, as it allows more of the lightweight PEBA foam to be used without the metabolic penalties typically associated with heavier footwear (Burns & Joubert, 2024).

Advanced footwear technology variability

While AFT shoes have been shown to improve RE on average by 4% (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019), there is interindividual variability reported, with some runners experiencing a large positive improvement in their RE measures and others seeing no change or impairments. For example, early research on AFT footwear using a Nike Vaporfly prototype reported an average 4% improvement in RE (W/kg) compared to the Adidas Adizero Adios Boost 2, the shoe worn by the World Record holder at the time. The interindividual variation reported from this study found runners RE improvements varied between 1.59% to 6.26% (Hoogkamer et al., 2018). A similar study comparing the Nike Vaporfly 4% to the Adidas Adios Boost 3 found an average 4.2% improvement in RE (mL/kg/min) and interindividual variation ranging between 1.72 and 7.15% (Barnes & Kilding, 2019). More recent studies have reported higher interindividual variations. Hébert-Losier et al. (2022) investigated RE measures and 3 km time-trial performances in recreational male runners in three footwear conditions, with improvements in RE (mL/kg/min) ranging between -8.6% to 13.3% and 3 km time-trial performances between -4.7% to 9.3% in the Nike Vaporfly 4% compared to runners' own running shoes. Furthermore, Knopp et al. (2023) reported RE (mL/kg/min) interindividual

variation when wearing AFT shoes ranged from -11.3% to 11.4% in world-class Kenyan runners, and 1.1% to 9.7 % in amateur European runners, compared to running in traditional flat racing shoes. Lastly, a study comparing seven different AFT racing shoes reported five models significantly improved RE compared to a traditional racing flat (Asics Hyperspeed). Most notably, the Nike Vaporfly Next% 2, Nike Alphafly, and the Asics Metaspeed Sky demonstrated the greatest RE improvements across the seven AFT models, with mean improvements of 2.7%, 3.0%, and 2.5%, respectively, and ranges of 0.8% to 3.8%, 0 to 5.3%, and 0.9% to 4.9%. This study highlights the interindividual variation in RE response across a range of AFT shoes (Joubert & Jones, 2022). As of now, the factors that underpin this reported variability in response to AFT shoes remain largely unknown and require further investigation to better inform footwear prescription and selection.

Defining responders

Comparing the characteristics of responders to non-responders can assist in identifying runners more likely to benefit from running in AFT shoes, which requires establishing what constitutes a meaningful response. Research by Saunders et al. (2004) placed the smallest worthwhile change in RE measures at 2.2%, 2.4%, and 2.6% at corresponding speeds of 14, 16, and 18 km/h respectively, based on 70 highly trained runners. Barnes and Kilding (2015a) suggest there may be lower smallest worthwhile change in measures when assessed at a relative rather than absolute running speed. Furthermore, a 2.6% improvement in RE has been used experimentally as a cut-off to define positive responders to training interventions (Patoz et al., 2021). More recently a study involving AFT recommended a slightly lower minimum threshold of 2.15% to delineate responders and non-responders (Brund et al., 2025). Together, these studies indicate thresholds ranging from 2.15 to 2.6% are acceptable for delineating responders to non-responders.

Differences between responders and non-responders

Some investigations have attempted to differentiate between responders and non-responders when investigating footwear and employed smaller thresholds (0.5 to 0.7%) derived from smallest worthwhile change and technical error of gas analyser equations. For example, Madden et al. (2016) explored responders to non-responders to changes in forefoot bending stiffness and used a responder value of 0.5% to differentiate between groups. Ten runners responded positively (mean 2.9%), while eight runners did not (mean -0.9%). Responders displayed reduced peak plantarflexion velocity, while non-responders had reduced MTP joint bending, suggesting the ankle gearing was altered by the changes in forefoot bending. A more recent study, exploring 96 individual responses to shoes with increased bending stiffness, clustered runners into three groups based on the smallest worthwhile change of 0.5 times the technical error of the gas exchange analyser (Chollet et al., 2023). The results of this study identified three clusters: cluster one had 29 runners improve RE in the stiffest condition (2.7%); cluster two had 26 runners with impaired RE (-2.7%); and cluster three had 43 runners experience no change in RE (-0.28 %). The main difference between groups was that cluster 1 runners had significantly higher aerobic speed (by 1.7 km/h) compared to cluster 2 ($p = 0.014$), indicating they were higher-level runners. These findings suggest that higher-level runners may benefit more from increased longitudinal bending stiffness. Additionally, Chollet et al. (2023) proposed that the gastrocnemius medialis muscle-tendon properties could modulate the effects of the longitudinal bending stiffness and may explain the differences between the clusters.

Advanced footwear technology factors

In terms of AFT, multiple factors have been speculatively linked with greater RE responses to AFT shoes. These factors include running speed, foot strike pattern, contact time, body

mass, leg stiffness, plantarflexion strength, foot size, foot arch stiffness, MTP joint range of motion, training level, and sex based on a narrative assessment of the literature (Barrons et al., 2024; Hunter et al., 2019).

Sex

Sex refers to biological differences between males and females, which includes components of anatomy, physiology, genetics, and hormones. Gender has a broader definition that encompass socially constructed and enacted roles and behaviours, and includes the terms men and women, among others. This thesis is considered on sex differences, although race performances are typically described as men and women. Sex differences have been observed in race times and World Record improvements since the introduction of AFT. Senefeld et al. (2021) investigated the top 50 race times before and after the introduction of AFT and found marathon race times improved 0.8% for men and 2.6% for women. Another study explored the top 20 and top 100 race times for the 10 km, half-marathon, and marathon between 2016 and 2019, reporting improvements of 1.9, 1.7, and 2.0% for female runners, and 1.1, 0.7, and 1.2% for male runners, respectively (Bermon et al., 2021). Furthermore, Mason et al. (2024) explored sex differences in running World Records since the introduction of AFT, identifying a greater progression in women (3.7%) than men (1.5%). Altogether, these observations suggest greater improvements in females than males, at least from a performance perspective when wearing AFT shoes. However, in a laboratory setting, Barnes and Kilding (2019) did not observe any differences between males and females in RE response to AFT shoes. Additionally, due to the relative underrepresentation of females in AFT research, it remains difficult to fully explain these sex differences. However, they have been speculatively attributed to a range of factors, including differences in leg length, shoe size, body mass, competition running speeds, muscle-tendon unit properties, and running biomechanics (Mason et al., 2024; Willwacher et al., 2024). As such, there is a need to explore these

speculated factors to determine whether a sex difference in AFT shoe response exists and whether these factors help explain the interindividual variability in response.

Speed

Improvements in RE with AFT shoes appear to be greater at faster running speeds. Initial research on AFT shoes was typically tested at speeds between 14 to 18 km/h, with reported improvements in metabolic costs (W/kg) of 4% across 14, 16 and 18 km/h (Hoogkamer et al., 2018) and oxygen consumption (mL/kg/min) of 2.9% across speeds of 14 to 16 km/h (Barnes & Kilding, 2019). Additionally Chollet et al. (2023) assessed the effects of increased midsole bending stiffness of AFT shoes across 96 runners and found that the group of responders to high midsole stiffness were on average 1.7 km/h faster than the group of negative responders.

However, AFT improvements are not limited to high-speed running. Further research comparing different absolute and relative testing speeds has found AFT may still be effective at slower speeds, although to a lesser extent. For example, Paradisis et al. (2023) found male and female recreational runners demonstrated an average improvement of 3.8% at a running speed of 65% of their velocity at $\dot{V}O_2$ peak ($v\dot{V}O_2$ peak) and 5.0% when the speed was higher at a speed of 80% $v\dot{V}O_2$ peak. Additionally, Knopp et al. (2023) reported elite runners showed both positive and negative RE (mL/kg/min) responses to AFT shoes (-11.3% to 11.4%) in world-class Kenyan athletes running at a mean speed of 17.1 km/h. In contrast, amateur European runners exhibited consistently positive responses (1.1% to 9.7%) at a slower mean speed of 13.1 km/h, suggesting AFT benefits may extend to recreational populations even at lower running speeds. Furthermore, in trained male and female runners, results were similar whereby RE (mL/kg/min) improvements were between 0.9% to 1.6% at speeds of 10 and 12 km/h, but reached 2.8% at 16 km/h (Joubert et al., 2023). Collectively, these findings suggest that while AFT effectiveness tends to increase with speed, but also that

improvements are not limited to high-performance contexts. To make valid inferences in terms of individual footwear responses in the presence of heterogeneous runners, assessing RE at a relative rather than absolute running speed appears appropriate.

Plantarflexion muscle-tendon unit properties

The ankle plantar flexors are primarily composed of the triceps surae muscle group, which includes the gastrocnemius and soleus muscles and their insertion via the Achilles tendon on the calcaneus (Aronow et al., 2006; Ferris & Hawkins, 2020). Runners with greater RE have typically been reported to exhibit greater triceps surae muscle strength and stiffness (Arampatzis et al., 2006), likely linked with more efficient use of elastic energy during ground contact (Jaén-Carrillo et al., 2021). According to a meta-analysis by Van Hooren et al. (2024), smaller vertical oscillation is associated with better RE, along with higher leg stiffness to store and release elastic energy more optimally. Similarly, Liu et al. (2022) reported that increased leg stiffness is generally associated with improved RE. Furthermore, Hunter et al. (2015) found that runners with longer Achilles tendons and greater leg strength had greater RE. In a separate study, Rogers et al. (2017) reported greater Achilles tendon stiffness measured via ultrasonography during maximal isometric plantarflexion contractions explained 49% of the variation in RE among 11 highly trained male runners. Furthermore, Konrad et al. (2023) found that greater Achilles tendon stiffness measured using the MyotonPro correlated with better RE, but did not observe the same relationship with triceps surae stiffness measured at the gastrocnemius medialis and lateralis. Nguyen et al. (2025) found similar results assessing passive stiffness using the MyotonPro. The MyotonPro is a handheld device that quantifies passive mechanical properties of soft tissues, such as stiffness, tone, and elasticity, by applying a brief mechanical impulse and measuring the tissue's oscillatory response (Nguyen et al., 2022). This method reflects passive muscle or tendon stiffness and has been increasingly used to assess musculoskeletal properties in

runners (Konrad et al., 2023; Nguyen et al., 2025). However, there are alternative methods to the MyotonPro to assess passive stiffness. Ueno et al. (2018) used a BIODEX dynamometer for this purpose and reported greater passive plantarflexion stiffness were related to improved RE at speeds of 16 km/h ($r = -0.379$) and 18 km/h ($r = -0.445$), with stiffer plantar flexors more important for improving RE at higher speeds. Dumke et al. (2010) used a free oscillation technique to assess passive triceps surae stiffness, demonstrating greater passive stiffness can positively influence RE. The somewhat inconsistent findings between the magnitude of association between Achilles tendon stiffness, triceps surae stiffness, and RE may be due to differences in measurement techniques, but overall, suggest a positive association to RE. As AFT shoes are designed to improve RE (Barnes & Kilding, 2019; Hébert-Losier & Pamment, 2023; Hoogkamer et al., 2018), individual differences in plantarflexion strength and lower-limb stiffness have been proposed as potential factors influencing the degree to which a runner benefits from AFT footwear (Barrons et al., 2024; Hunter et al., 2019).

AFT shoe properties may also affect how the ankle plantarflexion muscle-tendon unit functions during running. Cigoja et al. (2021) found that footwear with greater midsole bending stiffness allows the triceps surae muscle-tendon unit to operate in a more favourable position, lowering the muscle's shortening velocity and increasing the tendon's energy return. In AFT, the same phenomenon is likely to occur due to the greater longitudinal bending stiffness of AFT shoes compared to traditional running shoes. Supporting this theory, Hata et al. (2024) used electromyography to investigate the fascial and tendon behaviours of the ankle plantar flexors (gastrocnemius medialis and lateralis) during running at 14 km/h in AFT shoes compared to traditional shoes. These authors found AFT shoes to reduce metabolic costs and aid running propulsion via decreases in gastrocnemius medialis (53% lower) and lateralis electromyography during the push off phase. Despite operating in a more favourable

position, researchers have speculated that runners may need a certain level of plantarflexion strength to fully benefit from running in AFT shoes (Ortega et al., 2021). Therefore, exploring the relationship between triceps surae muscle-tendon unit properties and RE may help explain AFT shoe responses.

Metatarsophalangeal joint

The metatarsophalangeal (MTP) joint is the joint between the metatarsal bone and the phalanges. During running, this joint acts primarily as a shock absorber in the stance phase and contributes very little to energy generation during toe-off (Stefanyshyn & Nigg, 1997). This limited propulsive contribution is largely due to the MTP joint remaining in dorsiflexion throughout stance and toe-off, whereas effective propulsion would require significant plantar flexion and active energy generation. As such, the energy is absorbed during stance and dissipated into footwear and foot structures (Stefanyshyn & Nigg, 1997). Stefanyshyn and Nigg (1997) also noted that many athletic shoes at the time were often constructed with midsoles that were too compliant at the MTP joint, potentially reducing propulsion efficiency. Consequently, more recent running shoe design has incorporated stiffness into the midsoles, to reduce compliance at the MTP joint. For example, increasing longitudinal bending stiffness has been shown to reduce negative work and enhance positive work at the MTP joint (Cigoja et al., 2019; Willwacher et al., 2013), so long as the natural MTP joint flexion ability is not impeded (Oh & Park, 2017).

Incorporating a curved stiff plate, like those seen in AFT shoes, has been shown to reduce net energy loss at the MTP joint (Farina et al., 2019). Additionally, Hoogkamer et al. (2019) found similar results when looking specifically at AFT footwear, noting the AFT shoes reduced MTP dorsiflexion and decreased negative work at the MTP joint compared to the Adidas Adios Adizero Boost 2 shoe. Therefore, MTP joint mechanics are important to

consider in the context of running, footwear, and RE. Exploring individual's MTP joint range of motion in relation to RE response in AFT shoes may therefore help explain some of the interindividual variability.

Subjective measures

Subjective perceptions of footwear comfort are frequently proposed as a key factor that may improve RE. Research before the emergence of AFT reports positive associations between perceptions of shoe comfort and improvements in RE. Specifically, Luo et al. (2009) reported improvements of 0.7% in RE when wearing shoes perceived as being the most comfortable compared to the least comfortable. Similar results were found by Sinclair et al. (2016) where a positive association between perceived footwear comfort and improvements in RE was observed. Additionally, a literature review by Fuller et al. (2015) reported significant, yet small, improvements in RE when running in stiffer and more comfortable shoes. This finding was supported by a more recent review by Van Alsenoy et al. (2023), which reported a positive association between perceived footwear comfort and improvements in RE. However, there is some uncertainty as several studies have not found significant relationships between perceptions of comfort and RE. Lindorfer et al. (2020) reported no improvements in RE measures between shoes perceived as the most and least preferred based on comfort. Additionally, a study investigating shoe comfort and running biomechanics reported no significant relationship between perceptions of comfort and biomechanical parameters (Dinato et al., 2015).

In AFT research, a similar uncertainty exists regarding the relationship between subjective perceptions and comfort. Due to their lightweight construction and soft midsoles (Hébert-Losier & Pamment, 2023), AFT shoes may be perceived as more comfortable, although comfort perception is highly individual. Joubert and Jones (2022) found significant

relationships between subjective ratings of footwear and oxygen consumption of AFT shoes, including perceptions of cushioning, energy return, and stiffness. In contrast, Hébert-Losier et al. (2022) found that although runners reported their own shoes as being the most comfortable, they had superior RE and 3-km time trial measures in AFT shoes. Furthermore, a study exploring the potential placebo effect of AFT on RE and perceptual measures reported runners overall preferred and found AFT shoes described as performance enhancing as more comfortable than the same AFT described as knock offs. However, there were no significant differences in RE or biomechanics between shoes (Hébert-Losier, Ashlyne, et al., 2025). These findings suggest that while comfort may influence an individual's perception of footwear, its contribution to actual RE improvements in AFT shoes remains unclear and likely varies between runners.

Summary

Running performance has overall improved over the years, as has the technology in running shoes. The development of AFT shoes has led to improvements in World Records from the 5 km to the marathon distance (Muniz-Pardos et al., 2021). However, despite average improvements of approximately 4% in runners wearing AFT shoes compared to traditional, racing flats and their own shoes (Hébert-Losier et al., 2022; Hébert-Losier et al., 2024; Hoogkamer et al., 2019), there is great variability in how individuals respond to AFT shoes. Therefore, further investigation as to why some individuals experience greater RE benefits running in AFT shoes than others is warranted to assist in footwear prescription and selection. Proposed factors linked with AFT responses include triceps surae muscle-tendon unit properties, plantarflexion strength, sex, body mass, MTP joint range of motion, and running speed. Investigating a range of variables associated with RE in AFT may help to explain the high interindividual variability.

Research statement

Based on the literature reviewed, this thesis aimed to investigate the interindividual variability in RE response to AFT shoes and identify potential predictors of this variability. Specifically, this study examined how participant characteristics (e.g., sex, and training level), anthropometric measures (e.g., leg length, and body mass), neuromuscular measures (e.g., plantarflexion muscle strength, ankle inversion/eversion strength, and triceps surae muscle-tendon unit and leg stiffness), and subjective perceptions (e.g., shoe comfort) relate to RE changes when running in AFT compared to a CONTROL shoe. It was hypothesised that individuals with greater plantarflexion strength, leg stiffness, ankle inversion and eversion strength, and MTP joint range of motion would exhibit greater improvements in RE when running in AFT shoes. Furthermore, it was hypothesised that females and higher-level runners would experience greater RE improvements in AFT footwear.

Chapter Two – Experimental Study

Exploring factors to explain interindividual responses to running economy in advanced footwear technology shoes

Abstract

Aim: This study aimed to investigate the interindividual variability in running economy (RE) response to advanced footwear technology (AFT) and identify potential predictors of this variability. Specifically, this study examined how participant characteristics (e.g., sex, training level), anthropometric measures (e.g., leg length, body mass), neuromuscular measures (e.g., plantarflexion muscle strength, ankle inversion/eversion strength, triceps surae muscle-tendon unit and leg stiffness), and subjective perceptions (e.g., shoe comfort) relate to RE changes when running in AFT compared to a CONTROL shoe. **Methods:** Participants attended two laboratory sessions, two to seven days apart. The first session collected baseline information and participant characteristics for anthropometric, stiffness, strength, and VO₂ peak. The second session served as the experimental phase, during which RE variables were evaluated in the two different shoe conditions: Salomon S/Lab Phantasm 2 (AFT) and Salomon Aero Glide 2 (CONTROL). **Results:** The AFT footwear in this study improved RE by a mean improvement of 4.13% (± 1.6) and individual responses ranging from -2.62% to 11.01%. Between group differences were limited to differences in gastrocnemius medialis (GM) stiffness normalised to leg length in responders compared to non-responders, with responders being on average 33.4 N/m stiffer. Greater GM stiffness and greater navicular drop were both *moderately* correlated with improved RE response to AFT. Additionally, our multiple regression model revealed standing plantarflexion MVIC, navicular drop, gear ratio, and normalised GM stiffness explained 27% of the variance in our AFT RE responses. With GM stiffness normalised to leg length being the most significant

factor in this model ($\beta = 0.014$, $SE = 0.0056$, $p = 0.015$). **Conclusion:** Our results show that increased GM stiffness normalised to leg length and increased navicular drop appear to explain some of the interindividual variance in RE to AFT shoes. However, other factors such as foot-strike patterns may be contributing to the differences in AFT response and warrant further investigation.

Key words: advanced footwear technology, running economy, interindividual variability, gastrocnemius medialis stiffness, navicular drop

Introduction

In the last decade, the running landscape has changed due to advancements in footwear technology (Burns & Joubert, 2024). The introduction of the Nike Vaporfly 4% in May of 2017 via the Breaking 2 campaign was the beginning of the Advanced Footwear Technology (AFT) era, or footwear more commonly known as “super shoes”. Shown to improve running economy (RE) on average by 4% based on the energetic cost of transport (W/kg) (Hoogkamer et al., 2018), the key novel components of the Nike Vaporfly 4% were the incorporation of a light, thick, resilient, and compliant midsole foam made of polyether block amide (PEBA) and a stiff curved carbon fibre plate embedded within the midsole. Many footwear companies other than Nike Inc. now offer an array of AFT shoes (Joubert & Jones, 2022) and are competitive on the market. Although there is no consensus definition on AFT, the elements of a thick, lightweight, resilient, and high-energy returning midsole foam; a stiff element within the midsole; and a curved shoe geometry are cornerstones (Hébert-Losier & Pamment, 2023). As highlighted by Muniz-Pardos et al. (2021), since the introduction of AFT shoes, athletes wearing AFT shoes or spikes have broken all World Records from 5 km to the marathon, with a similar trend observed in middle-distance running (Healey et al., 2022).

Although AFT shoes have been shown to improve running economy (RE) measures on average by approximately 4% (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019), interindividual variability in response is evident, with some runners experiencing a large positive improvement in their RE measures and others seeing no change or impairments. For example, Hébert-Losier et al. (2022) investigated RE measures and 3 km time-trial performances in recreational male runners on a treadmill in three footwear conditions, with improvements in RE measures (oxygen consumption, mL/kg/min) ranging between -8.6% to 13.3% and 3 km time-trial performances

between -4.7% to 9.3% in Nike Vaporfly 4% compared to their own running shoes. In another study Knopp et al. (2023), improvements in RE measures (oxygen consumption, mL/kg/min) when wearing AFT ranged from -11.3% to 11.4% in world-class Kenyan runners, and 1.1% to 9.7 % in amateur European runners. The factors that underpin this reported variability in response to AFT remain largely unknown and require further investigation to better inform footwear prescription.

Comparing the characteristics of responders to non-responders can assist in identifying runners more likely to benefit from running in AFT, which requires establishing what constitutes a meaningful response. Research by Saunders et al. (2004) placed the smallest worthwhile change in RE measure at 2.2%, 2.4%, and 2.6% at corresponding speeds of 14, 16, and 18 km/h based on 70 highly trained runners, with a presumably lower smallest worthwhile change in measures when assessed at a relative rather than absolute running speed (Barnes & Kilding, 2015a). A cut-off of 2.6% in RE measures to define positive responders to training interventions has been used experimentally (Patoz et al., 2021), with a recent study involving AFT recommending a minimum threshold of 2.15% to delineate responders and non-responders (Brund et al., 2025). Together, these studies indicate thresholds ranging from 2.15 to 2.6% are acceptable for delineating responders to non-responders.

Factors speculatively linked with AFT response include running speed, foot strike pattern, contact time, body mass, plantarflexion strength, foot arch stiffness, metatarsal joint range of motion, training level, and sex based on a narrative assessment of the literature (Barrons et al., 2024). Mason et al. (2024) explored sex differences in running World Records since the introduction of AFT, identifying a greater progression in women (3.7%) than men (1.5%). Due to the relative underrepresentation of females in AFT research, it is difficult to explain

this sex difference, thought speculatively linked with differences in leg length, shoe size, body mass, competition running speeds, muscle-tendon unit properties, and running biomechanics (Mason et al., 2024; Willwacher et al., 2024). In terms of running speed, research suggests the benefits of AFT are greater at faster running speeds, with male and female recreational runners demonstrating an average improvement of 3.8% at a running speed of 65% of their velocity reached during peak oxygen uptake ($v\text{VO}_2$ peak) and 5.0% at a speed of 80% $v\text{VO}_2$ peak (Paradis et al., 2023). In trained male and female runners, results were similar whereby RE improvements were between 0.9% to 1.6% at speeds of 10 and 12 km/h, but reached 2.8% at 16 km/h (Joubert et al., 2023). To make valid inferences in terms of individual footwear response in the presence of heterogeneous runners, assessing RE at a relative rather than absolute running speed appears appropriate.

Runners with greater RE have typically been reported to have greater triceps surae muscle-tendon unit strength and energy storage during maximal voluntary contractions (Arampatzis et al., 2006). Cigoja et al. (2021) found that footwear with greater midsole bending stiffness allows the triceps surae muscle-tendon unit to operate in a more favourable position, lowering the muscle's shortening velocity and increasing the tendon's energy return. In AFT, the same phenomenon is likely to occur due to the greater bending stiffness of AFT shoes compared to traditional running shoes. Despite operating in a more favourable position, researchers have speculated that runners may need a certain level of plantarflexion strength to fully benefit from running in AFT shoes (Ortega et al., 2021). Exploring the relationship between triceps surae muscle-tendon unit properties and RE may help explain AFT shoe responses. In addition, AFT shoes typically have a thick midsole and have been reported to feel unstable around corners (Barrons et al., 2023). Biomechanical studies report that increased midsole thickness decreases frontal plane ankle stability, resulting in significantly greater ankle eversion ($\sim 2^\circ$) when running in footwear with 45 mm and 50 mm stack heights than in

footwear with 35 mm stack height (Barrons et al., 2023). Indicating a need to explore whether those with greater ankle strength may benefit more from AFT.

Based on a review of the literature, footwear comfort is positively linked with an improvement in RE measures (Van Alsenoy et al., 2023). However, uncertainty exists as some research exploring this concept report no improvements in RE measures in shoes as perceived as most and least preferred based on comfort (Lindorfer et al., 2020). In research involving AFT shoes, significant relationships have been identified between subjective ratings of footwear properties (i.e., cushioning, energy return, and stiffness) and 5-km and marathon race preferences to oxygen consumption measures in runners (Joubert & Jones, 2022). In contrast, runners in another study reported their own shoes as being the most comfortable yet had superior RE and 3-km time trial measures in AFT shoes (Hébert-Losier et al., 2022). Furthermore, when wearing the same AFT footwear but the two shoes were presented differently, the shoe rated as most comfortable, least likely to cause injury, and most likely to perform better in racing was not superior in terms of RE measures (Hébert-Losier, Ashlyne, et al., 2025). The role of subjective perceptions in AFT shoe response remains somewhat controversial, and its role in explaining interindividual variability not fully understood.

This study aimed to investigate the interindividual variability in RE response to AFT and identify potential predictors of this variability. Specifically, this study examined how participant characteristics (e.g., sex, training level), anthropometric measures (e.g., leg length, body mass), neuromuscular measures (e.g., plantarflexion muscle strength, ankle inversion/eversion strength, triceps surae muscle-tendon unit and leg stiffness), and subjective perceptions (e.g., shoe comfort) relate to RE changes when running in AFT compared to a CONTROL shoe. Based on existing literature, it was hypothesised that

individuals with greater plantarflexion strength, leg stiffness, ankle inversion and eversion strength, and metatarsophalangeal (MTP) joint range of motion would exhibit greater improvements in RE when running in AFT shoes. Furthermore, it was hypothesised that females and higher-level runners would experience greater RE improvements in AFT footwear.



Methods

Study design

This study employed a cross-sectional research design with repeated measures to investigate differences between responders and non-responders to AFT versus a CONTROL shoe, and the association between intrinsic variables to the RE responses of runners. The study required participants to attend two laboratory sessions (mean \pm standard deviation, 5.3 ± 4.6 days apart), two to seven days apart. Each session lasted between 1.5 to 2 hours. The initial session focused on ensuring proper shoe fit, familiarising participants with running in the two experimental shoes, and gathering baseline information and participant characteristics. The second session served as the experimental phase, during which RE variables were evaluated in the two different shoe conditions: Salomon S/Lab Phantasm 2 (AFT) and Salomon Aero Glide 2 (CONTROL). Shoe characteristics are presented in Table 1.

This research was part of a larger study aiming to identify indicators of RE responses to AFT and was carried out in line with the Declaration of Helsinki, and UNICEF's principles for guiding ethical research involving children (Graham et al., 2013). The study was approved by the Human Research Ethics Committee of the University of Waikato [HREC(HECS)2024 #11] (see Appendices 1). The trial was preregistered in the Australian New Zealand Clinical Trials Registry (ACTRN12624000753550).

Table 1. Experimental shoe characteristics

Shoe characteristics	Salomon S/Lab Phantasm 2	Salomon Aero Glide 2
		
Foam type	PEBA	EVA
Carbon plate	Yes	No
Drop (mm)	9	10
Stack (mm)	37	37
Resiliency at heel from impact test (%)	59%	43%
Resiliency at forefoot from impact test (%)	61%	45%
Penetration distance at heel from impact test (mm)	15.8	12.5
Penetration distance at forefoot from impact test (mm)	11.2	10.1
Bending stiffness from 7 to 10 mm (N/mm)	27	12
Mass (g)	219	230

Note. Resiliency reflects the energy return of the shoe. It is calculated by dropping a 5 kg mass from a height of 23 cm onto the shoe and measuring the rebound height. Resiliency is expressed as the ratio of drop height to rebound height.

Abbreviations. EVA, ethylene-vinyl acetate; PEBA, Polyether block amide.

Sample size

Sample size calculations for our primary outcome (difference in RE between responders and non-responders) indicated that 52 participants were required to detect a large effect size ($d = 0.80$) with 80% power at $\alpha = 0.05$. To improve sensitivity to detect a moderate correlation ($r = 0.30$) in measures to explain response to AFT, we aimed to recruit 85 participants.

Recruitment concluded at 64 participants (32 male, 32 female) due to resource constraints, exceeding the minimum requirement for large effects and providing power to detect a moderate effect ($d = 0.77$) and correlation ($r = 0.34$) at the overall group level. However, the imbalance between responders ($n = 53$) and non-responders ($n = 11$) reduced the effective power for between-group comparisons to 0.63 for large effects.

Participants

Prior to participating, the participants were explained the risks (e.g., injury from running in new footwear or delayed onset muscle soreness), the benefits (e.g., individualised report for their participation), 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 in line with New Zealand's Health Research Guidelines relating to research involving children (Health Research Council of New Zealand, 2021, March) and UNICEF's principles guiding ethical research involving children (Graham et al., 2013). The participants were required to be in good general health, injury-free, and have been running at least once a week for 30 minutes for the past 6 months. An equal number of male and female participants were targeted during the recruitment process. Upon study completion, participants received a \$30 petrol voucher and went in a draw to receive one of the 18 experimental footwear used as part of the study.

Procedure

Session 1: Baseline measurements and familiarisation

The properties assessed during Session 1 are summarised in Figure 2 and test images available in appendices 2. Briefly, participants were required to read and sign an informed consent form before participating in the study and then filled in a baseline questionnaire collecting information on their age, sex, and injury, running, and shoe use history. An Anthro Flex wall mounted stadiometer (Seca) was used to collect participants' height and right leg length barefoot (distance from the ground to greater trochanter in standing (Morin et al., 2005). A calibrated Kistler 9260AA6 force plate (Kistler, Winterthur, Switzerland) and the Measurement, Analysis, and Reporting Software (MARS version 5.2, S2P Ltd., Ljubljana, Slovenia) were used to collect participants' mass. Thereafter, participants underwent a series of assessments following the same sequence depicted in Figure 2, with all unilateral measures recorded on participants' right limb. Gastrocnemius medialis (GM), Achilles tendon, and plantar fascia stiffness were measured using the MyotonPro (Myoton, AS, Estonia). Then, anatomical foot markings were placed using a black marker, and digital photographs of the right foot were taken from the medial, lateral, posterior, and superior views using an iPad camera (model A1822, Apple Inc., California, USA). These images were used to measure foot dimensions, as detailed in Table 2 and the *Foot anthropometry* section.

Maximal voluntary isometric contractions (MVICs) were then assessed for the toe flexors, ankle inverters, ankle evertors, and ankle plantar flexors using a Lafayette handheld dynamometer (model 01165A, Lafayette Instrument Company, Indiana, USA) and the Kistler force plate. Leg stiffness was also assessed via hopping on the force plate. Participants were familiarised with the weighted plantarflexion power test (completed in Session 2). Lastly, peak aerobic capacity (VO_2 peak) was then assessed on a treadmill (HP Cosmos Pulsar 3p,

Germany) using an incremental speed protocol and 0% incline to inform the speed of RE trial during Session 2, which was planned at 70% $v\text{VO}_2$ peak. After five minutes of recovery, participants were fitted and familiarised to running in the two experimental shoes that would be used in Session 2, running two minutes at a self-selected speed in both shoes.

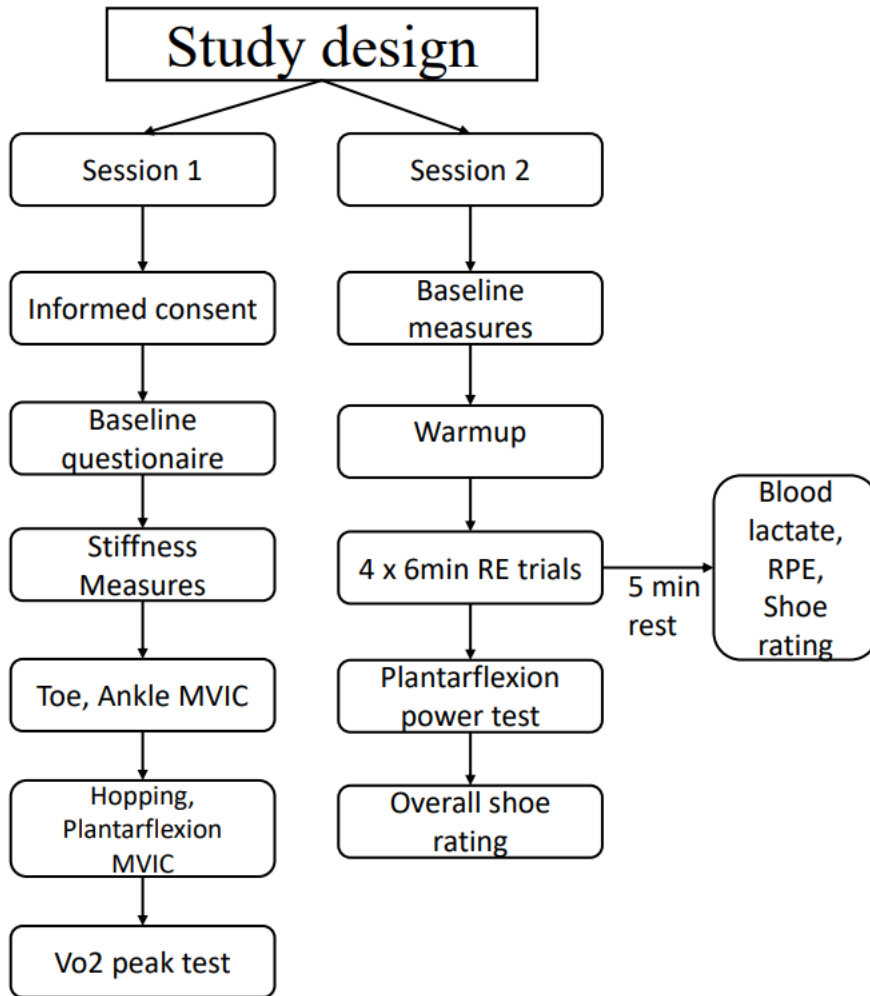


Figure 2. Overall study design and assessment tests

Session 2: Running economy trials

Before the RE trials of Session 2, height and mass were re-measured. Participants then completed a warm-up by running for six minutes on the treadmill with a 0% incline in their own shoes wearing the metabolic cart equipment (TrueOne 2400, Parvo Medics, Salt Lake City, UT, USA). The first three minutes were at a self-selected pace below the RE speed, and the final three minutes at the individualised RE speed of 70% of $\dot{V}O_2$ peak. Participants rested for five minutes in a seated position with their shoes removed and were familiarised with a shoe comfort questionnaire administered via Qualtrics (Qualtrics, Provo, UT (17.1.7)). The RE of participants was then assessed in the two experimental shoes running at 70% of $\dot{V}O_2$ peak twice in both shoes. Specifically, participants were randomly allocated to running in shoes in one of two orders: AFT–CONTROL–CONTROL–AFT or CONTROL–AFT–AFT–CONTROL. The RE trials were six minutes in length and separated by five minutes of rest in a seated position. Between trials, participants' lactate blood concentration levels were collected from earlobe sampling, and ratings of perceived exertion (RPE) measurements were taken on a 6- to 20-point Borg scale (Borg, 1982). Participants removed their shoes and completed a shoe comfort questionnaire on Qualtrics (Qualtrics, Provo, UT (17.1.7)). After the RE trials, participants performed a weighted plantarflexion power test and a triceps surae endurance test. These tests were done at the end of Session 2 to not impede the $\dot{V}O_2$ peak test during Session 1 or the RE trials of Session 2.

Gastrocnemius medialis, Achilles tendon, and plantar fascia stiffness

For stiffness measurements, participants lay prone on a plinth with their feet off the end. Three locations were identified on the limb: main muscle bulk of the GM muscle, 8 cm proximal from the Achilles tendon insertion on the calcaneus, and proximal insertion of the plantar fascia on the calcaneus. Using methods described by Nguyen et al. (2025) the digital

handheld MyotonPro device measured the biomechanical and viscoelastic properties of the underlying tissues delivering five mechanical impulses and recording the tissues' oscillation responses. The device was placed perpendicular to the skin surface of the identified locations, and recorded stiffness in N/m units. For statistical analysis, stiffness values for GM and Achilles tendon were normalised to each participant's leg length, whereas plantar fascia measurements were normalised to foot length (N/m²).

Foot anthropometry

To derive various anthropometric morphologic foot measurements, the following anatomical landmarks were placed on the medial side of the foot: middle of the hallux, 1st metatarsal head, base of 1st metatarsal, and most prominent aspects of the navicular and medial malleolus. On the lateral side, landmarks were placed on the 5th metatarsal head and the most prominent aspect of the lateral malleolus. Foot dimensions, composite measures of foot morphology, navicular drop, 1st metatarsal phalangeal active joint extension angle, plantarflexion moment arm, Achilles tendon moment arm, and gear ratio were measured using digital photographs, as described in Table 2.

For these various measurements, images were taken in sitting and standing with body weight evenly distributed between limbs monitored using mechanical scales, in line with previous studies (Fraser & Hertel, 2021; Keenan et al., 2007). Using methods previously described by Rowley et al. (2015); van der Worp et al. (2014) to assess maximal, functional, metatarsal phalangeal joint extension. A photo of the participants' metatarsal phalangeal joint was taken, standing in split stance during maximal plantarflexion, ensuring the hallux stayed in contact with the ground and the tested leg's knee was fully extended. In all cases, the iPad was positioned 60 cm away from the foot, with a calibration ruler in the plane of the foot visible

to enable extraction of length and angle measurements using Kinovea (version 2023-1.2, Free Software Foundation Inc, Boston, MA).

Table 2. Summary of key foot anthropometry and morphology variables and definitions.

Variable	Definition
Navicular drop	The difference in navicular height between seated and standing postures, reflecting medial arch mobility, (Fraser & Hertel, 2021)
Truncated foot length	Distance from the posterior heel to the first metatarsal head. Used to normalise foot dimensions (Fraser & Hertel, 2021).
PF moment arm	Distance from the medial malleolus to the first metatarsal head. Represents the internal lever arm for plantarflexion force application (Baxter & Piazza, 2014).
AT moment arm	Distance from the lateral malleolus to the posterior aspect of the Achilles tendon. Reflects the external moment arm acting on the ankle joint (Deforth et al., 2019).
MTP moment arm	The distance from the middle of the medial hallux to the middle of the medial MTP joint (Heng et al., heng 2016)
Gear ratio	Ratio of PF moment arm to AT moment arm. A higher ratio is theorised to improve mechanical efficiency during running (Ray & Takahashi, 2020).
MTP angle	Angle from horizontal to base of 1st metatarsal from 1st metatarsal head. Used to assess joint range of motion (Rowley et al., 2015; van der Worp et al., 2014)
Arch height index	Ratio of arch height to truncated foot length. Used to quantify arch structure (Fraser & Hertel, 2021).
Arch flexibility	Change in arch height between seated and standing positions, normalised to body weight. Reflects dynamic arch deformation (Fraser & Hertel, 2021).
Foot mobility magnitude	Composite measure of midfoot mobility using change in arch height and midfoot width between seated and standing postures (Fraser & Hertel, 2021).

Abbreviations. AT, Achilles tendon; MTP, metatarsophalangeal; PF, plantarflexion moment arm

Maximal voluntary isometric contractions

For all MVIC trials, familiarisation trials at 50% and 75% of the participants perceived maximum effort were performed before recording three maximal 5-s trials separated by 20-s rest. During each MVIC, participants could see their real-time force output and were verbally encouraged to push as hard as possible to elicit maximal efforts (Amagliani et al., 2010).

For the hallux flexors, we used procedures described by Miura et al. (2022). Participants sat upright with their arms across their chest on a seat raised on a platform with their forefoot on the edge and hallux off the edge of the platform, level with the top of the Lafayette dynamometer, ensuring the lesser toes were not in contact with the force sensing device.

To assess ankle eversion MVIC, we followed procedures similar to those reported elsewhere (Alfuth & Hahm, 2016; Carroll et al., 2013). Participants laid supine on a plinth with their feet at the edge. Participants pushed against the Lafayette dynamometer placed on their lateral MTP joint and secured by the tester's hand, forearm and elbow braced against a firm surface. The tester's other hand stabilised the ankle during testing. For ankle inversion, the set-up was similar, but the dynamometer was placed on the medial MTP joint.

Plantarflexion MVIC was assessed in both seated and standing positions using the calibrated Kistler force plate following methods previously described by Murray et al. (2019); O'Neill et al. (2023). For the seated position, the force plate was zeroed, and participants sat on a chair positioned outside of a squat rack. Their tested limb was positioned on the force plate and placed in 90° of knee flexion with their ankle in plantigrade (O'Neill et al., 2023), secured with a strap ratcheted across the distal end of their femur to prevent their heel from rising. Participants sat upright with their hands across their chest, and a mat was placed between the participant and the strap for comfort. A pre-tension of 400 N was applied via the ratcheted strap to secure participants prior to MVICs. For the standing position, the force

plate was zeroed, and participants stood single-leg with 0° knee flexion, ankles in plantigrade, and shoulders braced under a bar in the squat-rack frame, as in Murray et al. (2019).

For all MVICs, the peak force value (N) from each MVIC repetition was recorded, with the highest two measurements averaged and used for analysis (Rock et al., 2021). Peak force were expressed in body weight units (N/BW) (Mickle et al., 2009), and peak moments (Nm) calculated using the plantarflexion and MTP moment arms as lever lengths (N/m²).

Leg stiffness

Single leg hopping stiffness was assessed following methods described elsewhere (Hébert-Losier & Eriksson, 2014) on the calibrated Kistler force plate. Before the test, participants were familiarised with the task and rested for two minutes. For testing, participants stood on their right leg on the force plate with their hands on their hips. They were instructed to act like a pogo-stick and hop in place to the beat of 132 beats per minute metronome (2.2 Hz hopping frequency), hopping 33 times. The data were processed using customised script in Visual 3D v.2023.08.5 (HAS Motion Inc, Kingston, Ontario), taking the median 10 stiffness values (kN/m) using the double integration method described by (Hébert-Losier & Eriksson, 2014).

Maximal oxygen uptake

The VO₂ peak of participants was measured using an incremental speed protocol performed on a treadmill with a 0% incline. Starting speeds were based on participants' recent best 10 km times (8 km/h if 10 km ≥ 50 min; 10 km/h if 40 min ≤ 10 km < 50 min; 12 km/h if 35 min ≤ 10 km < 40 min; 14 km/h if 10 km < 35 min). During testing, the speed was increased by 0.5 km/h every minute until participants could not complete another 1-minute stage. For the

collection of VO_2 peak, a calibrated metabolic cart (TrueOne 2400, Parvo Medics, Salt Lake City, UT, USA) was used to determine oxygen consumption (VO_2) and respiratory exchange ratio (RER). Expired gases were collected with data averaged every 15 seconds. VO_2 peak was determined as the average of the two highest consecutive 15-second VO_2 values recorded during the last minute of the test, consistent with previous methodologies (Hébert-Losier, Ashlyne, et al., 2025). For each participant, RE data at the required 70% of VO_2 peak were excluded from analysis when RER values exceeded 1.0, indicating a shift to anaerobic energy sources, and thus surpassing the participant's anaerobic threshold. At the end of the test, the Borgs 6-20 RPE scale was shown to the participant to gauge their subjective effort (Edvardsen et al., 2014; Habibi et al., 2014), where ≥ 17 indicates VO_2 peak. The participant's blood lactate concentration levels were also recorded using a blood sample from the earlobe on the using a Lactate-Pro 2 analyser (Arkray Inc., Kyoto, Japan) to ensure blood lactate levels were over 4.0 and participants were running anaerobically. All participants reached this threshold during VO_2 peak testing.

Running economy

During each 6-minute RE trial ran at 70% $v\text{VO}_2$ peak, VO_2 and RER were continuously measured using the calibrated metabolic cart. Blood lactate concentration and RPE were recorded at the conclusion of each 6-minute RE trial. The metabolic cart data were averaged over the last two minutes and used to extract RE as VO_2 (mL/kg/min) and RER. The data from the two trials completed in each footwear condition were averaged and used for analysis. The RE data from a trial were excluded from analysis when RER values exceeded 1.0, indicating a shift to anaerobic energy sources, and thus surpassing the participant's anaerobic threshold.

Plantarflexion power

Prior to testing of plantarflexion power, a black circular sticker (24 mm diameter) placed on a white one (32 mm diameter) was positioned directly below the lateral malleolus on a flat surface of the foot, as described elsewhere (Hébert-Losier, Manawa, et al., 2025). Participants were familiarised with the test, completing three bodyweight repetitions first. For testing, participants wore a weighted vest adjusted to add 30% of their bodyweight.

The test required participants to stand with their forefeet on the edge of a 20 cm steel stand placed on the Kistler force plate, with heels over the edge (Hébert-Losier, Manawa, et al., 2025). Participants were required to keep their testing leg straight and use two fingertips from each hand as support on the squat rack frame in front of them. The participants were instructed to raise their heels as high as possible from the stand, shift their weight to their right foot, and perform a downward (eccentric) and upward (concentric) movement as quickly and strongly as possible. Participants performed three repetitions, separated by a few seconds pause at the top of each repetition. The repetition with the greatest peak power was used for analysis. The test was recorded at 60 frames per second in portrait on an iPad (Apple Inc., California, USA) placed on a stand 50 cm to the side of the foot using the Calf Raise application (version 1.5.1).

Plantarflexion strength-endurance

The same circular stickers used in the power test were used for strength-endurance testing of the triceps surae. Participants followed the protocol previously described by Hébert-Losier et al. (2023). They were instructed to stand on a 10° steel incline and perform bodyweight single-leg calf raises in time to a 60-bpm metronome, going up on one beat and down on the next, until failure. This test was only performed once and performance tracked using the valid and reliable Calf Raise App (Fernandez et al., 2023; Hébert-Losier, Manawa, et al., 2025).

The total number of repetitions completed, the peak height (cm) reached, and the total concentric work completed (J) were extracted as outcomes for this test.

Subjective ratings

After each RE trial and at the end of all trials, a series of subjective ratings were collected using 0 to 100 mm visual analogue scale (VAS) ratings administered using Qualtrics. The questions administered immediately after each individual RE trials collected runners' perceptions of their running experience in terms of overall comfort, pleasure/displeasure, easier/harder, performance, and injury risk (Hébert-Losier, Ashlyne, et al., 2025). For these questions, higher scores reflect more favourable ratings. Runners also rated their perceptions of heel cushioning, forefoot cushioning, shoe flexibility, and shoe stability using a Goldilocks scale where the midpoint reflected ideal, and the extremes reflected too little or too much of the shoe property. These measures were collected to determine the Running Shoe Comfort Assessment Tool (RUN-CAT) score (Bishop et al., 2020), where 0 reflects the least ideal shoe and 100 reflects the most ideal shoe. At the end of the four RE trials, participants ranked the two pairs (AFT, CONTROL) in a head-to-head, ranking comfort, race performance, and injury risk. Individual test images available in appendices 1.

Data analysis

Data were descriptively analysed and summarised using means, standard deviations, ranges (minimum, maximum), and counts. Participants were categorised using the oxygen consumption variable as responders when their RE improved by 2.5% or more, and non-responders when less than 2.5% based on previous literature (Brund et al., 2025; Patoz et al.). Between-group differences in participant characteristics and performance variables were examined using independent samples *t*-tests, with effect sizes and their 95% confidence intervals [lower, upper] calculated using Hedges' *g* given unequal sample sizes. Magnitudes

of differences between groups were interpreted as *small*, *moderate*, and *large* when significant and reaching thresholds of 0.20, 0.50, and 0.80 (Cohen, 1992). Fisher exact probability tests were used to examine categorical variables, with significant 10%, 30%, and 50% differences in proportions deemed to reflect *small*, *moderate*, and *large* differences (Cohen, 1992). Where appropriate, Cramér's V was used to estimate effect size, with values of 0.1, 0.3, and 0.5 interpreted as *small*, *moderate*, and *large effects* (Cohen, 1988). Odds ratios (OR) were calculated for 2×2 categorical comparisons using the standard formula: $OR = (A \times D) / (B \times C)$. When one or more cells contained a zero, a continuity correction of 0.5 was applied to all cells to enable estimation and avoid division by zero, following Haldane-Anscombe correction principles (Forthofer et al., 2007).

Pearsons's correlation coefficient (r) was used to assess the linear relationship between the change in oxygen consumption between shoes, expressed as a percentage, and the other variables of interest. Correlation coefficients (r) and their 95% confidence intervals were calculated, with P values extracted to determine their statistical significance. Magnitudes of correlations were interpreted as *small*, *moderate*, and *large* when significant and reaching thresholds of 0.10, 0.30, and 0.50 (Cohen, 1992). The significant correlations were inputted into a least-squares linear regression. The variance inflation factors, residual-versus-fitted plots, and Breusch-Pagan / Cook-Weisberg test for heteroskedasticity results were examined to verify the presence of multicollinearity, linearity, homoscedasticity, and outliers. Data analyses were performed in Excel version 2504 (Microsoft Corp., Redmond, WA, USA) and StataIC 16.1 (StataCorp LLC, College Station, TX). Statistical significance was set at $P \leq 0.05$ for all analyses.

Results

Responders and non-responders

The study recruited 82 participants. Of these, 64 participants (32 males, 32 females) completed both sessions and were included in the final analysis (Table 3). Eight participants withdrew from the study prior to completion, and data from a further 10 participants were excluded due to a change in testing location that prevented full protocol completion. Participants were primarily long-distance runners (67%) of recreational (52%) or experienced (42%) running level. Of the 64 participants, 53 (83%) were classified as responders to AFT (beneficial change in RE \geq 2.5%), while 11 (17%) were identified as non-responders (beneficial change in RE $<$ 2.5%). The average oxygen consumption in the AFT condition was 35.0 ± 5.0 mL/kg/min, compared to 36.8 ± 4.9 mL/kg/min in CONTROL. The mean RE improvement with AFT was $4.13 \pm 1.95\%$. There were no statistically significant differences in the characteristics of participants between responders and non-responders. However, among the performance-related variables, only normalised GM stiffness demonstrated a difference ($p = 0.046$), with a *large* effect size (Hedges' $g = 0.86$) (Table 4)

Table 3. Characteristics of participants, with values presented in means, standard deviations, counts, Heges *g* effect size, *p* values, and confidence intervals.

Characteristics	All (<i>n</i> = 64)	Responders (<i>n</i> = 53)	Non-responders (<i>n</i> = 11)	Heges <i>g</i> [CI]	<i>p</i> value
Age (y)	33.5 ± 15.6	34.0 ± 15.9	31.3 ± 14.9	0.17 [-0.48, 0.82]	0.598
Mass (kg)	69.5 ± 11.9	69.4 ± 11.4	69.9 ± 15.0	-0.04 [-0.69, 0.61]	0.921
Height (cm)	172.3 ± 7.9	172.4 ± 7.2	171.9 ± 11.1	-0.26 [-0.91, 0.39]	0.534
Leg length (cm)	88.3 ± 4.2	88.4 ± 3.7	88.2 ± 6.2	0.04 [-3.72, 4.08]	0.928
AFT shoe size	8.7 ± 1.9	8.8 ± 1.9	8.5 ± 2.2	0.174 [-0.474, 0.826]	0.643
BMI (kg/m ²)	23.26 ± 2.83	23.2 ± 2.6	23.5 ± 3.8	-0.09 [-0.74, 0.56]	0.825
Mileage per week (km)	33.6 ± 24.8	34.4 ± 24.9	30 ± 25.2	0.17 [-0.48, 0.82]	0.607
5 km time (min)	22.8 ± 4.2	22.6 ± 4.1	24.1 ± 4.1	-0.36 [-1.02, 0.29]	0.285
VO ₂ peak (mL/kg/min)	49.4 ± 8.3	49.9 ± 8.4	47.1 ± 7.3	0.33 [-0.32, 0.99]	0.279
vVO ₂ peak (km/h)	15.5 ± 2.16	15.6 ± 2.2	15 ± 2.1	0.24 [-0.41, 0.89]	0.460
70% vVO ₂ peak (km/h)	10.8 ± 1.5	10.9 ± 1.5	10.5 ± 1.5	2.6 [-0.60, 1.36]	0.453

Super shoe use (<i>n</i> Yes: <i>n</i> No)	19:45	17:36	2:9	2.13 [0.41, 23.13]	0.483
Male: Female (<i>n</i>)	32:32	28:25	4:7	0.51 [0.13, 2.19]	0.509
Sprinter: Middle: Long (<i>n</i>)	9:12:43	7:10:36	2:2:7	0.12	0.884
Rec: Exp: Nat (<i>n</i>)	33:27:4	27:23:3	6:4:1	0.12	0.880

Note. Statistically significant variables ($p < 0.05$) are displayed in bold for all participants, responders, and non-responders. Confidence intervals for categorical data (where appropriate) and odds ratios (OR) are also provided.

Abbreviations. BMI, body mass index; Exp, experienced; Nat, national; Rec, recreational; VO₂ peak; peak oxygen uptake, v VO₂ peak; speed at peak oxygen uptake.

Table 4. Results from tested variables for all ($n = 64$), responders ($n = 53$), and non-responders ($n = 11$). Displayed in means, standard deviations, Heges g effect size, p values, and confidence intervals.

Performance variables	Overall (Mean \pm SD)	Responders (Mean \pm SD)	Non-responders (Mean \pm SD)	Heges g [CI]	p value
Oxygen consumption					
AFT (mL/kg/min)	35.0 \pm 5.0	35 \pm 5.2	35 \pm 3.8	0.00 [-0.65, 0.65]	0.990
CON (mL/kg/min)	36.5 \pm 5.1	36.7 \pm 5.3	35.5 \pm 4.0	0.22 [-0.43, 0.87]	0.425
RE response	4.13 \pm 1.95	4.68 \pm 1.56	1.47 \pm 1.35	2.05 [1.32, 2.81]	0.000
Strength outcomes					
Seated PF MVIC (BW)	1.60 \pm 0.34	1.57 \pm 0.35	1.72 \pm 0.33	-0.41 [-1.07, 0.24]	0.211
Standing PF MVIC (BW)	2.56 \pm 0.42	2.53 \pm 0.41	2.74 \pm 0.45	-0.52 [-1.18, 0.14]	0.164
Seated PF MVIC (Nm)	132.4 \pm 31.2	130.5 \pm 32.1	141.6 \pm 27.2	-0.35 [-1.01, 0.3]	0.250
Standing PF MVIC (Nm)	217.4 \pm 60	214.5 \pm 55.1	231.4 \pm 68.5	-0.29 [-0.94, 0.36]	0.457
Toe flexion MVIC (BW)	0.19 \pm 0.06	0.19 \pm 0.06	0.21 \pm 0.05	-0.27 [-0.95, 0.41]	0.346
Toe flexion MVIC (Nm)	6.9 \pm 2.5	6.8 \pm 2.4	7.4 \pm 2.9	-0.21 [-0.89, 0.46]	0.595
Ankle Inversion MVIC (BW)	0.23 \pm 0.07	0.23 \pm 0.07	0.23 \pm 0.04	0.05 [-0.62, 0.73]	0.836
Ankle Eversion MVIC (BW)	0.23 \pm 0.06	0.24 \pm 0.06	0.22 \pm 0.05	0.22 [-0.45, 0.9]	0.462
Ankle Inversion MVIC (Nm)	19.5 \pm 7.3	19.6 \pm 7.6	18.9 \pm 6.0	0.09 [-0.59, 0.77]	0.766
Ankle Eversion MVIC (Nm)	18.1 \pm 5.2	18.4 \pm 5.2	16.6 \pm 5.2	0.35 [-0.33, 1.03]	0.328
Power (W)	466.7 \pm 168.8	469.4 \pm 168.6	452.8 \pm 187.3	0.10 [-0.58, 0.77]	0.799
Calf endurance outcomes					
Calf Endurance Total reps (n)	42.1 \pm 25.7	42.9 \pm 27.1	37.9 \pm 19.4	0.13 [-0.54, -0.01]	0.601
Calf Endurance Peak Height (cm)	10.0 \pm 1.4	9.9 \pm 1.4	10.1 \pm 1.9	-0.28 [-0.96, -0.68]	0.325
Calf Endurance Work (w)	2297.1 \pm 1174.0	2307.9 \pm 1140.1	2239.9 \pm 1460.6	-0.01 [-0.68, 0.67]	0.989
Stiffness					
GM raw value (N/m)	286.33 \pm 38.47	291.5 \pm 35.3	261.6 \pm 46.9	0.79 [0.13, 1.46]	0.068
GM normalized (N/m ²)	324.04 \pm 39.99	329.8 \pm 36.6	296.4 \pm 47.3	0.86 [0.20, 1.53]	0.046
Achilles tendon 8cm raw value (N/m)	641.33 \pm 133.27	640.4 \pm 132.6	645.7 \pm 149.2	-0.04 [-0.69, 0.61]	0.914
Achilles tendon 8cm normalized (N/m ²)	725.15 \pm 142.96	723.9 \pm 143.00	730.6 \pm 156.3	-0.05 [0.20, 1.53]	0.897
Plantar fascia raw value (N/m)	518.13 \pm 72.47	515.9 \pm 77.00	528.7 \pm 51.00	-0.17 [-0.82, 0.48]	0.500

Plantar fascia normalised value (N/m ²)	2062.05 ± 287.82	2045.3 ± 303.5	2142.4 ± 206.5	-0.33 [-0.99, 0.32]	0.200
Hopping (kN/m)	16848.0	16955.3 ± 4046.2	16311.6 ± 3132.1	0.16 [-0.52, 0.84]	0.582
Foot measurements					
Truncated length standing (cm)	18.9 ± 1.2	18.9 ± 1.2	18.5 ± 1.3	0.36 [-0.29, 1.01]	0.319
Arch height standing (cm)	7.3 ± 0.7	7.3 ± 0.6	7.4 ± 0.9	-0.26 [-0.91, 0.39]	0.534
PFarm standing (cm)	12.4 ± 0.9	12.5 ± 0.8	12.3 ± 1	0.17 [-0.48, 0.83]	0.656
Navicular drop (cm)	0.5 ± 0.3	0.5 ± 0.3	0.4 ± 0.2	0.48 [-0.18, 1.13]	0.077
MTP angle (°)	88.8 ± 11.9	89.3 ± 12.7	86.3 ± 7.1	0.25 [-0.40, 0.90]	0.283
Arch height index	-0.02 ± 0.02	0 ± 0	0 ± 0	-0.33 [-0.98, 0.32]	0.282
Arch flexibility	-1.45 ± 1.67	-1.5 ± 1.7	-1 ± 1.7	-0.29 [-0.95, 0.35]	0.388
Foot magnitude mobility	0.68 ± 0.78	0.7 ± 0.8	0.5 ± 0.4	0.26 [-0.39, 0.92]	0.205
Gear ratio	2.65 ± 0.37	2.7 ± 0.4	2.5 ± 0.4	0.55 [-0.10, 1.21]	0.151
Subjective ratings					
RUN-CAT absolute scores AFT	82.6 ± 13.2	82.1 ± 13.8	85.2 ± 10.6	-0.23 [-0.88, 0.42]	0.416
RUN-CAT absolute scores CON	82.7 ± 13.5	82 ± 14.1	85.9 ± 9.9	-0.29 [-0.94, 0.36]	0.282
RUN-CAT differences between shoes	0.1 ± 13.6	-0.1 ± 14.5	0.8 ± 8.4	-0.06 [-0.71, 0.59]	0.798
Shoe ratings differences (injury)	5.3 ± 20.6	5.8 ± 22.7	5.5 ± 18.9	-0.04 [-0.69, 0.61]	0.952
Shoe ratings differences (comfort)	-6.9 ± 19.9	-6.1 ± 20.8	-10.8 ± 15.3	-0.04 [-0.69, 0.61]	0.404
Shoe ratings differences (pleasure)	-11.4 ± 17.0	-10.8 ± 18	-14 ± 10.9	-0.08 [-0.73, 0.57]	0.451
Shoe ratings differences (effort)	-12.6 ± 16.3	-12 ± 17.2	-15.5 ± 11.2	0.02 [-0.63, 0.67]	0.417
Shoe ratings differences (performance)	-19.4 ± 16.6	-19.2 ± 17.5	-20.3 ± 11.9	-0.07 [-0.72, 0.58]	0.810
Overall preference count (<i>n</i>)	(AFT:CON)	(AFT:CON)	(AFT: CON)	OR [CI]	Fishers <i>p</i>
Lowest injury risk	17:46	12:40	5:6	0.36 [0.09, 4.63]	0.149
Performance	60:4	49:4	11:0	0.56 [0.03, 0.92]	1.000
Comfort	41:23	32:21	9:2	0.34 [0.07, 1.13]	0.301

Note. Statistically significant variables ($p < 0.005$) displayed in bold.

Abbreviations. AFT, advanced footwear technology; BW, body weight; CI, confidence interval; CON, CONTROL; MTP angle, metatarsophalangeal joint angle; MVIC, maximal voluntary isometric contraction; OR, odds ratio; PF, plantarflexion; PFarm, Plantarflexion moment arm; SD, standard deviation.

Correlation analysis

Pearson's correlation analysis revealed *small to moderate*, statistically significant associations between RE response and five variables: standing plantarflexion MVIC, navicular drop, gear ratio, raw GM stiffness, and normalised GM stiffness (Table 5).

Normalised GM stiffness was *moderate* positive correlation, indicating runners with higher GM stiffness have a greater RE response to AFT. The raw values of GM stiffness and gear ratio had similar *small* positive correlation to AFT. In addition, navicular drop had a *moderate* correlation, meaning that runners with a higher navicular drop have a greater RE response to AFT. Interestingly, standing plantarflexion MVIC had a *small* negative correlation, suggesting those with weaker standing plantarflexion MVIC strength may benefit more to AFT.

Table 5. Pearsons correlations for all variables, displayed in *r* coefficient, *p* values, and confidence intervals.

Variables	Pearson <i>r</i>	CI	<i>p</i> value
Participant characteristics			
Age (y)	-0.05	[-0.30, 0.19]	0.672
Mass (kg)	0.05	[-0.20, 0.29]	0.718
Height (cm)	-0.10	[-0.34, 0.15]	0.415
Leg length (cm)	-0.07	[-0.31, 0.18]	0.592
AFT shoe size (US M)	0.02	[-0.23, 0.26]	0.884
BMI (kg/m ²)	0.03	[-0.22, 0.27]	0.83
Mileage per week (km)	-0.04	[-0.28, 0.21]	0.783
5 km time (min)	0.06	[-0.20, 0.31]	0.672
VO ₂ peak (L/min)	-0.02	[-0.27, 0.22]	0.846
VO ₂ peak (mL/kg/min)	0.10	[-0.29, 0.20]	0.695
vVO ₂ peak (km/h)	-0.04	[-0.28, 0.21]	0.771
70% vVO ₂ peak (km/h)	0.22	[-0.28, 0.21]	0.798
Strength outcomes			
Seated PF MVIC (BW)	-0.23	[-0.45, 0.02]	0.067
Standing PF MVIC (BW)	-0.26	[-0.47, -0.01]	0.041
Seated PF MVIC (N/m)	-0.19	[-0.41, 0.06]	0.137
Standing PF MVIC (N/m)	-0.10	[-0.34, 0.14]	0.41
Toe flexion MVIC (BW)	0.00	[-0.25, 0.24]	0.972
Toe flexion MVIC (N/m)	0.04	[-0.21, 0.29]	0.749
Ankle inversion MVIC (BW)	0.12	[-0.13, 0.36]	0.352

Ankle eversion MVIC (BW)	0.05	[-0.20, 0.29]	0.70
Ankle inversion MVIC (N/m)	0.12	[-0.13, 0.36]	0.338
Ankle eversion MVIC (N/m)	0.11	[-0.14, 0.35]	0.396
Power (W)	0.06	[-0.20, 0.30]	0.666
Calf endurance outcomes			
Calf endurance total reps (<i>n</i>)	0.04	[-0.21, 0.29]	0.735
Calf endurance peak height (cm)	-0.20	[-0.43, 0.05]	0.109
Calf endurance work (<i>w</i>)	-0.03	[-0.27, 0.22]	0.843
Stiffness			
GM raw value (N/m)	0.29	[0.04, 0.50]	0.021
GM normalised (N/m²)	0.35	[0.11, 0.55]	0.005
Achilles tendon 8cm raw value (N/m)	-0.02	[-0.27, 0.22]	0.859
Achilles tendon 8cm normalized (N/m ²)	0.00	[-0.25, 0.24]	0.97
Plantar fascia raw value (N/m)	-0.15	[-0.38, 0.10]	0.236
Plantar fascia normalised value (N/m ²)	-0.18	[-0.41, 0.07]	0.148
Hopping (kN/m)	0.04	[-0.21, 0.29]	0.749
Foot measurements			
Truncated length standing (cm)	0.04	[-0.20, 0.29]	0.731
Arch Height standing (cm)	-0.10	[-0.34, 0.15]	0.415
PFarm standing (cm)	-0.05	[-0.29, 0.20]	0.713
Navicular drop (cm)	0.31	[0.07, 0.52]	0.012
MTP angle (°)	0.03	[-0.21, 0.28]	0.789
Arch height index	-0.10	[-0.34, 0.15]	0.424
Arch flexibility	-0.06	[-0.30, 0.19]	0.664
Foot magnitude mobility	0.06	[-0.19, 0.30]	0.664
Gear ratio	0.26	[0.01, 0.48]	0.040
Subjective ratings			
RUN-CAT absolute scores AFT	-0.03	[-0.28, 0.21]	0.791
RUN-CAT absolute scores CON	-0.06	[-0.30, 0.19]	0.672
RUN-CAT differences between shoes	0.05	[-0.19, 0.30]	0.672
Shoe ratings differences (injury)	0.02	[-0.23, 0.26]	0.901
Shoe ratings differences (comfort)	0.01	[-0.24, 0.25]	0.946
Shoe ratings differences (pleasure)	0.04	[-0.21, 0.28]	0.758
Shoe ratings differences (effort)	0.02	[-0.23, 0.26]	0.899
Shoe ratings differences (performance)	0.04	[-0.21, 0.28]	0.765

Note. Statistically significant ($p < 0.005$) variables in bold.

Abbreviations. AFT, advanced footwear technology; BW, Body weight; CI, confidence interval; CON, CONTROL; MTP angle, metatarsophalangeal joint angle; MVIC, maximal voluntary isometric contraction; PF, plantarflexion; PFarm, Plantarflexion moment arm; VO₂ peak: peak oxygen uptake, $v\text{VO}_2$ peak; speed at peak oxygen uptake.

Multiple linear regression

A multiple linear regression was run to examine the combined ability of standing plantarflexion MVIC, navicular drop, gear ratio, raw GM stiffness, and normalised GM stiffness to predict better RE response. However, two variables, normalised GM stiffness and raw GM stiffness were highly related, so normalised GM stiffness was used as it was the stronger variable (Table 6). The overall model was statistically significant ($F(4, 58) = 5.45$, $p < 0.001$), explaining 27.3% of the variance in RE ($R^2 = 0.2731$, adjusted $R^2 = 0.2230$). Among these predictors, normalised GM stiffness was a significant positive predictor ($\beta = 0.014$, $SE = 0.0056$, $p = 0.015$), indicating an increase in stiffness predicts a greater RE response. Additionally, navicular drop significantly predicted a RE response ($\beta = 1.85$, $p = 0.028$), meaning that an increase in navicular drop predicts a greater RE response. Neither gear ($\beta = 0.95$, $p = 0.133$) nor standing body weight plantarflexion MVIC ($\beta = -0.82$, $p = 0.135$) were significant predictors.

All predictors demonstrated low multicollinearity (variance inflation factors < 1.1), and diagnostic plots showed no major violations of regression assumptions. The Breusch-Pagan test was not statistically significant ($\chi^2(1) = 2.58$, $p = 0.108$), indicating no evidence of heteroskedasticity. Therefore, model assumptions were considered met.

Table 6. Multiple linear regression predicting RE response ($\Delta O_2\%$) from biomechanical and anthropometric variables from runners (n = 64).

Variables	B (Unstandardized)	SE B	t	p	95% CI (B)
Gear ratio	0.946	0.621	1.52	0.133	[-0.297, 2.189]
Navicular drop (cm)	1.849	0.820	2.25	0.028	[0.207, 3.491]
Standing plantarflexion MVIC (BW)	-0.819	0.541	-1.52	0.135	[-1.901, 0.263]
GM stiffness normalised (N/m²)	0.014	0.006	2.49	0.015	[0.003, 0.025]

Model statistics: $F(4, 58) = 5.45$; $p = 0.0009$; $R^2 = 0.273$; Adjusted $R^2 = 0.223$; Root MSE = 1.747
 * Statistically significant at $p < 0.05$

Abbreviations. Adj. R^2 , Adjusted R-squared; B, unstandardised regression coefficient; BW, body weight; CI, Confidence interval; MSE, Mean squared error; MVIC, maximal voluntary isometric contraction; N/BW, Newtons per body weight; N/m², newtons per square metre; P, Probability value; SE B, Standard error of the regression coefficient; t, t-statistic.

Discussion

Our study builds upon previous research touching on RE response to AFT shoes. To our knowledge, this is one of the first studies to explore RE responses to AFT shoes addressing a range of factors in a considerably large sample size of 64 runners, examining over 50 variables that may explain interindividual differences in response. Our overall average RE response of 4.13% and interindividual response range of -2.6% to 11.0% align with currently published literature, reporting an average RE improvement of approximately 4% (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019), and interindividual variability ranging between -11% to 13.3% (Hébert-Losier et al., 2022; Knopp et al., 2023).

Despite research suggesting to explore factors such as body mass, running speed, foot arch stiffness, joint range of motion, training level, sex, shoe size, and leg length as variables potentially underpinning RE response (Barrons et al., 2024; Hunter et al., 2019; Mason et al., 2024), our results suggest no significant difference between these variables in responders and non-responders to AFT shoes based on a 2.5% response threshold and no significant association between these factors and RE response. Although we expected females and higher-level runners to experience greater RE improvements in AFT shoes, our results

showed no significant differences in RE responses to AFT shoes between sex or running level, which encompassed weekly running mileage, running speed, VO₂ peak, type of runner, and running experience. These findings indicate that both recreational and well-trained runners may benefit similarly from AFT shoes in terms of oxygen consumption when tested in a laboratory setting at a relative submaximal running speed, regardless of sex.

Plantarflexion strength and stiffness

We hypothesised that greater plantarflexion strength and leg stiffness would be associated with greater improvements in RE when running in AFT shoes. While no significant group differences were observed for plantarflexion strength between responders and non-responders, a *small* negative and statistically significant correlation was found between standing plantarflexion strength normalised to body weight and RE response. This result contradicts our hypothesis, and while greater triceps surae strength is generally beneficial to RE (Arampatzis et al., 2006), the identified correlation suggests that runners with lesser plantarflexion strength may experience greater RE benefits from running in AFT shoes. On the other hand, GM stiffness when normalised to leg length was significantly greater in responders than non-responders and was *moderately* correlated with RE improvements, suggesting that mechanical properties of the triceps surae muscle-tendon unit may indeed contribute to individual RE responses, as proposed elsewhere (Mason et al., 2024).

Current literature exploring leg, triceps surae, and Achilles tendon stiffness relationships to RE report mixed results. For example, Liu et al. (2022) reported that increased leg stiffness is generally associated with improved RE based on a literature review. However, recent studies by Konrad et al. (2023) and Nguyen et al. (2025) both found Achilles tendon stiffness to be positively related to improved RE, while triceps surae stiffness was not based on myotonometry (i.e., application of mechanical impulses to soft tissues to record resulting

oscillation). Conversely, alternative methods to assess passive stiffness, such as the use of a BIODEX dynamometer (Ueno et al., 2018) or free oscillation techniques (Dumke et al., 2010), have shown that greater passive stiffness in the triceps surae can positively influence RE. As the triceps surae functions as a muscle-tendon unit (Arampatzis et al., 2006), it is plausible that a stiffer gastrocnemius could contribute to more effective force transmission through the Achilles tendon. In AFT shoes, it has been suggested that greater plantarflexion strength is necessary to maximise the benefits from the footwear (Ortega et al., 2021) due to the increases in vertical displacement and ground contact times (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Joubert et al., 2024). However, our data showed runners with weaker isometric plantarflexion strength and stiffer calf muscles (measured at GM) may benefit more from AFT shoes. This finding appears somewhat counterintuitive as greater leg stiffness is typically associated with shorter ground contact times (Liu et al., 2022), whereas AFT shoes have been consistently shown to increase ground contact times (Barnes & Kilding, 2019; Hoogkamer et al., 2018; Joubert et al., 2024). It is possible that runners with greater passive GM stiffness maintain functional stiffness throughout the prolonged stance phase or transfer forces to AFT shoes more effectively in a manner that benefits RE and responses to AFT shoes. When elastic strain energy from muscle-tendon units is aimed at reducing metabolic cost, having greater muscle stiffness to resist contractile element stretch may be beneficial (Holt & Mayfield, 2023; Roberts & Azizi, 2011). Chollet et al. (2023) proposed the GM may be important in modulating the effect of increased bending stiffness due to the bi-articular configuration of the muscle modulating moments and powers at the ankle joint (van Ingen Schenau et al., 1990; van Ingen Schenau et al., 1992). Cigoja et al. (2021) highlighted that stiffer midsoles allow the plantarflexion muscle-tendon unit to operate in a more favourable position by reducing muscle shortening velocity and enhancing tendon energy return. Although our results suggest GM stiffness may play a role in benefiting from AFT shoes,

further research is needed to determine whether enhanced passive stiffness translates to greater dynamic stiffness during running in AFT shoes.

Gear ratio

We also found a *small* positive and statistically significant correlation between static gear ratio at the ankle and RE response to AFT, indicating that greater gear ratios resulted in greater RE benefits. Gear ratio refers to the ratio of plantarflexion moment arm to Achilles tendon moment arm, and a higher ratio is theorised to improve mechanical efficiency during gait (Ray & Takahashi, 2020) and the mechanical advantage of the plantarflexion muscle-tendon unit during the push-off phase of running (Willwacher et al., 2014). Footwear with increased midsole bending stiffness has been speculated to increase effective foot length by shifting the centre of pressure anteriorly (Day & Hahn, 2019; Oh & Park, 2017; Willwacher et al., 2014), thereby increasing the ground reaction force lever arm and increasing gear ratio (Carrier et al., 1994; Willwacher et al., 2014). However, it is worth noting that anterior centre of pressure shifts have not consistently been observed in AFT shoes (Hoogkamer et al., 2019), and two different strategies have been identified in response to increases in gear ratio during running linked with increases in midsole stiffness (Willwacher et al., 2014). Some runners increase ankle joint moments and maintain similar push-off times, whereas other runners decrease ankle joint moments and increase push-off times in response to increased midsole stiffness and ankle gear ratio. Typically, AFT shoes incorporate a curved stiff plate in the midsole, which has been suggested to reduce the ankle-joint lever arm, increase ankle gear ratio, and lower plantarflexion mechanical energy expenditure during the middle portion of the stance phase (Miyazaki et al., 2024). Furthermore, the curved design of the footwear and plate creates a class-one lever and as the centre of pressure moves anteriorly during the second half of stance, it produces a force that

assists the heel upwards during take-off, or a so called “teeter-totter effect” (Nigg et al., 2020).

Despite research indicating the absence of such an effect (Hoogkamer et al., 2019), a recent proof-of-concept study rather supports its presence, confirming a greater propulsion moment, as well as a greater posterior shift of the centre of pressure during late stance (65-95%) in an AFT shoe compared to a control (Subramaniam et al., 2024). However, it is important to note that the proof-of-concept study (Subramaniam et al., 2024) supporting the “teeter totter effect” compared the Nike Vaporfly 4% (an AFT racing shoe) to the Nike Air Force 1, a casual lifestyle shoe not designed for running. This stark contrast in shoe function and design likely influenced the observed results, limiting the generalisability of the findings.

Overall, our findings suggest that individuals who already have a greater gear ratio at the ankle may be predisposed to exploit the more favourable position of the triceps surae muscle-tendon unit force-length-velocity relationship created by AFT, which lowers muscle shortening velocity and enhances tendon energy return (Cigoja et al., 2021). However, this interpretation remains speculative, particularly considering how joint gear ratios are not static, but dynamic, and that humans vary their gear ratios depending on the task or speed of movement (Carrier et al., 1994; Ray & Takahashi, 2020). For instance, the gear ratio at the ankle increases as the speed of running increases (Carrier et al., 1994). As such, the use of a static gear ratio may not be reflective of the dynamic gear ratio present during running, with some runners potentially increasing their ankle gear ratio to a greater extent than others for a given absolute or relative speed. Thus, further research is needed to explore the interaction between gear ratio and AFT shoes to clarify its role in RE responses.

Metatarsophalangeal joint

We hypothesised that runners with greater MTP joint extension would show greater RE responses in AFT as their joint range would be constrained due to the geometry and stiffness of the AFT shoe. This speculation was based on research showing that footwear with increased midsole bending stiffness reduces MTP dorsiflexion (Chen et al., 2022; Willwacher et al., 2013) and decreases the negative work at the MTP joint (Cigoja et al., 2019; Hoogkamer et al., 2019). Additionally, Farina et al. (2019) highlighted footwear with a stiff curved plate can reduce net energy loss at the MTP joint. However, our results did not support this hypothesis, as weight-bearing MTP joint extension was not significantly associated with RE responses in AFT. The methodology employed to assess first toe MTP joint extension was based on its relevance to running (van der Worp et al., 2014). The test, however, demonstrates only moderate intra-rater reliability (intraclass correlation: 0.62; standard error of measurement: 9.9°). It is possible that the measurement was not sufficiently reliable to detect differences between responders and non-responders, or that standing MTP joint extension does not reflect the dynamic mobility or function of the joint during running. Additionally, the geometry of the AFT shoes may standardise joint behaviour across individuals, thus diminishing the influence of individual anatomical variation in MTP extension on RE outcomes.

Ankle stability

It was hypothesised that greater inversion and eversion strength would be positively associated with RE improvements in AFT. Given that AFT typically features increased stack heights and softer low density midsole foams (Burns & Joubert, 2024; Rodrigo-Carranza et al., 2024), instability in the frontal plane may be exacerbated (Barrons et al., 2023; Hoogkamer, 2020). For example, Barrons et al. (2023) reported significantly greater ankle

everion angles in shoes with stack heights of 45 and 50 mm. Similarly, Kettner et al. (2025) found that in their highest stack height condition (50 mm), there was a prolonged period of foot eversion during stance compared to lower stack heights, indicative of reduced ankle stability. Additionally, Burns and Joubert (2024) describe a stability penalty, where there is an inherent trade-off between the mechanical benefits of increased midsole foam volume and thickness and the ability of runners to use the foam effectively because it is not fully elastically compressed during running. While these effects have been observed primarily in controlled laboratory settings, they may still be relevant for runners who use AFT shoes on varied surfaces outdoors (Hébert-Losier et al., 2024). Therefore, stronger inversion and eversion muscles might help counteract potential instability introduced by footwear design, contributing to improved RE. However, our results found no significant differences between responders and non-responders in ankle inversion and eversion MVIC strength, suggesting isometric inversion and eversion ankle maximal strength may play a lesser role in responses to AFT. Assessing runners on a more challenging surface than a treadmill might have yielded different results.

Navicular drop

While isometric ankle inversion and eversion strength did not explain differences between responders, our study also included static navicular drop as a measure of foot function and mobility. Although not a direct indicator of dynamic ankle stability, navicular drop has been used to reflect medial arch mobility (Fraser & Hertel, 2021) and as a composite indicator of foot pronation (García-Pinillos et al., 2021). Our study revealed a positive *moderate* and statistically significant correlation between navicular drop and RE response to AFT, with greater navicular drop linked with larger improvements in RE when wearing AFT shoes. Indirectly, this finding would indicate that individuals with greater arch mobility and foot pronation might benefit more from the use of AFT shoes. One possible explanation to our

findings relating to navicular drop is the interaction between arch stiffness and shoe mechanics. Holowka et al. (2022) reported that stiffer footwear restricts longitudinal arch compression, potentially influencing the natural energy return of the arch. Additionally, Cooke et al. (2019) found that individuals with lower arch stiffness demonstrated improved RE when using harder, high-arch insoles, likely by preventing arch deformation and allowing those with low arch stiffness to function like those with high arch stiffness who have better RE. In the context of AFT, which features include increased longitudinal bending stiffness and taller stack heights, it is plausible that runners with greater navicular drop (i.e., lower arch stiffness) benefit from the additional external stiffness provided by AFT shoes, explaining the positive association between higher navicular drop and improved RE response seen in our study. Nonetheless, the static navicular drop measure has limitations. Although it demonstrates good to excellent intra-rater (intraclass correlation: 0.83 to 0.95) and inter-rater (intraclass correlation: 0.90 to 0.96) reliability (Deng et al., 2009), it has been shown to be a poor predictor of dynamic navicular drop during running (Deng et al., 2009; Hoffman et al., 2015). Further research investigating the relationship between navicular drop and RE response to AFT is warranted to better understand the underlying mechanisms by which navicular drop may influence individual responses to AFT. Specifically, studies should examine whether individuals with greater static navicular drop exhibit greater dynamic navicular drop and pronation while running in AFT shoes, examining RE responses.

Subjective measures

Our study explored whether subjective measures were associated with responses to AFT footwear. However, our findings did not find any significant differences between responders and non-responders and no correlations between any of our subjective measures to RE responses in AFT shoes, including RUN-CAT scores and VAS ratings in terms of comfort, injury risk, pleasure, and performance. This result is similar to conclusions drawn by

Lindorfer et al. (2020) who found shoe comfort did not predict RE, and Hébert-Losier et al. (2022) reporting that responses to footwear were not predicted by the participants perceived VAS ratings. Furthermore, Hébert-Losier, Ashlyne, et al. (2025) examined the potential for a placebo effect in AFT shoes by providing runners with identical AFT shoes, one described as performance enhancing and the other as a knock off. Despite no significant differences in oxygen consumption, energy cost, or biomechanics between shoes, participants rated the “performance-enhancing” shoe as significantly more comfortable, enjoyable, and lower in injury risk, with 87.5% of runners preferring this shoe over the “knock-off”. These results demonstrate that perceptual differences can be strongly influenced by expectations alone, without influencing RE. Taken together, our findings suggest that subjective perceptions alone may not reliably predict RE responses to AFT footwear.

Multiple regression

Multiple linear regression was used to examine the ability of standing plantarflexion MVIC, navicular drop, gear ratio, and normalised GM stiffness to predict RE response to AFT shoes as these were the measures demonstrating a significant correlation to RE responses. The model was statistically significant and explained 27% of the interindividual variance in RE responses to AFT shoes in our population. Although these factors meaningfully contributed to interindividual variability in the RE response to AFT shoes, a substantial portion of the response remained unexplained and indicates that other factors not here considered contributed to the variations in AFT response.

Practical applications

The results from this study reinforce the notion that footwear prescription should be individualised and evidence based (Blazey et al., 2021). Specifically, not all runners in this study benefited equally from using AFT shoes based on RE, as reported elsewhere (Hébert-

Losier et al., 2022; Knopp et al., 2023), with considerable interindividual variation. As such, runners looking to use AFT should be aware of their possibility to be positive responders, non-responders, or even negative responders, although what individual characteristics drive these responses are challenging to determine. We found no significant differences between responders and non-responders based on sex or performance level, suggesting that AFT may be equally effective for both recreational and trained runners, irrespective of sex. However, our results indicate that individuals with greater GM stiffness, navicular drop, and static ankle gear ratio, and with lower standing plantarflexion isometric strength may benefit to a greater extent from AFT shoe wear. Hence, these measures may provide some assistance in determining whether individuals are likely to benefit or not from AFT shoes. Interventions that can improve these characteristics, such as plyometrics or eccentric calf raises to improve calf stiffness, may improve RE responses to AFT in addition to RE itself (Dumke et al., 2010). Furthermore, given that greater navicular drop and static ankle gear ratio were associated with more favourable RE responses, footwear design may be adapted to better accommodate runners with less advantageous characteristics. Research suggests that modifying the location or stiffness of the carbon plate can influence propulsion mechanics and joint loading. For example, Flores et al. (2021) found that positioning the plate higher in the midsole increased MTP dorsiflexion and ankle plantarflexion, while reducing joint torques and knee work. Similarly, Day and Hahn (2020) demonstrated that stiffer plates altered stride mechanics and improved RE at faster speeds, highlighting the potential for speed-specific shoe tuning. Therefore, future AFT innovations might explore customising plate stiffness and placement to better match an individual's anatomy, potentially improving AFT response.

Strengths

Our final sample size of 64 participants resulted in an ability to detect a *moderate* effect size difference between groups ($d = 0.77$) and a *moderate* correlation ($r = 0.34$) between variables. In contrast to most literature on AFT, this sample size of 64 is relatively large, with research typically involving 15 to 30 participants (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Rodrigo-Carranza et al., 2024). Furthermore, females are underrepresented in previous AFT literature (Mason et al., 2024). The inclusion of 50% female participants strengthens the ecological validity of our study and application to both sexes.

Our study incorporated a broad sample of participants with varying running levels, experience, anatomical, and physiological profiles, examining over 50 variables. Our results may be more applicable to a diverse population of runners due to the heterogeneity of our sample. Unlike tightly controlled studies with highly homogeneous samples, our design enhances the ecological validity of our findings and allows for the exploration of nuanced interindividual differences in RE response to AFT. Conversely, due to the large number of variables that were analysed, a larger cohort may have narrowed the confidence intervals and enhanced our ability to detect *small* correlations (Cohen, 1992). Additionally, the marked imbalance between responders ($n = 53$) and non-responders ($n = 11$) reduced the power of between-group comparisons to ~ 0.63 for large effects, below our intended 0.80. To account for this imbalance, we used statistical methods appropriate for unequal group sizes, including Hedges' g for between-group comparisons and continuity corrections in odds ratio calculations. Nonetheless, a sample with a more equal proportion of responders to non-responders may provide additional insight to the interindividual variance in AFT.

The two shoe models used in our research were within 39 g of each other, with this mass difference unlikely to influence our findings. For instance, a 100 g difference in shoe mass leads to a 1% beneficial change in RE (Franz et al., 2012; Hoogkamer et al., 2016; Rodrigo-Carranza et al., 2020). Additionally, Joubert and Jones (2022) reported no relationships between metabolic cost of running and shoe mass when shoes were within ~30 g. It has also been established that AFT shoes may improve the energetic cost of running (W/kg) by 4% compared to traditional shoes, even once 50 g has been added to an AFT shoe to match shoe mass (Hoogkamer et al., 2018).

Our study did not use a habituation intervention for participants to learn to run in AFT footwear. However, our research did not find any benefit to those who had used AFT shoes previously compared to new AFT users. This observation supports previous literature reporting that AFT habituation may not be needed for positive RE responses (Schwalm et al., 2024). Therefore, the acute responses observed in our laboratory-based trials may reasonably reflect first-use responses to AFT footwear.

Limitations

It is important to note that running in a laboratory setting on a treadmill is not directly reflective of outdoor overground running. Barnes and Kilding (2015a) highlighted how air and wind resistance are not factors influencing RE in laboratory settings. Additionally, treadmill running biomechanics are not the same as overground, due to further use of the hamstrings to aid in propulsion (Jones & Doust, 1996). Additionally, our study also used a HP Cosmos Pulsar 3p treadmill. It has previously been shown that oxygen consumption is greater when running on treadmills than outdoors or on stiffer surfaces (Colino et al., 2020; Kerdok et al., 2002; Smith et al., 2016). These findings may be due to lesser energy return when running on a more compliant surface. As such, the compliance of the treadmills surface

may be influencing some of the RE responses and the RE data collected during our sessions may be an underrepresentation of the true energy cost of running outdoors.

Another limitation to highlight is the use of only one brand and model of AFT and CONTROL shoe with limited shoe sizes. Although seven sizes were available in each shoe, some participants would have preferred half sizes, which may have affected individual comfort (Fife et al., 2023). Additionally, the use of a single model and brand of shoe may not be reflective of shoes across all brands and models, especially considering the range of AFT shoes on the market (Joubert & Jones, 2022).

Our study primarily collected static and passive measures over dynamic measures.

Specifically, the use of our static navicular drop, gear ratio, and passive GM stiffness results, may not be indicative of dynamic loads and measures during running (Carrier et al., 1994; Esmaeili et al., 2024; Hoffman et al., 2015; Liu et al., 2022; Ray & Takahashi, 2020).

Furthermore, this study did not control for running kinematics and explore the influence of foot strike pattern, cadence, ground contact time, and other biomechanical measures on RE response to AFT, which have been shown to be factors that influence RE response to wearing AFT (Hoogkamer et al., 2019; Hunter et al., 2019). We plan to explore running biomechanical factors in relation with RE improvements in AFT footwear in a future study, which was beyond the scope of the current thesis.

Conclusion

Overall, the AFT footwear in this study was effective at improving RE with a mean improvement of 4.13%, and individual responses ranging from -2.62% to 11.01%. Between group differences were limited to differences in GM stiffness normalised to leg length in responders compared to non-responders, with responders being on average 33.4 N/m stiffer. Correlation analyses further revealed that having both greater GM stiffness and navicular

drop improved the RE response wearing AFT. Additionally, lower isometric plantarflexion strength and a greater static ankle gear ratio exhibited a *small* significant relationship with improved RE in AFT shoes. Our results indicate there may be some anatomical and neuromuscular factors mediating the interindividual variation in RE response to AFT, specifically, in muscle-tendon stiffness, foot structure, and ankle geometry properties. Understanding these variables may help inform more personalised footwear recommendations and training strategies to optimise RE benefits from AFT. Nonetheless, a large proportion of the interindividual response remains unexplained and corroborating studies are needed to confirm generalisation of findings.

Chapter Three – Final Chapter

Summary, practical implications, strengths, limitations, and future research directions

Summary

Footwear with AFT have revolutionised the running landscape. Despite research identifying that running in AFT shoes improve RE measures on average by 4 % (Barnes & Kilding, 2019; Hébert-Losier et al., 2022; Hoogkamer et al., 2018; Hunter et al., 2019), large interindividual variability are noted, ranging from -11.3 % to 13.3% (Hébert-Losier et al., 2022; Knopp et al., 2023). A series of factors have been speculated to underpin this variability, including running speed, foot strike pattern, contact time, body mass, leg stiffness, plantarflexion strength, foot size, foot arch stiffness, metatarsal joint range of motion, training level, and sex (Barrons et al., 2024; Hunter et al., 2019). Therefore, the aims of this thesis were to investigate how participant characteristics (e.g., sex, training level), anthropometric variables (e.g., leg length, body mass), neuromuscular measures (e.g., plantarflexion strength, ankle inversion/eversion strength, triceps surae muscle-tendon unit stiffness, and leg stiffness), and subjective factors (e.g., shoe comfort) related to changes in RE when running in AFT compared to a CONTROL shoe. We hypothesised that individuals with greater plantarflexion strength, leg stiffness, ankle inversion and eversion strength, and MTP joint range of motion would exhibit greater improvements in RE when running in AFT shoes. Furthermore, it was hypothesised that females and higher-level runners would experience greater RE improvements in AFT footwear.

Contrary to expectations, only a few variables were significantly associated with RE responses to running in AFT. Specifically, no significant differences or correlations were observed between RE response in AFT shoes and plantarflexion strength, ankle inversion/eversion strength, or MTP joint range of motion. Similarly, neither sex nor running

level was associated with differences in RE response when wearing AFT shoes. Our results found mean improvements in RE of 4.13% and variability of -2.6% to 11% in the AFT shoes, consistent with previous research (Hébert-Losier et al., 2022; Knopp et al., 2023) reporting averages improvements of 3.5 % to 5.0 % and interindividual variability of -11.3% to 13.3 %. Of all the variables examined, only one was significantly different between responders and non-responders (GM stiffness normalised to leg length), and a few exhibited *small* (greater gear ratio and lower standing plantarflexion isometric strength normalised to body weight) to *moderate* (greater navicular drop and greater GM stiffness normalised to leg length) significant relations to RE responses to AFT. The findings suggested that individuals with greater passive GM stiffness and higher navicular drop experienced greater RE benefits from AFT, as did those with weaker standing plantarflexion maximal isometric strength and greater static ankle gear ratios. These characteristics may help identify runners more likely to benefit from AFT. Nonetheless, a considerable proportion of the responses to running in AFT footwear remains unexplained in our study.

Practical applications

The results from this study indicate that the benefits from running in AFT shoes may be experienced by a range of runners, beyond elite athletes. We found no significant differences across several participant characteristics between those who responded positively to running in AFT versus CONTROL shoes and those who did not respond favourably based on an 2.5% improvement in RE measures. Notably, there were no differences between sex, body mass, leg length, shoe size, training, and performance level. Nonetheless, it is important to highlight that not all runners responded positively, with 11 of the 64 runners assessed below the 2.5% threshold.

The findings from this thesis may aid runners and practitioners in informing footwear selection and prescription, namely by considering GM stiffness, static navicular drop, static gear ratio, and standing plantarflexion MVIC. The results suggest interventions geared at improving GM stiffness, such as plyometrics or eccentric calf raises, may improve RE responses to AFT. Additionally, the results may aid manufacturers to further explore footwear design based on individual factors, such as altering designs to promote positive responses in individuals with lower navicular drops and static ankle gear ratios.

Strengths

This study is strengthened by its relatively large sample size ($n = 64$), comprehensive testing protocol, and multidimensional approach to investigating interindividual variability in RE response to AFT. Employing a range of validated anthropometric, neuromuscular, physiological, and subjective measures, we were able to explore over 50 variables to help explain interindividual RE responses to AFT. Additionally, our participants equally represented male and female runners, adding to the ecological validity of our study, and improving the representation of females in AFT research. The results from this study provide a foundation for future studies to further explore factors, such as normalised GM stiffness and navicular drop, as well as variables not addressed in the current analyses, such as sagittal plane kinematics.

Another strength of our study was that our AFT and CONTROL shoe were only 39 g different in mass. Previous studies have shown that RE is impacted by 1% for every 100g of mass added to the shoes (Franz et al., 2012; Hoogkamer et al., 2016; Rodrigo-Carranza et al., 2020), and that AFT still improves RE whilst being weight matched against other shoes (Hoogkamer et al., 2018). Additionally, previous research found no significant relationship between metabolic cost of running and shoes within ~30 g (Joubert & Jones, 2022), further

supporting that the 39 g difference in shoe mass would not explain the average positive response of runners to running in AFT shoes. By not adding weight pellets to equalise mass, our study provides a more accurate representation of real-world between-shoe effects on RE, allowing to draw more ecologically valid inferences that can inform the running community.

Limitations

A limitation of our study is the use of a single brand of AFT shoe and CONTROL shoe within limited sizes. Although we had seven different sizes for each shoe, some runners may have preferred half sizes or different sizes, which may have interfered with their running comfort (Fife et al., 2023). Additionally, the use of a single brand of AFT may not be reflective of AFT responses across all brands and models. There is now a wide range of AFT manufacturers, with not all AFT providing equal benefits across runners (Joubert & Jones, 2022).

Another limitation is that we tested our participants in a laboratory setting on a treadmill. As a result, factors such as air and wind resistance were not accounted for and running biomechanics may not completely reflect those of outdoors. Furthermore, the use of the HP Cosmos Pulsar 3p treadmill is a more compliant surface than typical road conditions (Colino et al., 2020), potentially increasing energy dissipation into the treadmill. Therefore, the results from our study may not fully represent RE responses to AFT shoes when running on the road.

Lastly, our study relied on static and passive anthropometric and neuromuscular measures, rather than capturing dynamic data during running. Measures such as static navicular drop, gear ratio, and passive calf stiffness results may not be indicative of dynamic loads and measures during running. Furthermore, this study did not measure kinematics for running and explore the influence of foot strike pattern, cadence, ground contact time, on RE response to

AFT. Therefore, integrating dynamic measurements of navicular drop and calf stiffness along with kinematic data may provide a more comprehensive understanding of how our results interact with RE responses to AFT shoes.

Future research

Future research can build on this study by addressing some of the limitations and further explore the significant factors found to be associated with greater RE responses when wearing AFT shoes. Exploring factors contributing to interindividual variability across a wider variety of AFT shoes could help extend the applicability of these findings to more types of footwear. Another area to explore is interventions that can improve the significant variables (standing PF MVIC, and GM stiffness), such as plyometrics or eccentric calf raises to improve GM stiffness, may improve RE responses to AFT in addition to RE itself (Dumke et al., 2010). Moreover, future AFT design research could investigate whether varying plate stiffness (Day & Hahn, 2020) and location (Flores et al., 2021) could compensate for less advantageous biomechanics in runners with lower static navicular drop and gear ratio. Customised designs may help broaden the effectiveness of AFT footwear to more runners. Additionally, exploring dynamic versions of the passive calf stiffness and statics navicular drop taken in our study may yield even stronger relationships to AFT RE responses. Lastly, exploring the influence of running biomechanics, including foot strike pattern, cadence, and ground contact time, on RE response to AFT might prove beneficial (Barrons et al., 2024), but was beyond the scope of this thesis.

Conclusion

Overall, this thesis provides exploratory research to explain the interindividual variation in RE response to AFT footwear. The AFT footwear in this study were effective at improving RE with a mean improvement of $4.13 \pm 1.6\%$ and individual responses ranging from -2.62%

to 11.01%. Between group differences were limited to differences in calf stiffness in responders compared to non-responders, with responders being on average 33.4 N/m² stiffer. The correlations we explored found that having both greater calf stiffness and a greater navicular drop improved the RE response wearing AFT. Additionally, lower isometric plantarflexion strength and a greater static ankle gear ratio had a *small* relationship with improved RE in AFT shoes. These triceps surae muscle-tendon characteristics, foot structure, and ankle geometry may assist in determining whether individuals are more likely to respond or not to AFT shoes and guide footwear prescription and selection.

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Appendix

Appendices 1. Ethics

The University of Waikato
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17 May 2024

Kim Hebert-Losier
Patrick Rodrigues
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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

Appendices 2. Test procedure images

Neuromuscular function tests

Image

Gastrocnemius medialis stiffness

(Achilles tendon stiffness was assessed using a similar setup at 8 cm proximal from the Achilles tendon insertion on the calcaneus)



Plantar fascia stiffness



Hallux flexion maximal isometric voluntary contraction



Ankle inversion maximal isometric voluntary contraction



Ankle eversion maximal isometric voluntary contraction



Single leg hopping stiffness



Sitting plantarflexion maximal isometric voluntary contraction



Standing plantarflexion maximal isometric voluntary contraction



Plantarflexion power



Appendices 3. Questionnaires



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.

× SIGN HERE

clear

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.

× SIGN HERE

clear

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

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

What is your best 5km time in the last 6 months? (mm:ss)

What is your best 10km time in the last 6 months? (mm:ss)

What other sports do you participate in at least once per week for the last 6 weeks?

Please specify

None

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 distance (above 42.2km)

How many kms have you ran in the shoes you are wearing today?

0-150km

150-500km

500-800km

Above 800km

Have you run in super shoes or super spikes before?

If yes, what make and model?

No

Yes

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 cushioned 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

