Responses of male recreational runners during outdoor running in three shoes: Quantitative and qualitative studies

A thesis

submitted in fulfilment

of the requirements for the degree

of

Masters in Health, Sport and Human Performance

at

The University of Waikato

by

Hannah Knighton

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2023

Abstract

The introduction of advanced footwear technologies (AFT) in running shoes has sparked debate due to their significant impact on performance. However, there is a lack of research on how runners perceive them, especially compared to their own shoes and minimal shoes, which are also used in racing. Most research surrounding shoes with AFT is conducted in a laboratory environment, despite being designed for outdoor running. Therefore, this study aimed to provide a quantitative (Chapter 2) and qualitative (Chapter 3) assessment of runners running outdoors wearing three different shoes: Nike Vaporfly 4% (VP4), the original shoe with AFT; Saucony Endorphin Racer 2, a minimalist lightweight racing flat (FLAT); and runners' habitual running shoes (OWN). The thesis aimed to compare biomechanical and subjective measures between shoes and explore possible correlations between comfort measures and biomechanical and subjective measures. Additionally, the thesis aimed to provide qualitative insights into shoe comfort and preferences of recreational runners wearing novel footwear.

Chapter One briefly reviews the evolution of running shoes and research investigating the design, performance, comfort, and injury of minimalist shoes and shoes with AFT. Minimalist shoes are designed to mimic barefoot running and have been shown to improve running economy due to being lightweight. These shoes are perceived as potentially preventing injuries for being "closer to nature". Shoes with AFT typically contain a thick midsole of polyamide block elastomer foam and curved stiff plate. Shoes with AFT are reported to improve running economy; however, individual responses vary, especially in recreational runners. Comfort is a critical factor for runners when purchasing shoes and is proposed to enhance performance and minimise injury risk. However, comfort is multifaceted, and individuals value different factors during footwear selection.

Chapter Two is a quantitative study. In a cross-sectional study, 18 male recreational runners (age: 31.2 ± 10.5 y) ran three 1.5 km trials outdoors in OWN first, followed by FLAT and VP4 in random order. The first 1.1 km was run at a comfortable self-selected pace, and the final 400 m at a perceived 5 km race pace with a 30-second rest between speeds and 12-minutes rest between shoe conditions. Biomechanical measures were collected approximately 700 m into the 1.1 km run and 300 m into the 400 m run. Foot-strike angles were smaller in FLAT at both speeds (*small* to *large* effect size, ES) compared to both other shoes. The propulsion phase was shorter in VP4 (*moderate* to *large* ES) than in the other shoes. FLAT was ranked as being the least comfortable at the slower speed and perceived as the most likely to cause injury. OWN was ranked as the most comfortable at the slower speed and perceived as the shoe with the lowest injury risk. Comfort measures were more strongly correlated with subjective than biomechanical measures, illustrating the subjective nature of comfort.

Chapter Three is a qualitative study. The 18 male recreational runners were interviewed before and after running the 1.5 km trials in the three shoes (OWN, FLAT, and VP4). From the interviews, four main themes emerged with regards to comfort, performance, and injury risk: familiarity, cushioning, support, and ease of running. VP4 had the highest number of participants who most favoured it for performance as well as least favoured it for performance, exhibiting the divergent perceptions of runners with regards to the shoe (i.e., runners either liked or disliked them). The FLAT was described as light and quick, while the VP4 was described as bouncy and quick. Regarding cushioning, participants perceived OWN as balanced and reflecting a middle ground between the two extreme novel shoes. OWN provided a sense of familiarity and reassurance to runners regarding injury risk, while the lack of cushioning in the FLAT was perceived to increase injury risk. Overall, the interviews revealed the perceived link between comfort and performance in recreational runners and the variability in runners' footwear preferences.

The results of this thesis provide a more holistic understanding of running footwear comfort and performance in recreational runners. Comfort is a critical factor for shoe selection in runners, however, there is little association between comfort and biomechanics. Additionally, runners appear more likely to purchase shoes with AFT than minimalist possibly due to these being more similar to traditional running shoes and having more cushioning. Combining qualitative and quantitative analysis enables the extraction of a meaningful and nuanced interpretation from data. Furthermore, the valuable insights attained can help inform future shoe design and enhance the overall running experience for recreational runners.

Acknowledgements

I am deeply grateful to everyone who contributed to my thesis this past year. I would like to express my appreciation to my supervisor, Dr Kim Hébert-Losier, for her invaluable guidance, unwavering support, and remarkable patience. Working under her mentorship, I have acquired a wealth of knowledge and skills, and I am truly grateful for the opportunity to learn from her expertise.

I would also like to thank Steve Finlayson for his dedication in collecting the data and providing valuable guidance throughout the process.

Ben Peterson was crucial in aiding my comprehension of the qualitative data and his experience in thematic analysis proved invaluable. I am very grateful for his guidance and thank him for his assistance.

To my friends and family, thank you for your support, kindness, and understanding. You have always been there for me, lending an ear and helping me gain perspective. A special thanks to Sarah and my parents, who never hesitated to provide their guidance and support when I needed it the most.

I am also thankful to Greg O'Carroll and the Sir Edmund Hillary Scholarship program for its support during my six years of study at Waikato University. The program has provided financial assistance and allowed me to grow as an individual while pursuing triathlon around the world. Additionally, I would like to acknowledge the Prime Minister's Scholarship for the additional financial support, which has enabled me to continue my training and competition while studying.

I appreciate everyone who has contributed to my thesis and supported me along this journey. Your contributions have been invaluable, and I am honoured to have had your support.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D – Two dimensional

ABS – Absolute value

AFT – Advanced footwear technology

ANOVA – Analysis of variance

BP – Benjamin Peterson

cm – Centimetre

DF – Duty factor

ES – Effect size

EVA – Ethylene-vinyl acetate

FLAT – Saucony Endorphin Racer 2

F_{max} – Modelled maximum force

g – Grams

g – Gravitational acceleration constant

HK – Hannah Knighton

Hz – Hertz

IMU – Inertial measurement unit

KHL – Kim Hébert-Losier

K_{leg} – Leg stiffness

km – Kilometre

Kn/m – Kilonewton per metre

K_{vert} – Vertical stiffness

L – Leg length

m – Mass

min – Minutes

mm – Millimetre

m/s – Meters per second

n – Counts

NZD – New Zealand Dollar

OWN – Runners own habitual footwear

P# – Participant number

PEBA – Polyamide block elastomer

RUN-CAT – Running comfort assessment tool

RM ANOVA – Repeated measures analysis of variance

s – Seconds

SF – Stride frequency

SF – Steve Finlayson

T_c – Contact time

T_f – Flight time

TRA – Tibial resultant acceleration

US – United States

v – Velocity

VAS – Visual analogue scale

VP4 – Nike Vaporfly 4%

y – Years

ΔL – Peak displacement of the leg spring

Δy_c – Modelled centre of mass displacement

Thesis Overview

The primary objective of this thesis was to compare the running biomechanics, subjective measures, and perceptions of recreational runners running outdoors in three different shoes: the Nike Vaporfly 4% (the original shoe with advanced footwear technology), the Saucony Endorphin Racer 2 (a minimalist, lightweight racing flat), and their habitual running shoes. The thesis comprises four chapters, as depicted in Figure 1.

Chapter One provides an overview of the current literature on minimalist shoes, shoes with advanced footwear technology, and footwear comfort in running footwear. Chapter Two presents an experimental study investigating the biomechanical and subjective measures of runners in the three shoe types. The results are presented in an article format suitable for publication. Chapter Three, also an experimental study, focuses on the perceptions of the three shoes, examining factors such as purchasing decisions, comfort, performance, and injury. Chapter Four summarises the thesis, highlighting the practical implications derived from the research and suggesting potential avenues for future investigation.

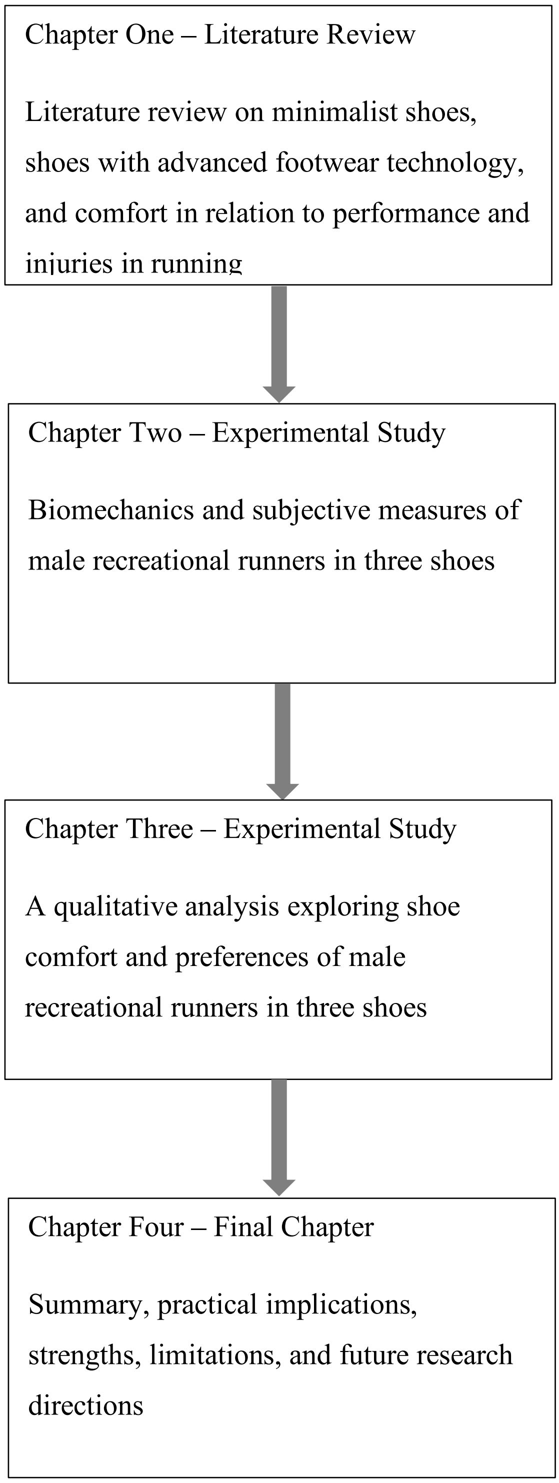

Figure 1. Flow diagram of thesis structure

Chapter One – Literature Review

Literature review on minimalist shoes, shoes with advanced footwear technology, and comfort in relation to performance and injuries in running

Introduction

The footwear purchasing preferences of runners can vary based on whether individuals prioritise comfort, performance, or the reduction of injury risk. Some runners may also seek a more barefoot-like experience or extreme footwear cushioning. The variation in footwear preferences and the increase in running as a form of physical activity drive the athletic footwear market, estimated to be worth $127.3 US billion in 2021 and expected to grow over the next ten years (Grandview-Research, 2022). Given the market value and growth of athletic footwear, manufacturers such as Nike and Saucony have invested many resources into developing footwear that has the potential to maximise comfort, aid runners' performance, and lower injury incidence. Over the last 50 years, footwear and footwear technology used for running has considerably evolved alongside the popularity for the sport (Bermon, 2021). Before the 1980s, only simple mechanical tests were carried out to optimise the midsole material of shoes. In more recent years, the interaction between runners and shoes and the effect of shoes on running economy and biomechanics are now recognised as crucial aspects to consider during running footwear development (Dinato et al., 2015) , not only the mechanical properties of the midsole.

History of running shoes

The development of running shoes dates to the early 1900s when running shoes were constructed with leather and had little cushioning. The primary purpose of shoes was to protect the sole from the external environment (Altman & Davis, 2012a). In the early 1900s, running shoes were a rare commodity because they were expensive, and people did not prioritise leisure-time exercise. From the 1920s to 1940s, brothers Rudolph and Adi Dassler began developing sports shoes. Eventually, they opened rival shops, now known as Adidas and Puma, which were the first to specialise in track and field footwear (Little, 2021). At this time, most top runners competed in cross country or track events, so shoes with spikes were in greater demand. In the 1960s, Bill Bowerman and Phil Knight started selling shoes with a sponge rubber midsole to offer cushioning for road running: The first of its kind. The pair then launched Nike in 1964, coinciding with athletic footwear gaining popularity in the general population. Following Bowerman and Knight's progression, in 1975, Brooks produced a shoe made from ethylene-vinyl acetate (EVA). EVA was lighter and more cushioned than the rubber midsole used in Nike footwear, but EVA was less durable. Over the next 20 years, as running shoes continued to gain popularity, companies added various features to shoes that could be marketed to target populations. Some of these features included a waffle-like sole pattern to increase traction, and pronation-controlling heel cups and arch supports as motion control features to presumably decrease injury risk. The characteristics of these shoes are now known as a traditional, conventional, or modern-day running shoe. Indeed, the traditional running shoe is typically characterised by a moderate amount of cushioning, stack height between 20 and 30 mm, heel-to-toe drop between 8-14 mm, and presence of motion control technologies (Hébert-Losier et al., 2022). These type of shoes were almost the exclusive type of road running footwear on the market until the early 2000s when barefoot running and minimalist shoes gained popularity (Hryvniak et al., 2014). The minimal shoe running popularity appeared to taper off a few years later, with most runners still tending to wear variations of a more traditional running shoe (Pollard et al., 2018). In the 2010s, maximalist shoes – characterised by their thick midsole cushioning and minimal heel to toe drop – increased in popularity (Pollard et al., 2018). From 2017 onward, shoes with advanced footwear technology (AFT) (Frederick, 2022) started to appear on the market and revolutionised the competitive scene (Antoine et al., 2022). These key dates are summarised in Figure 2. This Thesis focused on traditional, minimal, and AFT shoes, with their average shoe characteristics noted in Figure 3.

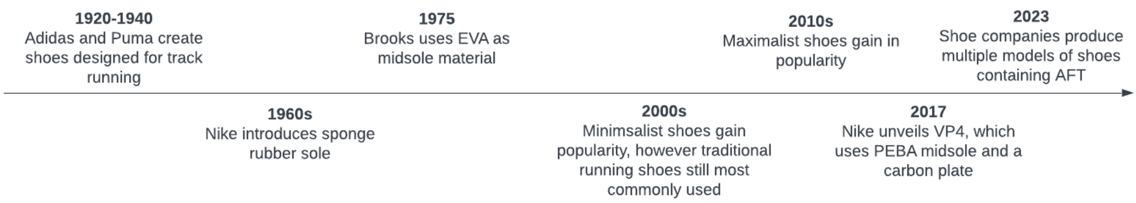

Figure 2. A brief timeline of running shoe development and popularity. *Abbreviations*; AFT, advanced footwear technology; EVA, ethylene-vinyl acetate; PEBA, polyamide block elastomer foam; VP4, Vaporfly 4%;

Figure 3. Summary of characteristics of traditional, advanced footwear technology (AFT), and minimalist shoes for men sourced from the literature (Coetzee et al., 2018; Esculier et al., 2015; Hébert-Losier et al., 2022; Hébert-Losier & Pamment, 2023; Joubert & Jones, 2022; Lodolo, 2011).

Minimalist shoes

Minimalist shoes are defined as "footwear providing minimal interference with the natural movement of the foot due to its high flexibility; low heel-to-toe drop, weight, and stack height; and the absence of motion control and stability devices" (Esculier et al., 2015). The concept behind minimalist shoes is similar to that of original shoes, which aimed to mainly protect the foot from the external environment (Ravilious, 2010) and mimicked being barefoot. Although minimalist shoes increase the loads at the foot and ankle compared to traditional running shoes (Bermon, 2021), they are proposed to prevent common running-related injuries, particularly at the knee (Bermon, 2021), and are perceived as “closer to nature” (Davis, 2014). A lack of cushioning promotes a forefoot strike pattern, which in turn has been proposed to decrease impact peak and loading rates of the vertical ground reaction forces (Rice et al., 2016), thus presumably decreasing injury rates. However, the claims that impacts are related to running-related injury overall lack substantiation (Gruber, 2023). Nonetheless, a gradual transition period is required when changing from a more traditional to a more minimalist shoe due to different structures being loaded (Altman & Davis, 2012a). In fact, the lack of forefoot cushioning and shift towards a forefoot strike may cause higher peak pressure on the forefoot and, in turn, increase the chance of metatarsophalangeal joint stress fractures in runners (Bergstra et al., 2015). When runners first use minimal shoes, running can feel different and perceived as positively or negatively affecting comfort and performance. It can take some time before runners feel comfortable in new footwear (Ramsey et al., 2022).

Minimalist shoes and performance

While the potential injury prevention benefits of a minimalist shoe may not be definitive (Rothschild, 2012), one aspect is clear: the weight of the shoe matters for performance. The lighter weight of minimal shoes compared to traditional shoes generally reduces oxygen consumption and energy cost, offering performance benefits to runners. In fact, Frederick (1984) found that for every 100 g of mass added to a shoe, the oxygen uptake of runners increased by 1%. Franz et al. (2012) observed similar increases in oxygen uptake when adding extra mass to shoes via lead strips. A strength of the study from Franz et al. (2012) was that the strips were added in a way that did not change the weight distribution of the shoe. These two studies (Franz et al., 2012; Frederick, 1984), however, were acute interventions and failed to capture the training effects of minimal shoe running and other aspects of footwear important to runners other than performance, such as injury prevention and comfort. In a training study, Fuller et al. (2017) found that experienced runners using minimalist shoes improved their 5 km time-trial performance (*small* effect size) and running economy (*moderate* effect size) over a 6-week training block, with these improvements being larger than conventional shoes. No adverse events were reported from minimal shoe running.

Overall, the possible performance gains from wearing lighter and more minimal shoes meant companies designed lighter racing shoes from the early 2000s to 2017 (Ruiz-Alias et al., 2023). The racing shoes still contained some cushioning given research showing a reduced metabolic cost in running with some compared to no cushioning at all (Tung et al., 2014). However, too much cushioning increases the mass of the shoe that can increase oxygen consumption and be detrimental to performance. This phenomenon is known as the cost of cushioning (Clarke et al., 1983).

Minimalist shoes and injuries

Minimalist shoes are proposed to potentially prevent common running injuries as they are "closer to nature" (Davis, 2014), with the caveat that the design of these shoes increases loading at the foot and ankle albeit reducing the loads at the knees (Bermon, 2021). However, a decrease in injury incidence running in minimal shoes has not been substantiated experimentally (Ryan et al., 2014). In fact, in one study, the risk of injury was greater in runners wearing a partial or fully minimalist shoe compared to runners wearing a neutral shoe (Ryan et al., 2014). If a gradual approach to initiate use of minimalist shoes is not taken, runners can be at an increased risk of certain types of injuries and pain, including Achilles tendinopathies, metatarsal stress reactions, and shin and calf pain (Cauthon et al., 2013; Ryan et al., 2014).

Shoes with advanced footwear technology

In 2017, Nike introduced a new racing shoe to the market containing novel technologies that revolutionised the design of performance running shoes. Specifically, Nike released the Vaporfly 4% (VP4) based on a prototype shoe worn by Eliud Kipchoge as part of a campaign aiming to break the 2-hour barrier to run the marathon distance. The VP4 has been called "the shoe that broke running" (Tucker, 2020) due to clear performance gains and has led to a new generation of racing shoes. The VP4 shoe contained multiple novel advanced footwear technology (AFT) (Frederick, 2022) features, ultimately reducing oxygen consumption and energy cost of running. Shoes containing AFT, like the VP4, typically have a thicker midsole than traditional shoes. This midsole is constructed from polyether block amide (PEBA) elastomer foam, which is lighter than EVA, allowing for a thicker midsole with negligible increase in shoe mass. Additionally, the PEBA is more resilient and returns more of the energy stored compared to the previously used EVA (Geoffrey & Nicholas, 2020). A stiff plate (e.g., made from carbon fibre) embedded in the midsole increases longitudinal bending stiffness, and it is usually curved to act as a fulcrum (Nigg et al., 2021), resulting in a shorter propulsive phase (Flores et al., 2021). The increased stiffness is proposed to reduce the energetic cost by minimising metatarsophalangeal dorsiflexion and the amount of mechanical energy lost at these joints (Venturini & Giallauria, 2022). The increased bending stiffness also lowers plantarflexion velocities (Hoogkamer et al., 2019; Ortega et al., 2021), indicative of slower triceps surae muscle shortening velocities that are less metabolically demanding. From a biomechanical perspective, shoes with AFT have been associated with longer flight times, lower ankle ranges of motion, increased vertical displacement, and lower cadences (Barnes & Kilding, 2019).

Shoes with advanced footwear technology and performance

The increased longitudinal bending stiffness from AFT has the potential to improve running economy by 2.2% compared to a control shoe with less bending stiffness (Rodrigo-Carranza et al., 2022). The 2.2% improvement in running economy is estimated to translate to an 1% improvement in performance over a marathon event (Rodrigo-Carranza et al., 2022). However, there is debate regarding to which extent the various AFT technologies contribute to the improved running economy, with no one feature in isolation contributing to the performance enhancements (Frederick, 2020). The VP4 has been found to reduce energy costs by an average of 4.3% in high-calibre (Hoogkamer et al., 2018) and 4.2% in recreational (Hébert-Losier et al., 2022) runners, resulting in an 2% improvement in a 3 km time-trial performance (Hébert-Losier et al., 2022; Hoogkamer et al., 2018). However individual responses are noted, particularly in recreational runners. Hebert-Losier et al. (2022) observed up to 13.3% reductions in oxygen consumption (positive responders), indicating an improved running economy, when running in VP4 compared to runners' habitual shoes. However, the oxygen consumption increased by 8.6% in some runners (negative responders), indicating a worsening of running economy in VP4 compared to their own shoes. There is currently no means of predicting responders from non-responders to shoes with AFT, with the individualised responses potentially due to several factors. A possible mediator is the foot-strike pattern of runners, as data indicate that non-rear foot-strikers respond less positively to shoes with AFT (Hébert-Losier et al., 2022). However, further investigations are needed to understand the potential causes behind these individual responses to acute footwear changes. In response to the technological advancements and trending improved performances, the International Amateur Athletics Federation (World Athletics governing body) introduced a rule stating that the midsole of running shoes worn in road running competition cannot exceed 40 mm to limit the advantage an athlete can gain from a greater midsole. While minimalist and traditional shoes are still in use, shoes with AFT have gained significant attention and interest among runners, especially for those competing in road running events. Anecdotally, wearing shoes with AFT is no longer seen as an advantage; instead, not wearing them is seen as a disadvantage in competitive runners (Metzler, 2019).

Shoes with advanced footwear technology and injuries

The design, construction, and material of shoes with AFT are aimed to improve performance and differ from minimal and traditional shoes. The potential to aid performance may appeal to recreational runners with performance goals in mind (Tenforde et al., 2023; Warne & Gruber, 2017). The impact of footwear on running biomechanics is an important consideration, as the preferred movement paradigm suggests that runners tend to maintain their movement patterns regardless of the type of footwear they wear (Nigg et al., 2017). However, when it comes to shoes with extreme features like minimalist shoes and shoes with AFT, footwear is expected to result in different running biomechanics due to their unique characteristics that deviate from the preferred movement path and possibly load different structures. There have been concerns raised regarding the rapid uptake of AFT and potential for injury (Hébert-Losier & Pamment, 2023). Of particular concern is the stack height and associated amount of cushioning in these shoes, which can compromise frontal plane stability. Consequently, there is a perceived risk of injury associated to this stack height and cushioning, including ankle sprains due to rolling ankles, with tight turns and corners during racing events (Hoogkamer, 2020). Tenforde et al. (2023) recently documented a case series of navicular bone stress injuries potentially caused by AFT shoes, which are concerning as these stress injuries have poor prognostics. A gradual transition is advised to shoes with AFT, although the adaptation period to these shoes is relatively unknown and likely to be individual-specific, like that of minimalist shoes (Fife et al., 2023).

Comfort

Comfort is important in running shoe selection (Dhillon et al., 2020). Footwear comfort has been linked to performance enhancements (Luo et al., 2009) and potentially minimising injury risk (Nigg et al., 2015). Comfort is multifaceted, and individuals value different factors during footwear selection, including shoe cushioning, fit, flexibility, stability, and shape (Ramsey et al., 2022; Tay et al., 2017). Individual preference and comfort was evident in a study that examined runners' vibration decay and pain responses to mechanical and pressure stimuli (Mills et al., 2018). Runners ran outdoors in different shoes, and those who tended to feel more pain in their heel and midfoot were more likely to prefer a more cushioned than minimalist shoe (Mills et al., 2018). In another study (Tay et al., 2017), participants rated their comfort levels for different shoe properties using visual analogue scales (VAS). The VAS score ratings demonstrated considerable variability, reiterating the individual nature of comfort and that no shoe suits all (Tay et al., 2017).

Comfort and performance

Comfort has been associated with improved running economy (Fuller et al., 2015; Van Alsenoy et al., 2023) and is critical for recreational runners when choosing footwear(Ramsey et al., 2022). Trying novel running footwear can benefit runners and help them find the most comfortable shoe that is best suited to their needs. There is a range of shoes available to runners, with considerable differences between minimalist, AFT, and traditional shoes that can ultimately affect comfort levels; and by extension, performance and presumably injury risk. When running on a treadmill, recreational runners are reported to find their habitual running shoes more comfortable than novel minimalist and shoes with ATF. However, their running economy was on average poorer in their own shoes. This discrepancy in the lack of association between comfort and economy might be due to runners wearing their own shoes compared to a standardised one, and the fact that they were familiar with their own shoes (i.e., enhanced comfort) that were heavier (i.e., decreased economy) than the two experimental shoes (Frederick, 1984; Hébert-Losier et al., 2022). Hence, when all shoes tested by runners are novel, the most comfortable shoe is on average has a 0.7% running economy compared to the least comfortable shoe (Luo et al., 2009). To date, there is limited research in the area of footwear comfort in recreational runners wearing shoes with AFT, with most studies performed in laboratories rather than outdoors.

Comfort and injuries

Enhanced footwear comfort has been proposed to minimise injury risk in runners (Nigg et al., 2015). There is very little research available to guide the transition to minimalist shoes (Warne & Gruber, 2017), maximalist shoes (Pollard et al., 2018), and shoes with AFT (Tenforde et al., 2023) from traditional running shoes. Furthermore, the time required for a runner to adapt and feel comfortable in new footwear is relatively unknown and likely individualised (Ramsey et al., 2022). A Bayesian approach has been suggested as a possible way of quantifying the adaption period (Koska & Maiwald, 2020). Other proposed theories linking comfort to injuries include the comfort filter paradigm that suggests runners select shoes that are the most comfortable, which will automatically reduce their injury risk (Nigg et al., 2015); however, there is an absence of evidence to support this theory (Agresta et al., 2022).

Comfort measures

Quantitative

Comfort can be assessed in various ways. Commonly used methods of assessing comfort include ranking shoes (Lindorfer et al., 2020) from most to least preferred, VAS to assess overall comfort (Mundermann et al., 2002), VAS to evaluate specific aspects of the shoes (Sterzing et al., 2013), and considering runners' overall running experience (Davis et al., 2008). The Running Shoe Comfort Assessment Tool (RUN-CAT) was recently developed as an objective measure of footwear comfort after running a distance of 1.1 km (Bishop et al., 2020). The tool uses four VAS that the runner scores to indicate their perceived comfort levels for heel cushioning, forefoot cushioning, forefoot flexibility, and stability. The four VAS scores are weighted and scaled (in the following order: forefoot cushioning, stability, flexibility, and heel cushioning), with an overall score of 0 representing the least comfortable and 100 representing the most comfortable shoe. The tool has been shown valid and reliable (Bishop et al., 2020), and offers an alternative to shoe rankings and overall comfort VAS that considers the footwear properties themselves.

Qualitative

Qualitative approaches, such as interviews, offer valuable insights for understanding runners' subjective experiences and perceptions of comfort. Previous research (Ramsey et al., 2022) has used this approach to investigate running footwear comfort. The rich data gathered from qualitative approaches highlighted how footwear comfort was associated with different factors for different people. For example, some runners associated comfort with a brand or model. In contrast, for other runners, comfort was related to specific shoe properties, such as the shape and cushioning of the shoe. This study also found that runners required different adjustment times before being comfortable in a shoe (Ramsey et al., 2022). Some runners required virtually no time at all, while others took up to a month to become comfortable (Ramsey et al., 2022). A qualitative approach was also used to investigate the perceptions of minimalist shoes, revealing that some individuals viewed them as extreme whereas others perceived them as being more natural (Walton & French, 2016). The thematic analysis showed that some people saw the benefits of running closer to barefoot. However, others tended to see minimalist shoes as an extreme and relied on their past experiences where shoes were more 'supportive' (Walton & French, 2016). At this time, there is limited research investigating runners' perceptions of shoes with AFT using a qualitative approach despite anecdotal reports of feeling like the shoes are "springy" or people are "running on clouds".

Other factors influencing comfort

Other than footwear-related features, the intended speed, environment, and activity can also affect a runner's perception of footwear comfort. Most running-related studies are conducted in laboratory settings using a treadmill. Although treadmill running biomechanics are largely the same to running outdoors on a solid surface (Van Hooren et al., 2020), biomechanical differences in running gait between treadmill and outdoor are possible due to various factors, such as previous experience running on a treadmill, surface stiffness, and shoe characteristics (Van Hooren et al., 2020). For instance, one study reported that overground and treadmill running significantly affected running patterns and ground reaction forces when evaluating the effect of shoe heel-to-toe drop (Chambon et al., 2015). Shoes with AFT are designed for racing in outdoor environments (Hoogkamer et al., 2018), where runners face different terrains, including corners. Therefore, it is important to trial shoes at multiple speeds, including faster speeds, to simulate racing and outdoor environments to ensure ecological validity of findings. There is a relative lack of footwear studies conducted in a real-world environment, limiting ecologically validity.

Summary

To summarise, the running shoe industry has witnessed significant growth and innovation over the last century to meet runners' priorities of comfort, performance enhancement, and injury prevention. While minimalist shoes have gained attention for their perceived potential to prevent injuries and improve running economy, the introduction of AFT shoes has sparked debate due to their significant impact on performance. Individual responses to AFT shoes vary, emphasising the need for further research to understand the underlying factors that influence these variations. Comfort, a multifaceted aspect of running shoes, plays a critical role in shoe selection for runners. Objective tools (e.g., VAS and the RUN-CAT) and qualitative approaches (e.g., interviews) provide valuable insights into runners' perceptions and experiences of comfort. As the industry continues to evolve, understanding the complex nature between comfort, performance, and injury prevention will be essential in developing future advancements in athletic footwear to meet runners' needs.

Research statement

This thesis aims to provide a quantitative (Chapter 2) and qualitative (Chapter 3) assessment of runners wearing VP4, minimal shoes, and their habitual shoes in an outdoor environment. The thesis aimed to compare biomechanical and subjective measures between shoes, and explore possible correlations between comfort measures, and biomechanical and subjective measures.

Chapter Two – Experimental Study

Biomechanics and subjective measures of male recreational runners in three shoes

Abstract

Aim: We aimed to compare biomechanical and subjective data from runners running outdoors in: habitual shoes (OWN), Saucony Endorphin Racer 2 minimalist racing flats (FLAT), and the Nike Vaporfly 4% (VP4). We also conducted an exploratory analysis of potential relationships between comfort measures and the collected data. ***Methods:*** Eighteen male recreational runners ran three 1.5 km trials, once in each shoe outdoors. The first 1.1 km was run at a self-selected comfortable (slower) speed, and the last 400 m at runners perceived 5-km race pace (faster). A GPS-enabled smartwatch, 15-m Optojump modular system, high-speed camera, and tibial accelerometer were used to collect biomechanical data. Subjective measures on comfort, shoe properties, and overall running experience were collected using visual analogue scales (VAS) and rankings. Repeated measures ANOVA, post-hoc t-tests, and effect sizes (ES) were used to identify and quantify differences between shoes; Friedman and post-hoc Goodness-of-Fit tests to analyse rank data; and repeated-measures correlations to explore potential relationships between comfort measures and the collected data. ***Results:*** Cadence, leg stiffness, and vertical stiffness were higher in FLAT than both OWN and VP4 at the slower speed (*trivial* to *small* ES). At both speeds, foot-strike angles were smaller in FLAT (*small* to *large* ES), while propulsion phase was shorter in VP4 (*moderate* to *large* ES). FLAT was ranked as the least comfortable at the slower speed and most likely to cause injury, whereas OWN was ranked as the most comfortable and least likely to cause injury. Comfort was not significantly different at the faster speed. Comfort measures were more strongly correlated with subjective than biomechanical measures. ***Discussion:*** The two novel shoes generally had non-significant or *small* effects on biomechanics of runners versus their own shoes. As VP4 are more like traditional than minimal running shoes, these were perceived as most comfortable and may require a shorter transition period, although caution is still advised. Running speed appeared to interact with subjective measures that should be considered when prescribing shoes.

Key words

Comfort, minimalist shoes, running, advanced footwear technology, super shoes

Introduction

Recreational runners comprise the majority of the running community (Besomi et al., 2018), with comfort, performance, and injury prevention considerations motivating their shoe choice (Dhillon et al., 2020). Minimalist shoes are defined as "footwear providing minimal interference with the natural movement of the foot due to its high flexibility, low heel to toe drop, weight and stack height, and the absence of motion control and stability devices" (Vincent & Vincent, 2020). The concept behind minimalist shoes is to mimic barefoot running whilst protecting the sole from the external environment. Minimalist shoes are proposed to potentially prevent common running injuries as they are "closer to nature" (Davis, 2014), with the caveat that the design of these shoes increases loading at the foot and ankle albeit reducing the loads at the knees (Bermon, 2021) . Indeed, running biomechanics in minimal shoes differs to conventional shoes and typically results in a lower foot strike angle and higher cadence (Barcellona et al., 2017). Furthermore, the lighter mass of these shoes overall decreases oxygen consumption (Fuller et al., 2015) with potential performance benefits. Racing shoes are typically lighter in nature for this reason. Therefore, minimal shoes might appeal to recreational runners from an injury prevention and performance perspective.

At the opposite end of the spectrum, technologically advanced shoes have become popular since 2017 when Nike released the Vaporfly 4% (VP4). The VP4 contained novel technologies claiming to return energy and ultimately reduce oxygen consumption and energetic cost while running; these developments led to the emergence of shoes containing advanced footwear technology (AFT) (Frederick, 2022), also known as "super shoes". Although there is no consensus definition (Hébert-Losier & Pamment, 2023), shoes with AFT typically contain a thicker midsole than previous racing shoes that is constructed of polyamide block elastomer foam (PEBA) instead of the traditionally used ethylene-vinyl acetate (EVA) (Geoffrey & Nicholas, 2020). PEBA contains greater energy-return properties than EVA (Bermon, 2021; Muniz-Pardos et al., 2022) and is lighter, meaning it is possible to have a thicker midsole with a negligible increase in shoe mass. A curved stiff plate is integrated into the midsole of shoes with AFT, which increases its longitudinal bending stiffness (Geoffrey & Nicholas, 2020) and is proposed to reduce the energetic cost of running via reductions in the mechanical energy lost at the metatarsophalangeal joints (Venturini & Giallauria, 2022) and plantarflexion velocities (Hoogkamer et al., 2019; Ortega et al., 2021). Although the VP4, on average, reduces energy cost by 4% in high-calibre (Hoogkamer et al., 2018) and recreational runners (Hébert-Losier et al., 2022), individual responses are noted, particularly in recreational runners (Hébert-Losier et al., 2022). Running in the VP4 has also been associated with longer flight times, lower ankle range of motion, and lower cadences (Barnes & Smith, 1994; Hébert-Losier et al., 2022) that could increase knee loading. A recent paper found that the running economy benefits of shoes with AFT were lower at slower speeds (Joubert et al., 2023), suggesting that slower runners may benefit less from shoes with AFT. Nonetheless, the potential performance benefits of shoes with AFT may appeal to recreational runners, particularly those with racing or performance goals. Shoes with AFT are more similar to conventional shoes than minimal ones in several regards (e.g., heel-to-toe drop, minimalist index rating) (Hébert-Losier et al., 2022), and could be an easier and more comfortable option for runners seeking performance enhancements than minimal shoes.

Comfort is a key factor for runners when purchasing shoes (Dhillon et al., 2020), with many aspects influencing shoe comfort (Menz & Bonanno, 2021). Shoe features can affect shoe comfort ratings, with forefoot and heel cushioning, shoe stability, and forefoot flexibility found to play an important role in overall running shoe comfort assessment (Bishop et al., 2020). The comfort filter paradigm suggests that runners select shoes that are the most comfortable and doing so automatically reduces their injury risk (Nigg et al., 2015), despite the absence of evidence to support this theory (Agresta et al., 2022). Overall, the factors contributing to comfort in recreational runners remains largely unexplored and primarily based in laboratories (Fife et al., 2023). There are limited studies assessing shoe comfort running outdoors in a more ecologically valid environment.

Therefore, our aims were to compare biomechanical and subjective measures of male recreational runners running outdoors in three different shoes: Nike Vaporfly 4% (VP4), the original shoe with AFT; Saucony Endorphin Racer 2, a minimalist lightweight racing flat (FLAT); and runners' habitual running shoes (OWN). The testing was planned at two different speeds given that VP4 and FLAT are designed for racing. A secondary aim was to examine possible relationships between comfort measures and the collected data (subjective and biomechanical) using exploratory analysis.

Materials and methods

Sample size

Sample size calculations were based on prior work identifying a moderate effect size difference ($f = 0.29$) in baseline visual analogue scale (VAS) comfort between VP4 and FLAT (Hébert-Losier et al., 2022). A minimal sample size of 17 runners was required to detect this effect size difference in comfort between shoes accounting for three repeated measures (assuming 0.60 correlation and sphericity) using repeated measures ANOVA (within factors) at a 5% significance level and 80% power based on G*Power 3.1.9.7 computations.

Participants

Eighteen male recreational runners participated (Table 1). To be included, runners needed to be free from injury for at least three months, run regularly (minimum once per week) for at least six months, and have a personal best 5 km time between 20 to 30 minutes in the past year (Hébert-Losier et al., 2022; Honert et al., 2020). Participants signed an informed consent document that outlined the benefits and risks involved with the study (e.g., delayed onset muscle soreness or injury due to running in unfamiliar shoes). The Human Research Ethics Committee [HREC(Health)2020#83] approved the experiment, which adhered to the Declaration of Helsinki.

Table 1. Characteristics of participants (n = 18). Data are mean ± standard deviation.

Characteristics	Males
Age (y)	31.2 ± 10.5
Height (cm)	180.2 ± 6.0
Mass (kg)	81.6 ± 10.0
Leg length (mm) †	912.1 ± 39.8
Running experience (years)	11.2 ± 8.1
5 km personal best time (min)	23.1 ± 2.1
Weekly training (km)	20.0 ± 12
Own shoe size (US sizing)	10.6 ± 1.0

†Greater trochanter to ground distance in a standing position barefoot.

Table 2. Shoe characteristics of shoes worn by participants (n = 18). Data are mean ± standard deviation.

Characteristics	OWN	FLAT	VP4
Mass (g)	308 ± 42	153 ± 8 $^{O, V}$	211 ± 12 $^{O, F}$
Stack height (mm)	24.6 ± 7.2	13.0 ± 0 $^{O, V}$	31.0 ± 0 ^{F}
Heel-to-toe drop (mm)	11.2± 5.7 ^{F}	1.0 ± 0 $^{O, V}$	7.0 ± 0 ^{F}
Minimalist index (%)†	28 ± 15	88 ± 0 $^{O, V}$	48 ± 0 ^{F}
Price (NZD)	156 ± 49 ^{N}	190 ± 0	380 ± 0 $^{O, F}$

Notes. Data from right shoes only (size: US 8.5 to 12). $^{O, F, V}$ Significant difference during post-hoc paired t-test comparisons ($p \leq 0.05$) vs OWN, FLAT, and VP4, respectively. †Minimalist index range: 0% (lowest) to 100% (highest) degree of minimalism. *Abbreviations.* FLAT, Saucony Endorphin Racer 2 road racing flat. OWN, runners own habitual running shoes. VP4, Nike Vaporfly 4%.

Protocol

A randomised crossover study design was used to investigate the effect of shoe on biomechanical and subjective outcomes (Figure 4). Participants attended one 90-minute session that involved running 1.5 km in three shoes: OWN, own habitual running shoe; FLAT, Saucony Endorphin Racer 2 racing flat; and VP4, Nike Vaporfly 4% (Table 2). Participants selected their OWN shoes knowing they were required to run 1.5 km outside on asphalt at a comfortable and 5 km race or tempo pace. All participants were rearfoot strikers in their own shoes except for one who was a midfoot striker based on foot strike angles (Altman & Davis, 2012b).

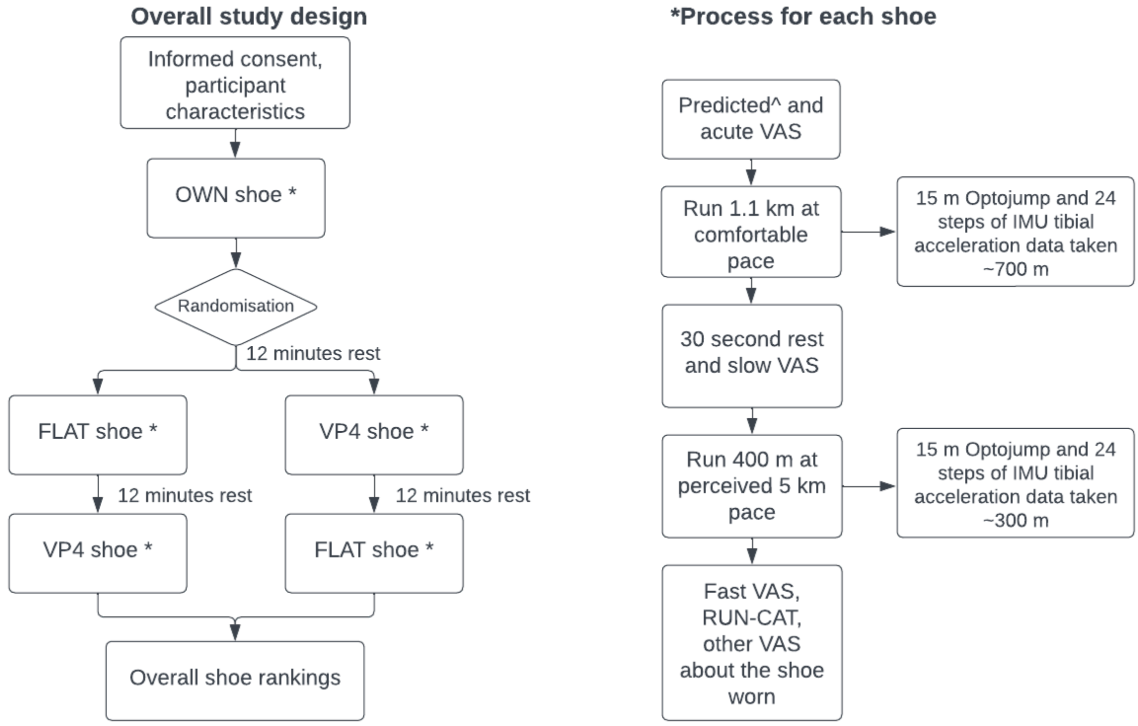

Figure 4. Overall study design (left diagram) and experimental process for each shoe (right diagram). ^FLAT and VP4 only. *Abbreviations.* FLAT, Saucony Endorphin Racer 2 racing flat. IMU, inertial measurement unit. OWN, own habitual running shoe. RUN-CAT, running

After providing informed consent, the characteristics of participants (age, height, mass, leg length, running experience, and training level) and OWN shoes (size, mass, cost, heel height, forefoot height, heel-to-toe drop, and reasons for purchasing their shoe) were recorded. Participants trialled the various available sizes of the two experimental shoes to ensure proper fit. The minimalist index of all shoes worn as part of the study was calculated using a valid and reliable tool (Esculier et al., 2015), where 100% represents the highest degree of minimalism and 0% the lowest. Of note, the experimental shoes were spray-painted black to obscure their brand and model and minimise their potential to influence subjective measurements.

All running trials were conducted outside around a flat concrete 740 m loop. Participants were first required to run 1.1 km at a self-selected comfortable pace sustainable for 30 minutes (~1.5 loops). After a 30 s standing rest, participants ran 400 m at a faster pace as if they were doing a tempo run or 5 km race. The 1.1 km distance was chosen to measure the running shoe comfort assessment tool (RUN-CAT) (Bishop et al., 2020). A faster speed was also examined, given that the VP4 and FLAT shoes are designed for racing. Participants ran the first of the three running trials in their OWN shoes to act as baseline, followed by the VP4 and FLAT in a random order (Figure 4).

Data collection

Biomechanical measures

During the experimental trials, participants wore a Garmin 245 Music watch (Garmin Ltd., Olathe, Kansas) that monitored their 1.1 km and 400 m running times and notified them when to start and stop running. Participants ran through 15 m of an optical measurement system (Optojump modular system, Microgate, Bolzano, Italy) 700 m into the 1.1 km trial and 300 m into the 400 m trial. The Optojump measured speed (m/s), cadence (steps per minute), step length (cm), flight time (ms), contact time (ms), and propulsive phase (%) at a sampling rate of 1000 Hz, where propulsive phase represents the time from heel lifting to toe-off as a percentage of contact time. A levelled iPad Pro 11 sampling at 240 frames per second was positioned on a 30 cm stand 5 meters to the left-hand side of participants in the middle of the 15-m Optojump. Videos were used to extract foot strike angle (°) using SiliconCoach Live (The Tarn Group, Dunedin, NZ) video analysis software. In addition, participants wore two IMeasureU blue trident inertial measurement units (Vicon Motion Systems Ltd., Oxford, UK) to capture tibial acceleration (Van den Berghe et al., 2019). The units were placed on the medial tibia just above the medial malleolus and secured using the manufacturer's straps and athletic tape. Each unit has a tri-axial accelerometer with a range of ± 200 g and 1600 Hz sampling rate.

Subjective measures

A range of subjective measures were collected pre- and post-running trials, which included a range of 0-100 mm visual analogue scales (supplementary material). All comfort VAS endpoints were "Not comfortable at all" and "Most comfortable imaginable". Before putting on the VP4 and FLAT shoes, participants completed a VAS (predicted VAS) on how comfortable they thought the shoes would be based on observing and holding them. For the three shoes, participants completed a pre-run, slow-run, and fast-run VAS. The pre-run VAS was completed before the running trials with participants wearing the shoes and permitted to walk and jog around as they would if selecting a shoe in store (acute VAS). The slow-run and fast-run VAS were completed immediately after the 1.1 km and 400 m trials, respectively. After the 1.5 km trials, participants completed a series of other VAS measures to rate their perceptions of the shoe properties and overall running experience (**Appendix two - supplementary material**). The midpoint of the VAS for shoe properties reflected ideal, and included heel cushioning, forefoot cushioning, forefoot flexibility, shoe stability, shoe stiffness, technical features, and shoe weight. Traditional VAS anchor points were used for overall running experience, which included pleasure/displeasure, easiness/hardness, overall performance, and injury risk, where the midpoint reflected a neutral response and endpoints reflected the two extremes. Participants then had a one-on-one interview to attain their feelings on each shoe.

At the end of the three running trials, participants were asked to rank the three shoes based on comfort (most to least), performance (best to worst), and injury risk (lowest to highest). Participants were also asked if they knew the make and model of the experimental shoes.

Data processing

Biomechanical measures

The 15-m Optojump data were averaged across recorded steps. Vertical stiffness (k_{vert}) and leg stiffness (k_{leg}) in kN/m were modelled using the spatiotemporal data from the Optojump and leg length measurements using the following equations (Morin et al., 2005):

$$k_{vert} = F_{max} \times \Delta y_c{}^{-1}$$

$$k_{leg} = F_{max} \times \Delta L^{-1}$$

$$F_{max} = mg \times \frac{\pi}{2} \times (\frac{t_f}{t_c} + 1)$$

$$\Delta y_c = \frac{F_{max} \times t_c^2}{m \times \pi^2} + g\frac{t_c^2}{8}$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y_c$$

where m is the mass of participants, g is gravitational acceleration constant (9.81 m/s^2), t_f is flight time (s), t_c is contact time (s), F_{max} is the modelled maximal force, Δy_c is the modelled centre of mass displacement, ΔL is the peak displacement of the leg spring, L is leg length (greater trochanter to ground distance in a standing position barefoot), and v is running speed (m/s).

The duty factor (*DF*) was also calculated using the Optojump metrics using the following calculations (Alexander & Jayes, 1980; Minetti, 1998).

$$DF = \frac{SF \times t_c}{2} \times 100\%$$

$$SF = 1/(\frac{1}{t_f + t_c})$$

where *SF* is stride frequency.

The raw IMU data was filtered using a double-pass fourth order 60 Hz Butterworth filter (Johnson et al., 2020) applied using RStudio® (version 2022.12.0+353) with R (version 4.2.22). The resultant tibial acceleration was then calculated as $\sqrt{(x^2 + y^2 + z^2)}$. Ten seconds of data were averaged (25 to 35 steps per participant) to provide a resultant tibial acceleration measure in vicinity to the 15-m Optojump placement (i.e., 700 m into the 1.1 km trial and 300 m into the 400 m trial).

Subjective measures

The VAS ratings (0 to 100 mm) were extracted from all VAS scores. The four RUN-CAT related VAS (heel cushioning, forefoot cushioning, flexibility, and stability scores) were used to calculate the RUN-CAT score using the following equation (Bishop et al., 2020):

$$RUN - CAT = ((100 - ABS(50 - Heel\ cushioning) * 2) * 0.175) + ((100 - ABS(50 - Forefoot\ cushioning) * 2) * 0.311) + ((100 - ABS(50 - Flexibility) * 2) * 0.247) + ((100 - ABS(50 - Stability) * 2) * 0.277)$$

where 0 represents the least ideal and 100 the most ideal comfort.

Statistical analysis

R was used to graph, visualise, and explore the data. Repeated measures analysis of variance (RM ANOVA) was used to identify any significant difference in biomechanical and subjective outcomes between shoes, and post-hoc paired t-tests for pairwise comparisons. Effect sizes (ES) for paired samples using an average variance and their 95% confidence intervals (CI) were extracted and defined as *small*, *moderate*, and *large* when reaching 0.20, 0.50, and 0.80, respectively, and *trivial* when less than 0.20 (Cohen, 1992). Effects were deemed *unclear* when the 95% CI overlapped the threshold for small positive (d = 0.20) and small negative (d = -0.20). The Friedman test was used to analyse the ranking data and Goodness-of-Fit in post-hoc tests to determine which rankings significantly differed between shoes. Repeated measures correlation (rmcorr R package) (Bakdash & Marusich, 2017) and 95% CI were used to investigate possible relationships between comfort and biomechanical or subjective measures. Given the exploratory nature of this analysis and number of correlations examined, *moderate* ($|r| \geq 0.30$) and *large* ($|r| \geq 0.50$) correlations reaching statistical significance were deemed to reflect potentially meaningful relationships worth exploring in future research (Cohen, 1992). Significance level was set at $p \leq 0.05$ for all analysis.

Results

Biomechanical measures

Biomechanical measures for each shoe at the two different speeds are reported in Table 3 and ES differences with 95% CI are provided as supplementary material (Table S1). There were no significant differences in speed between shoes, except within the 15-m Optojump section when running at the slower speed. In this 15-m section, runners ran faster in FLAT (ES 0.37, *small*) and VP4 (ES 0.28, *small*) than OWN. The FLAT also demonstrated a greater cadence (OWN ES 0.35, *small*; VP4 ES 0.28, *small*), k_{vert} (OWN ES 0.34, *small*; VP4 ES 0.21, *small*), and k_{leg} (OWN ES 0.19, *trivial*; VP4 ES 0.21, *small*) measures at the slower speed, as well as lower foot strike angles at both speeds than the two other shoes (ES 0.47 to 0.89, *small* to *large*). In addition, FLAT also exhibited a smaller duty factor compared to OWN at the slower speed (ES 0.37, *small*). The only other significant biomechanical difference was seen for the propulsion phase, where VP4 had a significantly shorter propulsion phase at both speeds than OWN and FLAT (ES 0.53 to 1.18, *moderate* to *large*).

Subjective measures

Comfort VAS

Subjective measures for each shoe are reported in Table 4 and ES differences with their 95% CI in the supplementary material (Table S2). FLAT had a lower acute comfort compared with OWN (ES 1.20, *large*) and VP4 (ES 0.77, *moderate*). FLAT also had lower scores for slow speed comfort compared to the two other shoes (OWN ES 1.08, *large*; VP4 ES 0.68, *small*). There were no significant differences between shoes for predicted or fast speed comfort.

Shoe properties VAS

OWN had a significantly higher (more ideal) RUN-CAT than VP4 (ES 0.63, *moderate*) and FLAT (ES 0.95, *large*), with no significant difference detected between the latter. Heel cushioning scores significantly differed between all three shoes (ES 1.22 to 2.60, *large*), with VP4 exhibiting the highest and FLAT the lowest mean score. FLAT had significantly lower forefoot cushioning and weight scores than OWN (ES 0.87 and 1.88, respectively, *large*) and VP4 (ES 1.07 and 0.81, respectively, *large*); whereas VP4 had a significantly lower flexibility score, but higher technical features and stiffness scores than OWN and FLAT (ES 1.23 to 1.66, *large*).

Overall running experience VAS

Runners perceived a lower risk of injury in OWN than VP4 (ES 0.82, *large*) and FLAT (ES 1.27, *large*). No other significant differences were detected.

Rankings

The overall rankings of the shoes are reported in Table 5. Overall, OWN was ranked more frequently as the most comfortable shoe at the slow speed, and FLAT as the least comfortable. Runners also more frequently ranked OWN as the shoe with the perceived lowest injury risk, followed by VP4. FLAT ranked as the shoe with the highest injury risk. There were no other significant differences in rankings.

Exploratory analysis

The findings from the exploratory analysis of repeated measures correlations between the comfort measures and the subjective and biomechanical ones are shown in Table 6 and their CIs in supplementary material (Table S3). Overall, the subjective measures (comfort, shoe properties, and overall running experience) were more often meaningfully correlated (i.e., significant, and *moderate* or *large*) to comfort than the biomechanical metrics. Ratings of pleasure/displeasure were significantly correlated to all comfort measures (r = 0.481 to 0.776), as were perceptions of running difficulty (easier/harder, r = 0.402 to 0.757). Most measures that were meaningfully correlated to acute comfort were also correlated to slow speed comfort, but not necessarily to fast speed comfort. For instance, forefoot and heel cushioning VAS and injury risk VAS were significantly and *moderate* or *largely* related to acute and slow speed comfort (r = 0.478 to 0.637), but not fast speed comfort. RUN-CAT scores were significantly correlated to all three comfort VAS scores, but the most strongly correlated to fast speed comfort (r = 0.720). Performance VAS was meaningfully correlated to fast speed comfort only (r = 0.468)

Table 3. Variables (mean ± standard deviation) collected from the 1.1 km trial at a self-selected comfortable pace (slower) and a 400 m trial at a perceived 5 km pace (faster) ran by participants (n = 18).

Variable	Distance	OWN	FLAT	VP4	RM ANOVA (*p* value)
Overall speed (m/s)	1.1 km	3.57 ± 0.30	3.62 ± 0.35	3.65 ± 0.40	0.447
	400 m	4.18 ± 0.35	4.09 ± 0.36	4.15 ± 0.38	0.071
Optojump measurements					
Speed (m/s)	1.1 km	3.67 ± 0.33 $^{V, F}$	3.80 ± 0.38 ^{O}	3.78 ± 0.42 ^{O}	0.010
	400 m	4.30 ± 0.36	4.29 ± 0.46	4.34 ± 0.40	0.650
Cadence (steps/minute)	1.1 km	168.0 ± 7.5^{F}	171.1 ± 8.8^{O,V}	168.8 ± 8.5^{F}	0.005
	400 m	174.6 ± 8.8	176.2 ± 10.1	174.7 ± 9.1	0.080
Step length (cm)	1.1 km	130.9 ± 12	133 ± 11	129 ± 14	0.101
	400 m	148.1±11.8	146.1±14.4	149.3±12.4	0.301
Flight time (s)	1.1 km	0.093±0.019	0.097 ± 0.017	0.097 ± 0.020	0.133
	400 m	0.109 ± 0.016	0.107 ± 0.020	0.110 ± 0.018	0.415
Contact time (s)	1.1 km	0.265 ± 0.02^{F}	0.254 ± 0.022^{O}	0.259 ± 0.022	0.001
	400 m	0.236 ± 0.018	0.234± 0.022	0.234 ± 0.018	0.650
Propulsive phase (%)	1.1 km	45.3 ± 4.1 ^{V}	46.6 ± 3.7 ^{V}	43.1 ± 3.9 $^{O, F}$	< 0.001
	400 m	45.7 ± 3.5 ^{V}	47.2 ± 4.0^{V}	42.6 ± 3.8 $^{O, F}$	< 0.001

k_{vert} (kN/m)	1.1 km	27.7 ± 3.5 [F]	29.2 ± 4.3 [O,V]	28.3 ± 3.6 [F]	< 0.001
	400 m	31.5 ± 4.1	32.2 ± 4.3	31.9 ± 3.8	0.208
k_{leg} (kN/m)	1.1 km	12.3 ± 2.7 [F]	12.9 ± 2.9 [O, V]	12.4 ± 2.6 [F]	0.019
	400 m	12.8 ± 2.9	13.2 ± 2.8	12.9± 2.8	0.250
Duty factor (%)	1.1 km	37.1±0.03[F]	36.1 ± 0.02[O]	36.4±0.03	0.026
	400 m	34.3±0.02	34.3±0.03	34.0±0.02	0.575
2D camera data					
Foot strike angle (°)	1.1 km	15.6 ± 6.4 [F]	12.4 ± 4.6 [O, V]	15.6 ± 6.2 [F]	0.003
	400 m	15.5 ± 0.4 [F]	12.2 ± 5.5[O, V]	16.9± 5.1 [F]	<0.001
IMU sensor data					
TRA (g) [a]	1.1 km	17.3 ± 3.4	19.0 ± 3.3	18.6 ± 4.2	0.134
	400 m	21.1 ± 4.4	22.2 ± 2.8	20.7± 3.7	0.421

Notes. [F, O, V] Significant difference ($p \leq 0.05$) vs FLAT, OWN, and VP4 during post-hoc comparisons, respectively. Significant differences ($p \leq 0.05$) are in bold. [a] Missing data from 4 participants. *Abbreviations.* 2D, two-dimensional. FLAT, Saucony Endorphin Racer 2 road racing flat. IMU, inertial measurement unit. k_{leg}, leg stiffness. k_{vert}, vertical stiffness. OWN, runners own habitual running shoes. RM ANOVA, repeated measures analysis of variance. TRA, tibial resultant acceleration. VP4, Nike Vaporfly 4%.

Table 4. Visual analogue scale (0 to 100 mm scale, mean ± standard deviation) scores on comfort, shoe properties, and overall running experience of participants (n = 18).

Characteristics	OWN	FLAT	VP4	RM ANOVA (*p* value)
Comfort VAS				
Predicted	--	34.3±21.8	43.5±20.1	0.136
Acute	66.2 ± 16.7 ^{F}	42.9 ± 21.7 $^{O, V}$	60.1 ± 23.0 ^{F}	0.003
Slow speed	65.1 ± 14.9 ^{F}	42.8 ± 24.4 $^{O, V}$	59.4 ± 24.3 ^{F}	0.003
Fast speed	64.7 ± 16.8	51.3 ± 23.1	57.4 ± 24.3	0.149
Shoe properties VAS				
Heel cushioning*	48.8 ± 14.3 $^{F, V}$	25.6 ±14.9 $^{O, V}$	68.4 ± 17.8 ^{O,F}	<0.001
Forefoot cushioning*	45.4 ± 11.0 ^{F}	31.5 ± 19.9 $^{O, V}$	52.9 ± 20.1 ^{F}	<0.001
Forefoot flexibility*	53.4 ± 14.4 ^{V}	58.4 ± 14.9 ^{V}	38.4 ± 14.5 $^{O, F}$	<0.001
Stability*	46.5 ± 11.7	38.3 ± 16.7	43.4 ± 17.4	0.310
RUN-CAT **	81.3±10.8 ^{V,F}	64.2±23.1 ^{O}	70.8±19.4 ^{O}	0.031
Stiffness*	39.4 ± 14.1 ^{V}	37.8 ± 18.2 ^{V}	58.1 ± 11.7 $^{O, F}$	<0.001
Technical features*	38.0 ± 13.0 $^{V, b}$	34.3 ± 11.0 ^{V}	55.7 ± 14.9 $^{O, F}$	<0.001
Weight*	58.7 ± 9.7 $^{F, b}$	41.7 ± 8.9 $^{O, V}$	50.9 ± 12.9 ^{F}	<0.001
Overall running experience VAS				
Pleasure/displeasure	59.1 ± 15.7 ^{b}	40.0 ± 25.3	52.1 ± 26.6	0.068
Easiness/hardness	55.9 ± 14.0 ^{b}	44.4 ± 22.7	50.8 ± 23.1	0.237
Performance (worse/improved)	49.4 ± 9.7 ^{b}	47.6 ± 22.7	52.8 ± 23.5	0.740
Injury risk (lower/higher)	46.5 ± 20.0 $^{F, V, b}$	70.1 ± 16.4 ^{O}	60.2 ± 17.7 ^{O}	0.002

Notes. $^{F,O, V}$ Significant difference during post-hoc comparisons ($p \leq 0.05$) vs FLAT, OWN, and VP4, respectively. Significant differences ($p \leq 0.05$) are in bold. ^{b} missing data from 1 participant. * midpoint (50 mm) represents ideal, 0 mm indicates an absence of the property and 100 mm indicates too much of a property. **RUN-CAT weighted average of four preceding properties, where 100 represents ideal. *Abbreviations.* FLAT, Saucony Endorphin Racer 2 road racing flat. OWN, runners own habitual running shoes. RUN-CAT, running shoe comfort assessment tool. VAS, visual analogue scale. VP4, Nike Vaporfly 4%.

Table 5. Ranking of shoes by participants (n = 18). Values are count (percentage %).

Shoe	Rank 1 (most preferred)	Rank 2	Rank 3 (least preferred)	Friedman (*p* value)
Comfort at slow speed				0.011
Own	10 (55.6%)	7 (38.9%)	1 (5.6%)	
Flat	1 (5.6%)	7 (38.9%)	10 (55.6%)	
VP4	7 (38.9%)	4 (22.2%)	7 (38.9%)	
Comfort at fast speed				0.607
Own	3 (16.7%)	12 (66.7%)	3 (16.7%)	
Flat	5 (27.8%)	1 (5.6%)	7 (38.9%)	
VP4	10 (55.6%)	5 (27.8%)	8 (44.4%)	
Race performance				0.678
Own	6 (33.3%)	9 (50%)	3 (16.7%)	
Flat	5 (27.8%)	6 (33.3%)	7 (38.9%)	
VP4	7 (38.9%)	3 (16.7%)	8 (44.4%)	
Lowest injury risk				<0.001
Own	14 (77.8%)	4 (22.2%)	0 (0%)	
Flat	1 (5.6%)	2 (11.1%)	15 (83.3%)	
VP4	3 (16.7%)	12 (66.7%)	3 (16.7%)	

Notes. Significant differences ($p \leq 0.05$) in rankings using Freidman and Goodness-of-Fit in post-hoc tests are in bold. *Abbreviations*. FLAT, Saucony Endorphin Racer 2 road racing flat. OWN, runners own habitual running shoes. VP4, Nike Vaporfly 4%.

Table 6. Correlations between comfort measures and subjective and biomechanical measures of data from 18 participants.

	Predicted comfort	Acute comfort	Slow comfort	Fast comfort	RUN-CAT
Comfort VAS					
Predicted comfort	1.000	--	--	--	--
Acute comfort	0.376	1.000	--	--	--
Slow comfort	0.270	0.679	1.000	--	--
Fast comfort	0.369	0.534	0.715	1.000	--
Shoe properties VAS					
Heel cushioning*	0.428	0.498	0.505	0.157	0.122
Forefoot cushioning*	0.553	0.637	0.478	0.262	0.281
Flexibility*	0.097	0.088	-0.217	0.082	-0.107
Stability*	-0.139	0.050	0.305	0.126	0.540
RUN-CAT**	0.004	0.436	0.673	0.720	1.000
Stiffness*	0.103	-0.081	0.187	0.143	0.204
Technical features*	0.546	0.363	0.121	0.092	-0.087
Weight*	0.186	0.204	0.394	0.104	0.216
Overall running experience VAS					
Pleasure/displeasure	0.481	0.534	0.647	0.776	0.714
Easier/harder	0.511	0.402	0.560	0.757	0.582
Performance (worse/improved)	0.367	0.175	0.171	0.468	0.400
Injury risk (lower/higher)	0.014	-0.567	-0.564	-0.396	-0.579
Biomechanical measures					
Overall speed	0.045	0.131	0.078	0.189	0.260
Speed	0.027	0.111	-0.002	0.279	-0.044
Cadence	-0.494	-0.236	-0.117	-0.160	-0.127
Step length	0.157	0.202	0.053	0.353	0.011
Flight time	0.109	0.137	0.066	0.275	0.043
Contact time	0.228	0.018	-0.013	-0.146	0.043
Propulsive phase	-0.128	-0.307	-0.217	-0.095	-0.099
k_{vert}	-0.436	-0.135	-0.103	0.026	-0.123
k_{leg}	-0.308	-0.159	-0.055	-0.098	-0.066
Duty factor	0.157	0.027	0.117	-0.145	0.029
Foot strike angle	0.018	0.237	0.162	0.108	0.223
TRA	-0.462	-0.243	-0.214	-0.235	0.054

Notes. Significant correlations ($p \leq 0.05$) that are *moderate* ($|r| \geq 0.30$) or *large* ($|r| \geq 0.50$) are deemed meaningful and shown in bold. *midpoint (50 mm) represents ideal, 0 mm indicates an absence of the property and 100 mm indicates too much of a property. **RUN-CAT weighted average of four preceding properties, where 100 represents ideal. *Abbreviations.* k_{leg}, leg stiffness. k_{vert}, vertical stiffness. RUN-CAT, running shoe comfort assessment tool. TRA, tibial resultant acceleration. VAS, visual analogue scale.

Discussion

Overall summary

Our study adds to the growing body of knowledge surrounding the effects of minimalist and shoes with AFT on running biomechanics and subjective measures, including comfort. It is one of the first study to examine footwear comfort running outdoors in a more ecologically valid environment. Our findings align with previous research reporting changes in biomechanics in minimalist (Squadrone et al., 2015) and shoes with AFT (Hoogkamer et al., 2019), as well as differences in perceived comfort in these shoes (Dinato et al., 2015). The significant biomechanical differences between shoes were generally of *small* ES, except for propulsion phase and foot strike angle measures where *moderate* and *large* ES differences were evident. In contrast, the significant differences in comfort and subjective ratings were *large*. Running speed appeared to affect comfort levels and shoe rankings, an aspect not often addressed in research. Furthermore, our results reinforce the subjective nature of comfort as indicated by the lack of association between biomechanical measures and overall comfort.

Biomechanical measures

Both novel shoes affected the biomechanics of our recreational runners. Notably, FLAT involved higher cadence and lower foot strike angles than the two other shoe conditions, which is consistent with previous research on minimalist shoes (Barcellona et al., 2017; Nigg et al., 2020; Perkins et al., 2014). Although the changes in biomechanics were generally of *small* magnitude with potentially limited impact on load distribution, the minimal cushioning of shoes would increase loading at the foot and ankle (Bermon, 2021), warranting caution in transitioning too quickly to more minimalist shoes to minimise injury risk to these structures. We also noted *moderate* to *large* differences in the propulsive phase between shoes, with the VP4 having a shorter propulsive phase than FLAT and OWN. This finding could be due to the proposed teeter-totter effect associated with the curved stiff carbon fibre plate and forefoot geometry of the VP4 (Nigg et al., 2021), leading to a quicker transition from midstance to toe-off. Our findings overall suggest that running in VP4 is more like running in traditional shoes than minimalist ones, indicating that the adaptation period to novel shoes may be quicker for super than minimalist shoes for recreational runners used to traditional shoes. Nonetheless, care is still advised in the process of integrating shoes with AFT in training and racing given that foot injuries can still occur while wearing carbon fibre plated shoes (Tenforde et al., 2023). There is currently a lack of research on how these shoes interact with the foot and affect foot mechanics.

Comfort vs speed

Runners rated the comfort of FLAT shoes as lower than OWN and VP4 acutely and at the slower running speed, whereas differences were not significant at the faster speed. These findings suggest that running speed affect comfort ratings. This link between shoe comfort and speed has been proposed elsewhere (Blazey et al., 2021) despite the limited research on this topic. It could be that runners focus less on footwear comfort when running at race pace and experience greater physiological discomfort.

Comfort is a key factor in running shoe selection (Dhillon et al., 2020; Fife et al., 2023). In-store, runners typically decide to try shoes on based on their look and feeling in their hands. This initial perception was encapsulated in our predicted VAS score. It is worth noting that this predicted VAS score did not significantly relate to the acute, slow, or fast comfort VAS scores once runners had worn the shoes. The acute comfort reflects the initial perception of runners in-store when trying on shoes. This acute comfort was largely related to slow and fast speed comfort ratings, although only these latter two only explained 29 to 46% of the variance in acute comfort. Hence, it is important that runners have the opportunity to run in shoes more than a few steps to properly assess running comfort. Similarly, although comfort ratings at the slow and fast speeds were largely correlated (r = 0.715), the correlation was not perfect. Together, these results highlight the potential for speed to affect comfort and the importance of trialling shoes at multiple running speeds. The different rankings of shoes at the slower and faster speeds also reinforce this implication. Indeed, FLAT was most frequently ranked as the least comfortable at the slow speed, but shoe rankings were more evenly spread across the three shoes at the fast speed and for race performance. These results reflect how different shoes might be selected based on their requirements (e.g., performance versus training) and goals of runners (Agresta et al., 2022), and how shoe preference is individual in nature (Kong & Bagdon, 2010).

Shoe properties VAS

A noteworthy observation is the lower variation (i.e., smaller SD values) in the comfort VAS and RUN-CAT scores for OWN shoes compared to the two novel shoes. Runners likely selected their own shoes based on comfort and were familiar with running in them, leading to lower variance. The greater variance in VAS and RUN-CAT scores in VP4 and FLAT reflect the individualised preferences and responses of runners to novel shoes (Kong & Bagdon, 2010). The RUN-CAT is a composite score that reflects deviations from ideal comfort. RUN-CAT scores were similar between

FLAT and VP4, but for opposite reasons. The two experimental shoes are at opposite ends of the spectrum with regards to several shoe characteristics, which was reflected in the VAS ratings of runners with regards to shoe properties. For example, the VP4 heel cushioning score implies that the shoe was perceived as too cushioned at the heel despite having close to ideal forefoot cushioning. In contrast, the FLAT was perceived as having too little cushioning at both the heel and forefoot. Additionally, runners perceived the VP4 as having too little forefoot flexibility when compare to FLAT and OWN likely due to the carbon plate increasing longitudinal bending stiffness (Nigg et al., 2020) that was unfamiliar to most runners. Although the tool was designed to assess comfort at the slower speed (i.e., 1.1 km self-selected pace run), we found RUN-CAT scores were more strongly correlated with comfort at the faster (r = 0.720) than the slower (r = 0.673) speed. This observation suggests the RUN-CAT is valid for assessing overall shoe comfort at faster running speeds, particularly when involving shoes designed for racing. However, the results might also reflect the fact that the RUN-CAT data were collected immediately at the end of the 1.5 km trials, after the participant had just completed their fast effort in the shoe. A comprehensive study on this topic is needed to confirm RUN-CAT relevance and differences with change in speed.

Injury prevention

Injury prevention is an important consideration to runners when selecting shoes (Dhillon et al., 2020). The majority of runners (83.3%) ranked the FLAT as the shoe with the highest injury risk. This finding may be due to lower familiarity to minimalist shoes like the FLAT in recreational runners, while shoes like the VP4 are more similar in construct to traditional running shoes. Plantar sensitivity is lowered in cushioned shoes (Francis & Schofield, 2020), with minimal shoe running increasing loads on the intrinsic foot muscles (Johnson et al., 2016).It could be that runners were more sensitive to mechanical-induced pain sensations (Mills et al., 2018) and not adapted from a neuromuscular perspective to minimal shoe running, hence the perception of greater injury risk. We do acknowledge however, that these results may have differed in a population of habitual minimal shoe wearers. The comfort filter paradigm (Nigg et al., 2015) posits that runners intuitively select the most comfortable shoe using their own comfort filter, which will match their function and movements and reduce injury risk. Despite the lack of convincing evidence to support a comfort – injury link (Agresta et al., 2022), in the current context, it is likely that comfort would be a relatively good indicator of runners' neuromuscular readiness for minimal shoe running. Transitioning to novel shoes can increase the risk of injury in the short term due to changes in biomechanics and loading. Caution is needed during transitioning to novel shoes, with the minimum time and training volume needed for accommodation and adaptation remaining relatively unknown and likely to be individual and shoe dependent (Tenforde et al., 2023; Warne & Gruber, 2017).

Correlations

The results of the exploratory study relating comfort to collected data suggest that subjective VAS measures are more strongly related to comfort ratings than biomechanical measures. This finding re-emphasises the subjective nature of comfort (Menz & Bonanno, 2021) and potentially limited relationship between comfort and running biomechanics, as reported elsewhere (Dinato et al., 2015). The pleasure or displeasure experienced by runners when wearing a particular shoe was strongly correlated with all measures of comfort. This finding is not entirely surprising, given that people are likely to enjoy their running experience more if they feel comfortable in their shoes. Similarly, the more comfortable the participants were in a shoe, running felt "easier" on the perceived effort scale. This finding again reflects the comfort filter paradigm (Nigg et al., 2015). The correlation of feeling (easiness-hardness) and effort (pleasure-displeasure) to comfort ratings was *large* and significant at both the slow and fast speed, although the magnitude of the relationship was stronger when running fast. The increased strength of the correlation suggests that the perception of comfort may change depending on the speed at which one is running, or again reflect the temporal proximity of the ratings. Future research could investigate the use of comfort tools at multiple running speeds to determine their relative interchangeability.

Limitations and strengths

This study has limitations to acknowledge. Participants self-selected their running speed for all trials. Although there were no significant differences in the overall speed for both the slow and fast running segments, differences in speed were significant in the 15-m Optojump section during slow running when the biomechanical measures were collected. This difference in speed over the 15-m may have impacted running biomechanics; however, the largest difference in average speed (0.13 m/s) was of a *small* effect size magnitude and less than 5% between shoes, which is the usual threshold applied when prescribing a set speed in running research (Bergstra et al., 2015; Queen et al., 2006).

Our relatively small sample size is another limitation, particularly in interpreting results from our exploratory analysis as some findings could be due to chance. For this reason, we set a more conservative threshold ($|r| \geq 0.30$) and encourage future research in these areas to confirm the presence of a relationship. Our sample contained only male recreational runners that were primarily rearfoot strikers apart from one midfoot striker. Consequently, the generalisation to females and other cohorts of runners is constrained.

Our study also only looked at one model of minimalist shoe and show with AFT. The VP4 model is typically known as being the first shoe with AFT. Now, many running shoe companies have several shoes incorporating advanced shoe technology with slightly different shoe properties (Joubert & Jones, 2022). Hence, although generalisation of findings to other shoes with AFT is not ensured, previous research examining a range of shoes with AFT indicate little biomechanical differences between shoes (Joubert & Jones, 2022) and strong correlations between subjective rankings and running economy rankings in shoes.

Strengths of our study include conducting the study outdoors, which enhances the ecological validity of findings. Most running training and racing are conducted outdoors, hence the importance of assessing shoe-related performances in such environments. Previous studies (Benson et al., 2020; García-Pérez et al., 2014; Milner et al., 2020; Van Hooren et al., 2020) have demonstrated differences in running biomechanics between laboratory and outdoor running. Our resultant tibial acceleration values are relatively high, but these values are consistent with studies comparing laboratory to outdoor running (García-Pérez et al., 2014; Milner et al., 2020). Another strength of the study is the focus of recreational runners who represent the largest proportion of runners and who have historically not been considered in shoes with AFT research. Furthermore, our study examined both subjective and biomechanical measures, which are useful in investigating the multifactorial nature of shoe comfort.

Conclusion

The two novel shoes generally had non-significant or *small* effects on runners' biomechanics versus their OWN shoes, except for foot strike angles in FLAT and propulsive phase in VP4 where effects were *moderate* to *large*. Participants were more comfortable in their habitual shoes and VP4, potentially preferring VP4 more than FLAT because these are more like traditional running shoes. The FLAT minimalist shoes were perceived as the least comfortable and having a higher injury risk. Running speed appeared to affect comfort levels and shoe preferences, which should be considered in research as well as in shoe prescription to align with the running demands and goals of individuals.

Our results re-emphasize the subjective nature of comfort and individualised shoe preference, as well as the general lack of association between comfort and biomechanical measures.

Acknowledgement

The authors would like to thank Courtney Mitchell for her assistance in the data collection process. The authors also thank the participants for their time.

Chapter Three – Experimental Study

A qualitative analysis exploring shoe comfort and preferences of male recreational runners in three shoes

Abstract

Aim: We aimed to analyse insights into the shoe comfort and preferences qualitatively for male recreational runners wearing shoes with AFT (Nike Vaporfly 4%, VP4) and lightweight, minimal shoes (Saucony Endorphin Racer 2, FLAT in an outdoor environment. The runners' experiences were examined with their habitual shoes (OWN) as a baseline. ***Methods:*** Eighteen male recreational runners ran three 1.5 km trials, once in each shoe outdoors. The first 1.1 km was run at a self-selected comfortable (slower) speed, and the last 400 m at runners perceived 5-km race pace (faster). The participants ranked the shoes from most preferred to least preferred for different conditions, and one-on-one interviews collected deeper insights into the participants' experiences with the shoes. Thematic analysis, guided by the runners' responses, was used to identify and develop themes. ***Results:*** OWN was perceived to have the lowest injury risk, FLAT the highest. VP4 was both the most and least preferred for overall performance. OWN was the most comfortable at the slow Speed and VP4 at the fast speed. FLAT was least comfortable at both speeds, although more people preferred it at the faster speed. Both novel footwear was described as quick, VP4 was also described as bouncy, and FLAT was described as light. ***Discussion:*** Runners had different perspectives and preferences for running footwear. Ultimately, one shoe will not be preferential for all runners. Despite what shoe runners use, they should be familiar with it, particularly for performance events such as racing.

Key words:

Minimalist, advanced footwear technology, comfort, performance, injury, perception

Introduction

Running is a popular recreational activity with many health enhancing benefits (Lee et al., 2017). Selecting the right running shoe for an individual can enhance comfort (Kong & Bagdon, 2010; Menz & Bonanno, 2021) as well as running pleasure (Honert et al., 2020), and potentially mitigate injury risk (Dhillon et al., 2020). Although most runners wear traditional running shoes, typically characterised by a moderate amount of cushioning, a stack height between 20 and 30 mm, heel-to-toe drop between 4-14 mm, and motion control technologies (Hébert-Losier et al., 2022; Murphy et al., 2013), the running shoe market has expanded in recent years. Companies now offer a variety of shoes, ranging from maximalist (Richard Blake, 2018) to minimalist (Davis, 2014) and shoes with advanced footwear technology (AFT) (Frederick, 2022).

Minimalist shoes aim to mimic barefoot running, while protecting the sole of the foot from the external environment. They minimally interfere with the natural movement of the foot due to their high flexibility, low heel-to-toe drop, low weight, low stack height, and absence of technological features (Esculier et al., 2015). The minimal index is a scale that quantifies the previously mentioned characteristics to determine the how minimalist a shoe is (Esculier et al., 2015). A shoe needs to be above 70% on the minimalist scale to have an impact on the biomechanics of a runner (Rice et al., 2016; Roca-Dols et al., 2018). Minimal shoes are often described as more "natural" with previous research showing that people perceive "the body's sort of designed to be without trainers"(Walton & French, 2016). Since these shoes are lightweight, they offer a potential performance advantage as shoes with lighter mass reduce the metabolic cost of running (Franz et al., 2012; Frederick, 1984). Minimalist shoes are proposed to potentially prevent common running injuries (Davis, 2014), by reducing the loads at the knees (Bermon, 2021) with the caveat that the design of these shoes increases loading at the foot and. However, a decrease in injury incidence has not been substantiated experimentally (Ryan et al., 2014).

In contrast, shoes with AFT has a thick midsole made of polyamide block elastomer foam (Bermon, 2021; Muniz-Pardos et al., 2022) and a curved stiff plate that increases the longitudinal bending stiffness of the shoe (Geoffrey & Nicholas, 2020; Nigg et al., 2021). Together, the AFT features are designed to reduce the energetic cost of running and improve performance. Anecdotally, AFT shoes are often described as feeling "bouncy" and runners "never experiencing something like them before" (Dalek, 2018). There have been concerns raised regarding the rapid uptake of AFT and potential for injury (Hébert-Losier & Pamment, 2023). Of particular concern is the stack height in these shoes, which can compromise frontal plane stability. Consequently, there is a perceived risk of injury associated to this stack height, including ankle sprains due to rolling ankles, with tight turns and corners during racing events (Hoogkamer, 2020). In addition recent case series of navicular bone stress injuries potentially caused by AFT shoes (Tenforde et al., 2023).

Despite the novel technological features, shoes with AFT tend to be more similar in construct to traditional running shoes than minimalist and are considerably cushioned. Consequently, these shoes may feel more comfortable to runners, especially in comparison to minimalist (Hébert-Losier et al., 2022). Runners are often most comfortable in shoes they are familiar with and that are cushioned (Ramsey et al., 2022), both of which contribute to why runners purchase their shoes (Dhillon et al., 2020). The perceptions and comfort of individuals running in novel shoes is seldom examined outside of laboratory constraints, which may not accurately reflect their experience in the real-world.

Footwear comfort is multifaceted and subjective in nature (Menz & Bonanno, 2021). Personal preference influences subjective ratings of several footwear features, including fit, cushioning, and supportive technologies. Visual analogue scales (VAS) (Lindorfer et al., 2019; Mills et al., 2010; Mohr et al., 2017) and ranking from the most to the least preferred shoe (Che et al., 1994; Miller et al., 2000; Mills et al., 2010) are some of the most common methods used to measure footwear comfort and preference. Although other tools have been developed and used to objective shoe comfort, such as the Running Shoe Comfort Assessment Tool (Bishop et al., 2020) and plantar pressure distribution (Hennig, 2014), comfort nonetheless remains a "feeling of a human" (Vink & Hallbeck, 2012). Hence, qualitive approaches can provide rich data that explore the experiences of runners, such as via one-on-one interviews. Using open-ended questions, a deeper and more holistic understanding of footwear comfort and personal preferences can be attained. The predominate approach for qualitative studies are interviews conducted without runners engaging in actual running prior to the interview. The interviews are typically focused around overall running experiences and perceptions (Dhillon et al., 2020; Peterson et al., 2022). Hence there is a limited gap in research that qualitatively analyses runners' immediate experiences following running in novel footwear.

Therefore, we aimed to provide qualitative insights into the shoe comfort and preferences of recreational runners wearing novel shoes in an ecologically valid environment. Specifically, the experiences of runners wearing AFT (Nike Vaporfly 4%, VP4) and lightweight minimal shoes (Saucony Endorphin Racer 2, FLAT) was examined and involved running outdoors, with their own habitual shoes (OWN) acting as a baseline.

Methods:

Participants

Posters at local gyms, word of mouth and social media was used to engage volunteers to participate in the study. Eighteen male recreational runners participated (Table 7). To be included, runners needed to be free from injury for at least three months, run regularly (minimum once per week) for at least six months, and have a personal best 5 km time between 20 to 30 minutes in the past year (Hébert-Losier et al., 2022; Honert et al., 2020). Participants also needed to fit the available shoe sizes. Participants signed an informed consent document that outlined the benefits and risks involved with the study (e.g., delayed onset muscle soreness or injury due to running in unfamiliar footwear). The Human Research Ethics Committee [HREC(Health)2020#83] approved the experiment, which adhered to the Declaration of Helsinki.

Table 7. Characteristics of participants. Data are mean ± standard deviation

Characteristics	Males (*n* = 18)
Age (y)	31.2 ± 10.5
Height (cm)	180.2 ± 6.0
Mass (kg)	81.6 ± 10.0
Running experience (years)	11.2 ± 8.1
5 km personal best time in last year (min)	23.1 ± 2.1
Weekly training (km)	20.0 ± 12
Own shoe size (US sizing)	10.6 ± 1.0

Table 8. Shoe characteristics of shoes worn by participants (*n* = 18). Data are mean ± standard deviation.

Characteristics	OWN	FLAT	VP4
Mass (g)	308 ± 42	153 ± 8 $^{O, V}$	211 ± 12 $^{O, F}$
Stack height (mm)	24.6 ± 7.2	13.0 ± 0 $^{O, V}$	31.0 ± 0 ^{F}
Heel-to-toe drop (mm)	11.2± 5.7 ^{F}	1.0 ± 0 $^{O, V}$	7.0 ± 0 ^{F}
Minimalist index (%)†	28 ± 15	88 ± 0 $^{O, V}$	48 ± 0 ^{F}
Price (NZD)	156 ± 49 ^{N}	190 ± 0	380 ± 0 $^{O, F}$
Age of shoe (months)	10 ± 8.9	-	-

Notes. OWN, runners own habitual running shoes. FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%. Data from right shoes only (size: US 8.5 to 12). $^{O, F, V}$ Significant difference during post-hoc paired t-test comparisons ($P \leq 0.05$) vs OWN, FLAT, and VP4, respectively. †Minimalist index range: 0% (lowest) to 100% (highest) degree of minimalism.

Study design

A randomised crossover study design was used to investigate the effect of shoe on outcome. Participants attended one 90-minute session that involved running 1.5 km in three shoes: OWN, own habitual running shoe; FLAT, Saucony Endorphin Racer 2 racing flat (minimalist shoe); and VP4, Nike Vaporfly 4% (shoe with AFT), as shown in Table 8. Participants selected their OWN shoes knowing they were required to run 1.5 km outside on asphalt at a comfortable pace for 1.1 km and a 5 km race or tempo pace for the final 400 m. All participants were rearfoot strikers in their own shoes except for one who was a midfoot striker based on foot strike angles collected using 2D videos during trials (Altman & Davis, 2012b). Before and after each shoe trial, participants were asked a series of questions about how they felt about each shoe. A final interview at the end of all three running trials was conducted to further assess their perceptions. An outline of the questions is provided in Table 9. Versions of the scripts were iteratively tested before finalisation for data collection, which included consulting a qualitative researcher with over 5 years of research experience, as well as recreational runners themselves.

Protocol

After informed consent, the characteristics of participants (age, height, mass, leg length, running experience, and training level) and OWN shoes (size, mass, cost, stack height, forefoot height, heel-to-toe drop, and reasons for purchasing their own running shoes) were recorded. Participants trialled the various available sizes of the two experimental shoes to ensure proper fit. The minimalist index of all shoes worn as part of the study was calculated using a valid and reliable tool (Esculier et al., 2015), where 100% represents the highest degree of minimalism and 0% the lowest. Of note is that the experimental shoes were spray-painted black to disguise their brand and model.

All running trials were conducted outside around a flat concrete 740 m loop. Participants were first required to run 1.1 km at a self-selected comfortable pace sustainable for 30 minutes (~1.5 loops). After a 30 s standing rest, participants ran 400 m at a faster pace as if they were doing a tempo run or 5 km race. The 1.1 km distance was chosen as this is the distance used in the Running Shoe Comfort Assessment Tool (Bishop et al., 2020). A faster speed was also examined, given that the VP4 and FLAT shoes are designed for racing. Participants ran the first of the three running trials in their OWN shoes to act as baseline, followed by the VP4 and FLAT in a random order. Half the participants ran in VP4 before FLAT, and the other half ran in FLAT before VP4.

Data collection

Participants had one-on-one interviews, lasting one to three minutes in duration, before and after the running trials to discuss their perceptions and feelings of each shoe. An interview script was used to ensure the questions were consistent for all participants (Table 9). Prompting questions such as "why?" or "what do you mean?" were used to investigate participants' perceptions more thoroughly and achieve data saturation for each participant. No repeat interviews were carried out. The same trained researcher conducted all interviews (SF). Interviews were voice recorded and then transcribed *verbatim* using otter.ai. All transcribed scripts were verified for accuracy without being returned to the participants.

Table 9. Questions asked before and after running with novel shoes at two different speeds for a total of 1.5 km.

Before running
What stands out to you when you look hold and feel these shoes?
Imagine you're in a shoe store trying them out. How do they feel?
Would you buy these shoes?
After running
What did it feel like running in these shoes?
How did running in these shoes feel compared to your own shoes?
How did these shoes influence your running style?

Did these shoes feel different at the slower and faster speeds?
Use three words to describe how you felt running in these shoes.
Did you enjoy running in these shoes?
Would you buy these shoes now?
After running in all three shoes
Overall, please rank the three shoes from most to least comfortable when running at the slower speed.
Why did you rank them this way?
Overall, which shoe was the most comfortable in running at the faster speed? Why did you rank them this way? (*Participants were asked to rank the three shoes from most to least comfortable*)
Overall, what shoe do you think would perform the best under a race situation? Why did you rank them this way? (*Participants were asked to rank the three shoes from best to worst performance*)
Overall in which shoe do you think your injury risk would be lowest. Why did you rank them this way? (*Participants were asked to rank the three shoes from lowest to highest injury risk*)
Do you know what brand or type of shoe this is (shoe 1)?
Do you know what brand or type of shoe this is (shoe 2)?

Data processing and analysis

A thematic analysis process was used to analyse the data (Braun & Clarke, 2006). Initial familiarisation to the data occurred while formatting the transcripts for analysis and then reading the transcripts while taking notes (BP). We used all the data and transcripts available to guide the coding process without preconceived theories or frameworks. Some of the data in regard to purchasing choices for the novel shoes was lost and therefore not included in the analysis. For this section of the results, 15 participant responses for FLAT and 13 participant responses for VP4 were analysed. We generated the runners' perspectives into initial codes to capture the runners' views on the shoes regarding performance, injury, and comfort. The codes and relevant quotes were organised and categorised in an Excel spreadsheet for thematic development (BP, HK). The interviews were dissected into comments about each of the trialled shoes and then categorised as positive or negative. Initial themes were derived by identifying commonalities among the codes and continually refining code assignments until a coherent pattern of codes and themes emerged. As participants did not provide feedback on the findings, we also considered underlying concepts implied, but not directly expressed by runners. The themes were reviewed to ensure they accurately represented the data's main ideas (KHL, HK), and then supporting quotes from the participants were extracted to provide evidence and context. We defined and named the themes to capture their essence within the study. Figures were generated to provide an overarching view of the findings.

Results:

Runners identified comfort as the top reason for purchasing their current footwear, with 83.3% of participants ranking it in their top three reasons (Figure 5). This finding was also emulated in quotes from Participant 10 indicating he would not purchase FLAT and VP4 due to comfort:

> *"They don't feel comfortable."* P10

> *"They don't feel very comfortable, like running long distances I don't think they'd be too good on the feet."* P10

Cost was the second most common response from runners as to reasons for buying their current shoes. For Participant 13, price was the determinant of whether he would purchase the FLAT or not:

> *"Probably. Yeah, they're my size. Yeah. I'll see it depends on how much they cost."* P13.

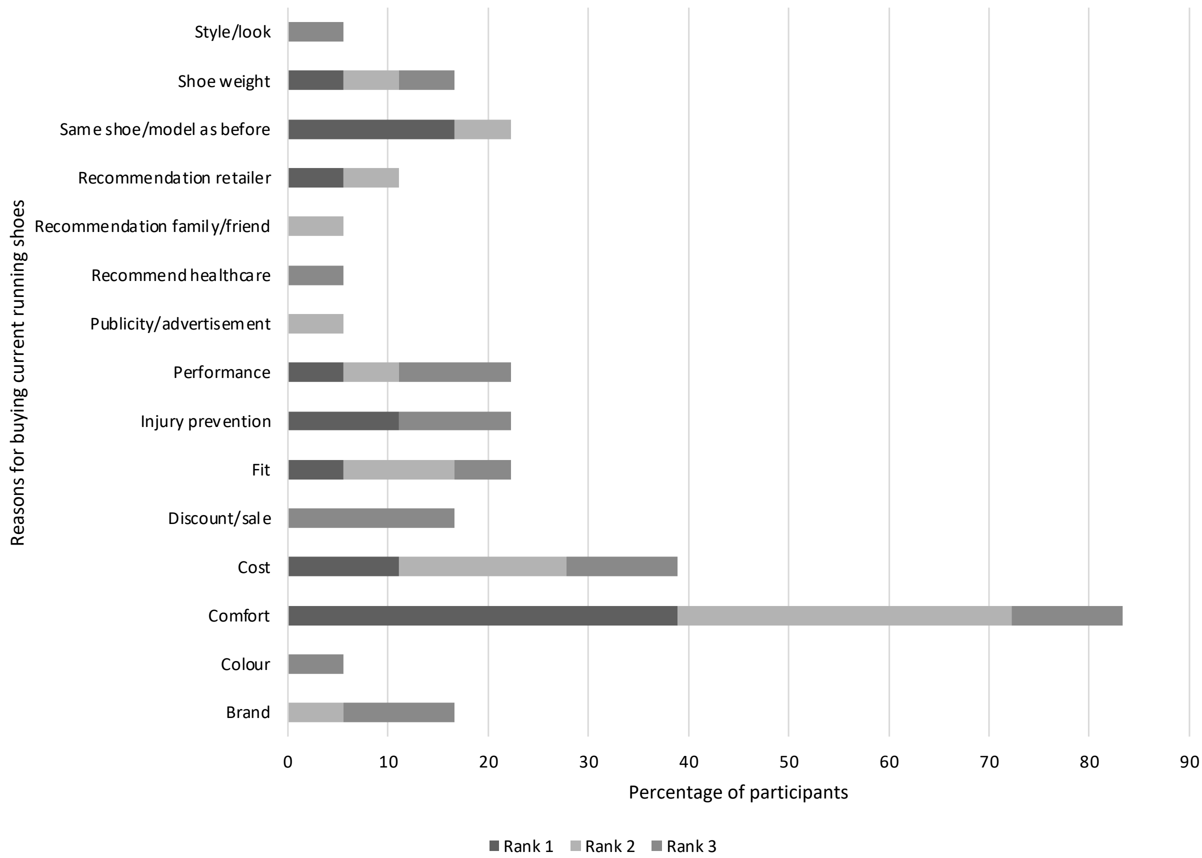

Figure 5. Top three self-reported reasons cited by participants (n = 18) for purchasing their current habitual running shoes.

After running in the novel shoes, some participants changed their mind as to whether they would purchase the novel shoes (Figure 6). After initially trying on these shoes, five participants would purchase the FLAT and four would purchase the VP4. After running in the shoes for 1.5 km, only one participant would purchase the FLAT and six would purchase the VP4. The reason for not purchasing FLAT was often due to lack of comfort, as exemplifies the following quote:

> *"Probably not. Just that lack of comfort."* P11

Participant 1 was also concerned about the injury risk of FLAT:

> *"I do a little bit of off road and I feel like not having any support might actually cause more injury to my potential high injury body, potential."* P1

The six participants who were satisfied with the VP4 would purchase them because they felt good. However, some runners wanted further information before purchasing:

"Yes. Because they feel better than my own running shoes at this point." P18

"Yes, but I would want to talk to someone about them, who can explain what's going on. If we're just basing it on the feel, then yes." P14

Other participants were not confident their running style suited the VP4, and would therefore not purchase them:

"No. Because they do not fit my running style." P6

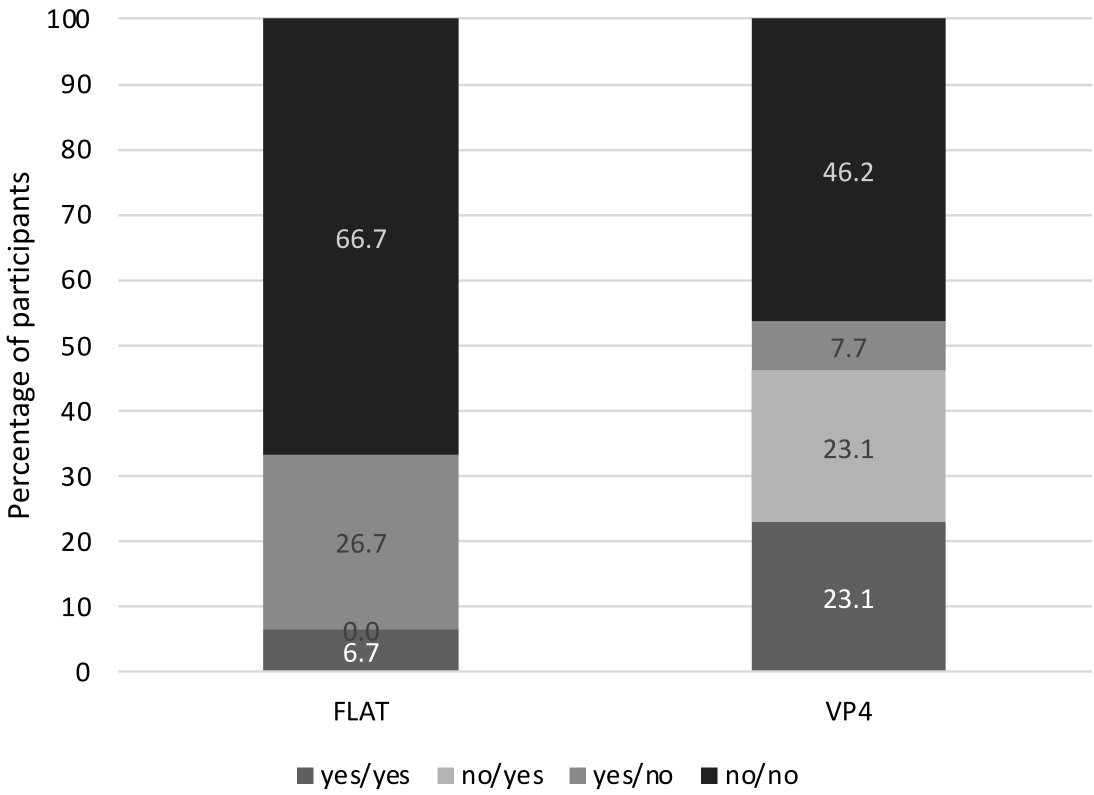

Figure 6. A stacked bar chart of runners (*n* = 15 for FLAT, *n* = 13 for VP4) answers to whether they would buy the novel shoes. Yes/yes, would buy shoes before and after running in them. Yes/no would buy shoes before running in them, but not after. No/yes, would not buy the shoes before running in them, but would after. No/no, would not buy the shoes before or after running in them. *Abbreviations:* FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%.

When participants used three words to describe each novel shoe (Figure 7), the FLAT was most often described as light (44.4% of participants) and fast or quick (38.9%). VP4 was most often described as bouncy (44.4%) and fast or quick (33.3%).

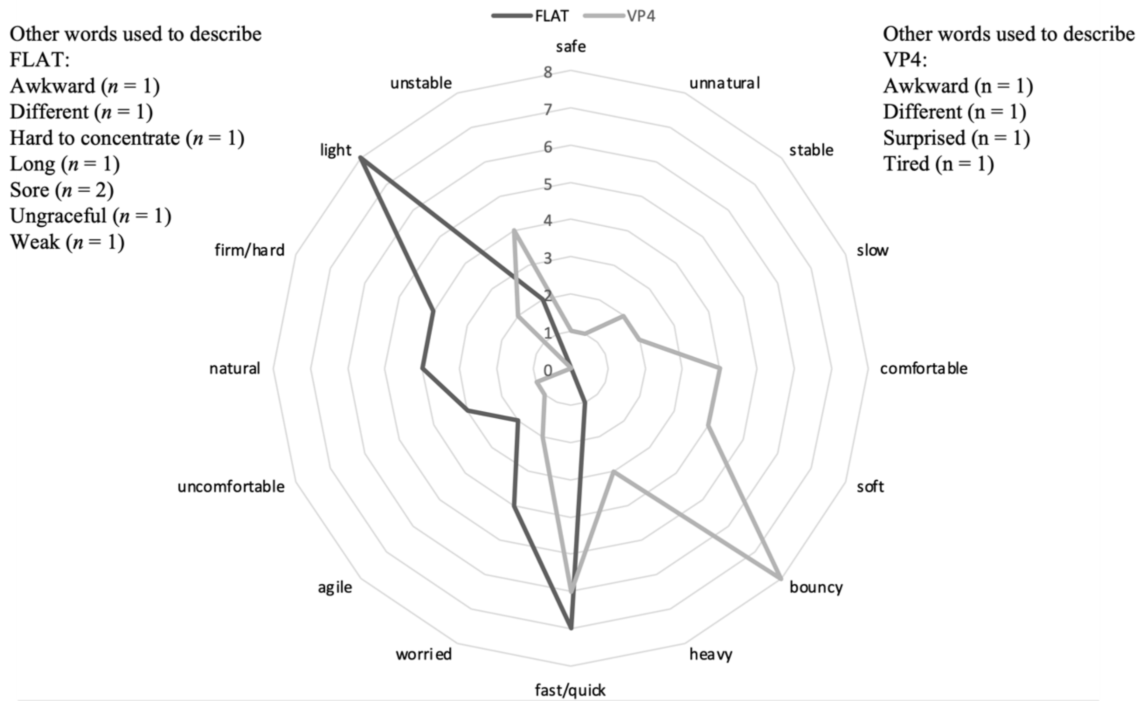

Figure 7. Summary of the three words used to describe the novel shoes after running in them by participants (n = 18). Synonyms were counted as the same word. *Abbreviations:* FLAT, Saucony Endorphin Racer 2 road racing flat. VP4, Nike Vaporfly 4%.

The reported rankings for comfort at the slow and fast speed, overall performance, and injury risk are displayed in Figure 8. At the slow speed, OWN was ranked the most comfortable (55.6%) and FLAT the least comfortable (55.6%) most often. At the fast speed, VP4 was ranked the most comfortable (55.6%) and FLAT the least comfortable (44.4%) most often. VP4 had the highest frequencies for both the most (38.9%) and least (44.4%) preferred for overall performance, highlighting how runners either liked or disliked the shoe.

> "*…the black ones (VP4) feel the fastest for the least amount of effort."* P2

> *"The black shoes (VP4) are (ranked) the lowest because they are too heavy and don't provide enough flexibility."* P6

OWN was most often ranked as the shoe with the lowest perceived injury risk (77.8%) mainly due to being familiarity with the shoe. FLAT was most often ranked as the shoe with the highest perceived injury risk (83.3%) due to lack of cushioning.

> *"Because I've run in my own shoes a lot, so I rank that one because I haven't really had an injury on them properly."* P7

"I know them (OWN). I know how I can run in them well." P11

"…when running on any hard surfaces and everything, I'll just be getting a lot more jarring (in FLAT) through my joints and lower back and everything else so it's not very good for me." P8

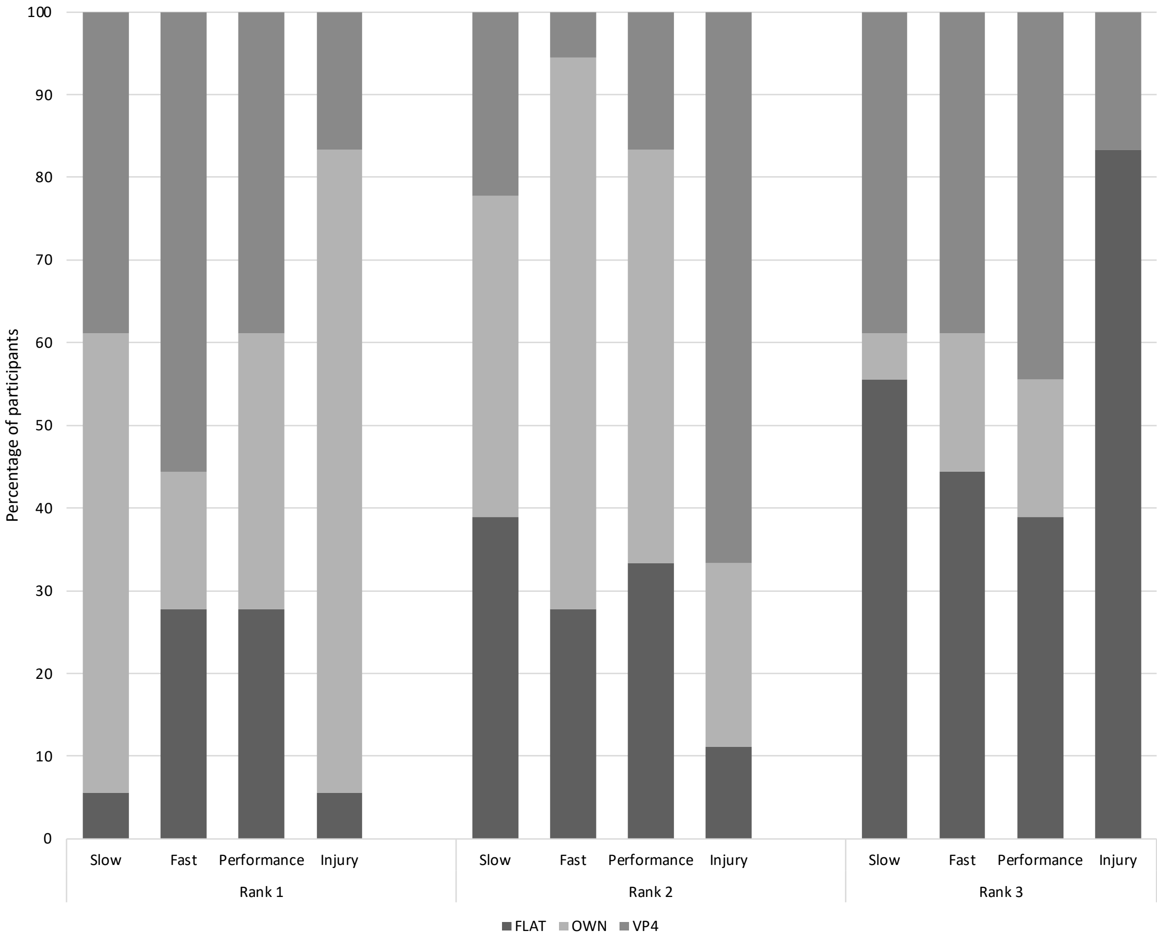

Figure 8. A stacked bar chart of runners (*n* =18) preferences for different criteria following running a total of 1.5 km at two different speeds. Most preferred (rank1) to least preferred (rank 3) for comfort at the slow and fast speed and overall performance. Lowest injury risk (rank 1 to highest injury risk (rank 3) for injury. *Abbreviations:* FLAT, Saucony Endorphin Racer 2 road racing flat. OWN, runners habitual footwear. VP4, Nike Vaporfly 4%.

Thematic analysis

The thematic analysis categorised responses into comfort, performance, and injury at the slow and fast speeds. The overall main themes emerging from the data were familiarity, cushioning, support, and ease of running. Other sub themes mentioned include novelty, versatility, balance, and stability.

Comfort

The rankings of comfort changed based on the prescribed running pace (Figure 8). During the interviews, the themes of ease of running, cushioning, and familiarity emerged.

Theme 1 – Ease of running

At the slower running speed, there was a spectrum of perspectives from participants who felt running in the VP4 was easier and less exerting, to others who felt running in VP4 was harder because of the extreme cushioning and thickness.

The runners who felt VP4 made running easier stated:

> *"I felt like it was a lot easier to run with these black (VP4) ones because they were a lot more springy. You're not putting in as much energy at the same pace."* P2
>
> *"I felt the blacks (VP4) provided the most support to my feet, and that overall made the running a lot more comfortable and I felt like I could do it for longer."* P10

However, some runners had more negative views:

> *"The black (VP4) were just way too extreme…Too soft, too cushioned."* P5
>
> *"Yeah like the entirety of the shoe and the sole just felt like it was too thick to properly do it (run) for a longer period of time at that slower speed…"* P6

Participant 4 who favoured the VP4 at the slower speed changed his opinion when running at the faster speed, noting they were *"a bit heavy"*.

Participant 6 found the VP4 had too much heel support, and instead preferred the sensation of the FLAT at ground contact:

> *"Orange (FLAT) was more comfortable because there was probably less heel support and that just made the contact to the ground a lot smoother."* P6

The minimal design of FLAT was perceived to "ground" the runner at the faster speed:

"I think probably quite a big jump in between orange (FLAT) being far out in front compared to the other two. A lot based on just feeling quite as if you're running pretty much on the surface of the ground, you're well supported and yes, pretty sturdy." P3

"Orange (FLAT) because it was lighter and I could put more pressure into the ground and felt the ground easier." P6

"I thought the orange (FLAT) ones they're quite lightweight shoes and they sort of just feel faster…, just feels like you've got the higher cadence." P12

However, there were other participants who did not enjoy the FLAT because of the impact sensation and feeling of working harder to maintain their pace:

"There's a lot more energy for I felt like the same pace." P2

"The orange (FLAT) were just too hard to run slow in, with no cushioning." P5

"…just that minimalistic sort of the feeling when you're impacting onto the ground sort of is the least (comfortable)." P8

Theme 2 – Cushioning

Participants viewed both novel shoes as extreme. OWN was seen as an ideal compromise between the VP4 and FLAT:

"My own just feel like they have more of what I needed, more cushioning more support. They were stiff enough. They weren't too extreme either way." P5

"My own was most comfortable as the heel and sole were a nice balance and it was comfortable to put pressure on both parts of the shoe." P6

I think (the VP4) are a bit too much one way, as opposed to the other ones (FLAT) which are a bit too much the other way." P4

However, the extra cushioning of the VP4 was more positively perceived than the lack of cushioning of the FLAT as exemplified by Participant 14:

"Worst obviously the orange (FLAT) one, too light and not enough cushioning." P14

"Black (VP4) was really comfortable. Just the cushioning. A comfortable run. A little more cushion than my own, which was nice for a change." P11

Theme 3 – Familiarity

The familiarity participants had wearing their OWN shoes was perceived as positive at both slow and fast speeds:

> *"Quite used to my own ones, so that kind of yeah, that familiarity was just a bit better than the orange (FLAT)… I'm probably just a bit more used to them, which is why I was able to kind of run a bit better than I felt I could in the orange (FLAT), which were not very comfortable."* P10

In contrast, some participants preferred the novel shoes to their OWN. Participant 16 noted they were:

> *"both probably better than mine".*

However, some found the VP4 to be too different and unfamiliar:

> *"…the black (VP4) ones they just didn't really feel natural to me… for the black (VP4) ones (I am) just not used to them."* P12

Performance

When ranking the three footwear conditions according to their perceived performance in a race situation (Figure 8), several themes emerged: ease of running, familiarity, stability, and versatility.

Theme 1 – Ease of running

With respect to perceptions of effort and efficiency when running in the VP4, there were mixed responses. Several runners were positive, citing comfort, lightness, and effort-free running as facilitators of good running performance:

> *"…the black (VP4) ones feel the fastest for the least amount of effort."* P2
>
> *"Black (VP4) again, because it's comfortable. They felt like they're designed for racing."* P10
>
> *"They felt comfortable no matter what I was doing. They felt light as well, at the same time. I felt like I could go fast and not get injured."* P18

However, these perspectives were not common amongst all runners, with others suggesting that the shoes felt too cushioned at the expense of mass, flexibility, and performance:

> *"The black (VP4) one just because I felt as though it was too cushioned. I felt as though I had to work a bit (more) than the others."* P3

"I think in a race situation, I'd probably sacrifice a bit of comfort for a bit more lightness and performance." P4

"The black (VP4) were just not be doing anybody any favours in a race situation." P5

The desirability for lighter shoes that move more naturally was reinforced by a small number of runners who rated the FLAT favourably:

"Feel quite supported, there's some cushion but not too much cushion so you're not fighting against that. I think I was able to run a more natural flow get a bit more of a natural flow." P3

"… the orange (FLAT) because they have more, because they're lighter and they feel like running fast in them, if you were concentrating and you knew what you were doing they would be a better shoe." P5

However, these same features were also described unfavourably by other runners, who perceived the FLAT to be too light, without adequate cushioning for faster and longer running efforts:

"Orange (FLAT) was worst. Too light, not enough cushioning." P14

"The orange (FLAT) ones would just be a nightmare, I think. I was just saying, the faster I went, longer, they would just start to really bear down on the balls of my feet and the heel, I think." P18

Mass and comfort were also raised by a single runner when referring to their OWN, reinforcing the requirement for shoes to be light and comfortable to be considered appropriate for race situations:

"…it'd be interested to do a race in them (VP4), but I would just fear that we get more and more uncomfortable the longer went on a short distance maybe wouldn't be a problem. But yeah, doing multiple races or anything, I just wouldn't want to do. My ones get heavier." P18

Theme 2 – Familiarity and stability

The runners frequently perceived the familiarity and stability of their OWN footwear to be desirable with regard to race performance, indicating their preference for the security of the shoe they know over other potentially performance enhancing features, such as lower mass:

"My own are quite, I guess I am used to my own, and they're quite stable." P2

"I put my own in there because they have, yes they're heavy but they're supportive. They're soft under foot." P5

"... I'm obviously quite used to them so I'd probably be more comfortable with that overall. I think I'd perform better because I'm used to the feeling." P8

Despite familiarity being quite widely perceived as a positive aspect of running footwear, one runner noted that their footwear was ageing and hence may not perform as well in a race situation:

"My own's getting a bit worn." P15

Participants were fearful of potential adverse events of racing in the novel shoes. In the case of the FLAT, longer race situations was perceived as potentially problematic and that adaptation of running style may be required to run safely in this shoe:

"... I think the longer the race went or performance, the more impact and sore in the joints (I) would be." P8

"I wouldn't feel secure running in those unless I got my running style better." P15

In the case of the VP4, some runners believed that the shoes would contribute to lesser impact, less soreness, and a have a protective effect against injury in the context of performance:

"...because I've got the cushioning and I think depending on the length of the race. The longer it went, I'd have the least impact on me so I'd give a less of the sore joints, etc." P8

"I felt like I could go fast and not get injured." P18

However, this cushioning comes at a cost of stability:

"...it's like I said: too rolly." P16

Theme 3 – Balance and versatility

When referring to their OWN, runners considered the balanced (that is, the balance of support, mass, and cushioning) and versatile design of their footwear to be closely linked with optimal performance in a race situation:

"It depends what kind of race run we're in, if I need to change pace from slow to fast and change corners I feel like I've got everything I need in that." P5

"I went with my own ones, just I think for the amount of the cushioning, it's not too much, but it's not minimal." P8

However, there were also instances where runners recognised that the features of their own shoes were not optimal for racing:

> (the FLAT) *"...probably would be more suitable than my own, which are definitely not meant for racing and probably in a proper race wouldn't be too suitable to the conditions."* P10

When it came to the VP4 one participant expressed concerns the cushioning may not suit the terrain where they usually run:

> *"I just think that that'd be too soft in the heel and…where I usually run is a lot more sort of turning in uneven stuff, so they wouldn't be so good with the heel."* P8

Participant 12 had similar views, however related to the FLAT, that the shoe was not suited to his current needs:

> *"No, not for what I am doing at the moment. Just because I feel like, I've tried to do a marathon so I need a shoe with more support for those longer runs."* P12

Injury risk

The participants most frequently chose OWN as the condition which would be least likely to contribute to injury (Figure 8). The perceptions of the various footwear conditions as risk or protective factors against injury varied; however, the themes of familiarity, cushioning, and support emerged.

Theme 1 – Familiarity

Runners' familiarity with OWN partly explains the high frequency of participants ranking them as the one with the lowest injury risk:

> *"Probably my own first purely because I know the shoe. It's worn to me…I know them. I know how I can run them well."* P11

Some runners expressed feelings of reliability or security associated with their own footwear, as encapsulates the quote from Participant 18:

> *"…because I've run a lot in them and I've never been injured in them so that plays into it. Plus they're incredibly stable, around every part of my foot."* P18

In addition, participants expressed a level of comfort and stability in OWN that was linked to a lower perceived risk of injury:

"I went with my own ones. Just for the way the cushioning and everything is it's not as soft as the black (VP4) ones. I don't feel that I pronate as much and I think that obviously that would happen in the long term." P8

The importance of familiarity with footwear was reinforced by a quote from an individual participant regarding running in the VP4:

"…because they're the closest to it (the runner's own shoes). There's a lot more, there's a lot of padding on the bottom, but less on the top so depending on what I'm doing like a road race, I'd be totally comfortable. If it was a bit off road as well, then maybe it increases." P18

Theme 2 – Cushioning

Runners considered the cushioning properties of their footwear as being important for the mitigation of impact forces, which they associated to injury potential. Runners frequently cited a lack of cushioning as a risk factor for injury with respect to the FLAT, demonstrated in the following quote:

"I felt like with the or the orange (FLAT) ones, if I were if I were training for a race, I'd be much more likely to develop splints or something from the from the impacts…when running on any hard surfaces and everything, I'll just be getting a lot more jarring through my joints and lower back and everything else so it's not very good for me." P8

Runners' perceptions about the protective effect of footwear cushioning was reinforced by their response about the VP4:

"…they're really comfortable – they felt like they cushion the foot really well." P10

"I think because of the cushioning it'll reduce that factor on your joints and everything." P14.

Theme 3 – Support and stability

The perceived importance of shoe construction was not limited to the cushioning properties of running footwear, but also extended to the support and stability characteristics of shoes. When running in OWN, runners cited the supportive features of their shoes as being important for injury avoidance:

"My own because there is support up into the ankle and the way that the shoe is designed has a more secure fitting around the outside." P6

"I guess my shoes have some good mix of support and weight in them." P12

These beliefs of the importance of supportive features for injury prevention were also supported by runners linking the perceived supportive properties of the VP4 to a lesser risk of injury:

"Putting black (VP4) as the number one as…I'm thinking about maybe support in your joints." P3

"…even though they feel a bit different I felt like they still had quite good support. So as you're doing some decent k's, they will give you that support that you need." P12.

Likewise, the VP4 perceived to have less support were considered to be less protective against injury:

"…there was no real stability going sideways.." P2

FLAT was most often perceived as the shoe with the highest injury risk. Participants cited too little cushioning and support as reasons for this ranking:

"Orange (FLAT), just that lack of support was already hurting on a short run, so I don't think it'd be a good long term shoe for me." P11

"Too light. Not enough cushioning." P14

"…I just felt like after running for a while you just sort of yeah, just gradually get injured I think. I just don't think they have that support and then other ones do." P12

Discussion

Our study revealed unique and deep insights of participants' perceptions of running in novel shoes. Four main themes of "familiarity", "cushioning", "stability" and "ease of running" give a comprehensive picture of runners' perceptions related to comfort, performance, and injury risk. There were additional sub themes that emerged, including "support", "versatility", and "balance". While the perceptions of runners regarding footwear can often be complex, multifaceted, and greatly individualised; there are some commonalities that emerged between participants. The nature of the qualitative data here gathered allows for a broader perspective and deeper understanding of runners' views with regards to running footwear than what is commonly encapsulated through more quantitative data using visual analogue and Likert scales.

The thematic analysis categorised the participants responses into comfort at the fast and slow speeds, performance. The overall main themes of the data were familiarity, cushioning, support, and ease of running. Other sub themes mentioned include versatility, stability, and fear of adverse events.

Comfort

Ease of running

The participants' comfort impacted their perception of the ease of running. Both novel shoes had positive and negative feedback surrounding comfort. More participants expressed positive feedback on the VP4 compared to the FLAT. The perceived lower effort involved in running in VP4 than FLAT could indicate that their running economy improved due to being more comfortable (Van Alsenoy et al., 2023); or that they were more comfortable because their running economy improved. It might be that runners' perceptions of ease of running in a novel shoe is a valid indicator of being a responder or non-responder. Future research could investigate links between perceived exertion/effort and running economy in shoes.

Cushioning and balance

The participants often referred to VP4 as being soft and bouncy, seen in figure 7. However, some runners found them to be too extreme (i.e., too cushioned, and too soft). Likewise, there were both positive and negative perceptions of the FLAT. One participant enjoyed the natural feel of the shoe, but like the VP4, others found it too extreme in terms of its minimalism. This finding is similar to that seen in previous research which found barefoot and minimalistic shoe running to be perceived as an extreme despite being more natural (Walton & French, 2016). Some participants in our study referred to their OWN shoes as balanced, and not too extreme in either direction. The divergent nature of these opinions demonstrates the range in preferences for runners and highlights the subjective nature of comfort (Mills et al., 2018; Tay et al., 2017). Recreational runners may perceive the novelty of FLAT and VP4 as extremes and preferer a balance between too much and too little cushioning (Walton & French, 2016) and could be why only one participant would purchase the FLAT after trialling the shoe.

Familiarity and novelty

Like extremes of the novelty shoes being perceived both positive and negative, the familiarity of OWN was not always positive. Some runners preferred the novel footwear compared to their own, showing that trying new footwear can benefit runners and they may find a more comfortable footwear option. A possible reason for runners preferring novel shoes might be due to the amount of wear in their own shoes, with research indicating a reduce amount of cushioning at the heel with increased mileage over time in rear-foot strikers (Cornwall & McPoil, 2017). On average the participants OWN shoes were 10 months old (Table 8.) and may not be in optimal condition. However, our findings also show that the perception of being familiar with a shoe, especially when running faster or in a performance context, is an important factor.

Performance

Ease of running

Runners expressed multiple views regarding their perceived effort while running in VP4. Some participants felt the shoe was light and that they could run faster with less effort than in FLAT and OWN. However, other runners felt the VP4 had too much cushioning and lacked flexibility, hindering their performance. A possible explanation for this finding is the variation also observed in the running economy of recreational runners wearing VP4 (Hébert-Losier et al., 2022) compared to habitual shoes. Non-responders to shoes with AFT may notice their perceived effort increase in the shoes as a result of their running economy being negatively impacted. Similar to the variation in running economy seen in previous research (Hébert-Losier et al., 2022), Figure 8 shows VP4 was both the most and least favoured for performance showing its differing influence on runners. Furthermore, this study was acute in nature and participants did not have time to become accustomed to wearing the novel shoes prior to experimentation as the interest was in their acute perceptions and responses. It could be that with a period of wear, participants would become more favourable to novel footwear. Another finding shown in figure 7, is that both novel shoes are described by the participants as fast/quick, there are no other major commonalities between the shoes descriptors. Hence, participants could find the shoes beneficial in a performance environment.

Familiarity and stability

Many participants in our study prioritised the familiar support of their OWN shoes instead of other potential performance-enhancing features, such as a lower shoe mass. The runners perceive they could perform better in a comfortable and familiar shoe. Footwear comfort has been linked to improved running economy (Nigg et al., 2017). A meta-analysis concluded with moderate confidence that a more comfortable shoe can be associated with an improved running economy (Dhillon et al., 2020; Luo et al., 2009), which potentially explain the perception of some runners feeling as if they would perform better in their OWN shoes. In any case, these observations indicate that runners should familiarise themselves with their running footwear to ensure they are comfortable before using them in a race environment. Familiarising oneself with running footwear gradually can help reduce fears of adverse events occurring in races. That said, it has been proposed, with no evidence, that runners replace their footwear every 500-700 kilometres (Fredericson, 1996) to optimise performance and minimise injury risk (Fredericson, 1996).

Balance and versatility

The participants tended to prefer the balanced nature of their OWN shoes and their versatility to be used in different running scenarios. In contrast to propositions that intended running purpose is an important attribute to footwear recommendation and selection (Agresta et al., 2022), our results highlight that recreational runners might prefer running footwear that are multipurpose and versatile. However, in alignment with previous research (Agresta et al., 2022; Ramsey et al., 2022), some participants did desire a shoe with a specific use. The conflicting views demonstrate the variability in runners preferences (Ramsey et al., 2022), and that there is no one-size-fits-all.

Injury

Familiarity

Participants most frequently selected OWN as the shoe with the lowest injury risk. Their OWN shoes were predictable in the sense that they knew what the shoe would feel like and how it would react. In contrast, participants felt the novel shoes lacked stability and increased their risk of injury in comparison to OWN; a sensation that aligns with previous research demonstrating that runners unfamiliar with barefoot running were more unstable when running barefoot (Ekizos et al., 2017). It also aligns with propositions that the greater amount of cushioning and stack height in shoes with AFT could lead to frontal plane instability (Hébert-Losier & Pamment, 2023; Hoogkamer, 2020). The runners are justified in perceiving their footwear as the least likely to cause injury as changing footwear can acutely increase injury risk while adaptation occurs (Warne & Gruber, 2017). The comfort filter paradigm also suggests runners choose the most comfortable and biomechanically optimal footwear (Nigg et al., 2015), although this paradigm is yet to be proven. Shoes with AFT are more similar in construct and design to traditional running shoes in terms of cushioning, heel height, heel-to-toe drop, and minimalist index rating. The familiarity of the cushioning and other footwear characteristics could explain why the VP4 was perceived to have a lower injury risk than the FLAT.

Cushioning

The importance of cushioning in running footwear for mitigating ground reaction forces and minimising injury risk is controversial. There is currently insufficient evidence to justify the presence of an association between ground reaction forces and running-related injuries (Agresta et al., 2022). Nonetheless, our participants noted the FLAT had an increased injury risk due to the lack of cushioning perceived to cause jarring and impacts. Heel cushioning is associated with loads at the ankle and – to a lesser extent – the knee (Meardon et al., 2018), which could cause the perception of jarring and impact. The opposite was perceived for the VP4; participants believed the cushioning would reduce the load on joints, despite the primary purpose of the PEBA foam being to enhance performance rather than prevent injury (Nigg et al., 2020). In fact, recent research advocate that a gradual transition to shoes with AFT is needed, similar to minimalist shoes, as case studies were linked to navicular bone stress injuries (Tenforde et al., 2023). However, this increased cushioning and stack height also is perceived to cause instability, particularly around corners which aligns with suggestions from previous research (Hoogkamer, 2020).

Support and stability

Feeling supported was also important for runners when evaluating the injury risk of the three shoes. Participants tended to enjoy the stable and supportive nature of their OWN running shoes. The FLAT was noted to have the least support, which the participants believed increased their injury risk. Running footwear has the potential to alter foot pronation of runners (Cheung et al., 2011), as shown for footwear containing motion control technologies (Anselmo et al., 2018). However, the perceptions of our participants regarding stability and support went beyond pronation control. Some runners referred to how the footwear supported their ankles, joints, or body in general, with these sensations of support linked to shoe mass and cushioning. This finding reiterates how individuals' experiences and perceptions differ, which will impact their running footwear preferences. The runners' perceptions were also not always associated with the intended feature for the shoe. For instance, we found runners associated the sensation of stability to be linked with the mass of the shoe rather than motion control or arch support features, demonstrating the disconnect in terminology between manufacturers and runners (Dhillon et al., 2020).

Limitations and strengths

While interpreting our findings, certain limitations need to be considered. Firstly, it is important to recognise that our sample is exclusively comprised of male recreational runners. Consequently, the generalisation of our results to females and other running cohorts cannot be confirmed. The physiological and biomechanical differences between male and female runners (Helgerud et al., 1990; Xie et al., 2022) and variations across different running experiences (Leskinen et al., 2009) may change the perceptions of comfort. Therefore, caution is needed when extending our conclusions beyond the scope of our specific sample.

Another limitation lies in the selection of shoes examined. We focused on one model of shoe with AFT and one minimalist shoe model. There are many running shoe models with AFT now available (Joubert & Jones, 2022) and a range of minimal shoes (Sinclair et al., 2013) , each with variations in shoe properties and design. Consequently, the comfort perceptions observed in our study may not represent the entire range of AFT and minimalist shoes on the market. Future research should consider investigating a broader range of running shoes to comprehensively capture the comfort experiences associated with different running shoe models.

Due to cost constraints, we had limited shoe sizes available. One participant noted that the size used during the trial was slightly larger than their optimal fit, potentially influencing their comfort perceptions. Shoe fit is one factor identified as important in running footwear selection (Fife et al., 2023). Hence a substandard fit could have affected comfort ratings of participants.

Despite these limitations, our study has several strengths. The qualitative approach resulted in a rich data set that allowed for a thorough and multi-facetted exploration of runners' experiences and perceptions of comfort, injury risk, and performance in three footwear. This is the first study examining subjective perceptions of runners in AFT and expands on the footwear perceptions of runners wearing minimal shoes. By incorporating two different running speeds for a prolonged duration, we were able to capture a more comprehensive understanding of the participants' experiences.

Furthermore, the ecological validity of our study is a notable strength. By conducting the running trials in an outdoor environment where runners would use the shoes if they were training or racing, we ensured that the observed perceptions were more representative of real-world conditions. This consideration is important, as some studies indicate significant differences in running biomechanics between outdoor and treadmill running (Benson et al., 2020; García-Pérez et al., 2014; Milner et al., 2020; Van Hooren et al., 2020). In addition, the baseline condition used was the participants OWN shoes which ensured the participant was familiar with the condition. Due to runners OWN shoes were used there is a range of different shoes used in the trial, however all of these shoes were below 70% on the minimalist index so it is unlikely to have impacted the biomechanics of the runner (Rice et al., 2016; Roca-Dols et al., 2018).

Conclusion

The OWN shoe was favoured to minimise injury risk and FLAT was perceived to have the highest injury risk. VP4 had the highest number of participants who most favoured it for performance and most people who least favoured it for performance. At the slow speed OWN was perceived as the most comfortable, at the fast speed VP4 was perceived as the most comfortable. FLAT was perceived as the least comfortable for both, however more participants found the shoe preferable at the faster speed which shows speed could influence comfort levels and shoe preferences. Our results show the perceived link between comfort and performance in recreational runners and the variability in footwear preference runners' have.

Chapter Four – Final Chapter

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

Summary

When purchasing footwear, runners may prioritise comfort, performance, or injury reduction. Shoe manufacturers have invested in developing shoes that meet the needs of runners, and as a result, there is now a range of shoes available to cater for all preferences (Bermon, 2021). The range of shoes includes minimalist shoes, which gained popularity in the early 2000s and aim to mimic barefoot running. Minimalist shoes offer a potential performance benefit due to their lightweight nature. It is shown that for every 100 g of mass added to a shoe, the oxygen uptake during running increases by 1% (Franz et al., 2012; Frederick, 1984). Minimalist shoes are also proposed to potentially decrease common running-related injuries by decreasing the load at the knees (Bermon, 2021); however, these claims are still debated (Gruber, 2023). More recently, in 2017, Nike introduced a new racing shoe to the market, which contained novel advanced footwear technologies (AFT). These features include increased longitudinal bending stiffness from a carbon or stiff curved plate and a thick midsole constructed of resilient foam, polyether block amide. The AFT ultimately was shown to improve running economy, on average, by 4% (Hébert-Losier et al., 2022; Hoogkamer et al., 2018). However, individual responses are noted, particularly in recreational runners (Hébert-Losier et al., 2022). Concerns have been raised regarding potential injuries caused by AFT (Hébert-Losier & Pamment, 2023; Hoogkamer, 2020; Tenforde et al., 2023). A gradual transition is advised with both minimal shoes and shoes with AFT to allow for adaptation; however, the adaptation period is relatively unknown and likely to be individual-specific (Fife et al., 2023). Aside from performance and reducing injury risk, comfort is a critical and multifaceted factor for recreational runners when choosing footwear (Ramsey et al., 2022). Footwear comfort can potentially improve performance (Fuller et al., 2015; Van Alsenoy et al., 2023) and has been proposed to minimise injury risk (Nigg et al., 2017); however, both of these claims are debated (Agresta et al., 2022; Hébert-Losier et al., 2022). Most research on minimalist shoes and shoes with AFT is conducted in a laboratory setting, despite being designed for outdoor use (Hoogkamer et al., 2018), which limits the ecological validity of findings. Research on footwear is typically conducted quantitatively, which fails to capture valuable insights from runners gained via qualitative analysis. A combined quantitative and qualitative approach can help better understand the complex nature between running footwear comfort, performance, and injury risk.

In this thesis, two experimental studies were undertaken to investigate the biomechanics, comfort, and overall running experience of male recreational runners in three different running footwear. The first study provided a quantitative analysis of the effect of three different running shoes (FLAT, VP4, and OWN) on the biomechanics, comfort, and overall running experience of runners. OWN shoes were more comfortable than VP4 and FLAT, where the effects were *moderate* to *large*. The novel shoes

had non-significant or *small* effects on runners' biomechanics, except for foot strike angles in FLAT and the propulsive phase in VP4. The second study was qualitative in nature to better understand the perceptions around novel footwear in recreational runners. The main themes found via thematic analysis of interviews with runners were familiarity, support, cushioning, and ease of running. Runners favoured the familiarity of their own shoes. The participants perceived the VP4 as bouncy and potentially unstable. The FLAT was perceived as lightweight and to lack cushioning. Both novel shoes were associated with quickness and running fast. Despite the association with quickness, only one participant would consider purchasing the FLAT after running in them for 1.5 km, and six would consider purchasing the VP4. Our results overall re-emphasise the subjective and complex nature of comfort, individualised shoe preference, and the general lack of association between comfort and biomechanical measures.

Practical applications

Several practical implications emerge from the findings of this thesis. Runners experienced a greater level of comfort and, therefore, may be more likely to purchase shoes with AFT over minimalist shoes. Shoes with AFT are closer in design than traditional footwear and have greater cushioning. Ultimately, runners may perceive the AFT shoes and its cushioning to be more familiar to their habitual shoe choices than minimalist shoes. When runners are trialling or switching to novel footwear, caution is advised when transitioning as an adaptation period is required to minimise injury risk and optimise comfort. Furthermore, the intended use and running speed should be considered when selecting footwear. For instance, the comfort ratings and perceptions of our runners suggest that greater cushioning was potentially more important for comfort at slower speeds and preferred in running footwear, while its importance was less for faster-paced running. Although, the resilient polyamide block elastomer foam and longitudinal stiffness may still be beneficial for performance. Manufacturers and retailers should continue offering various options that cater to the different running experiences and preferences of runners. The subjective nature of individuals' views on footwear should not be overlooked. Each person has unique preferences, and what may be optimal for one runner may not be for another.

Strengths

The findings presented in this thesis add to the research on running footwear. While numerous studies have been conducted on running shoes in controlled laboratory settings, very few have explored the effects of outdoor environments, particularly in shoes with AFT. The ecological validation of footwear is crucial since race shoes are designed to be worn outside. Testing shoes in outdoor settings accounts for various factors, notably ground stiffness and bends, that can influence runners' perception of comfort. These aspects should continue to be addressed in future research.

One of the key strengths of this thesis is the consideration of the multifaceted nature of comfort, which is subjective to each person. Despite its importance, there is a noticeable lack of qualitative studies focusing on running footwear comfort. The research conducted in this thesis addresses this gap by using interviews that investigate the experiences and perceptions of runners: A novelty for shoes with AFT. The qualitative approach combined with the quantitative analysis generates a rich dataset that thoroughly examines the runners' experience.

Limitations

One limitation of this thesis is the relatively small sample size and that it consists only of male recreational runners. Consequently, the findings may not be generalised to females and other groups with different levels of running experience. Including a more diverse sample could provide a more comprehensive understanding of how comfort varies across different running populations.

Another limitation is that only one type of shoe with AFT and one type of minimalist shoe were investigated. Since the Nike Vaporfly 4% launch in 2017, other leading footwear brands have also developed versions of AFT shoes. Furthermore, many companies now offer multiple variations of AFT shoes. While minimalist shoes are designed to replicate barefoot running, it is important to note that there may still be variations among different models and brands. Investigating one type of AFT and minimalist shoe may not capture the variation of shoes currently available.

Future research

Future studies can build upon the current research by addressing the limitations and lack of generalisability. Increasing the sample size, including other running populations, and exploring a wider range of AFT and minimalist shoe models would contribute to a more comprehensive understanding of comfort in running. Furthermore, research in this area should seek to combine quantitative and qualitative approaches to gain a more comprehensive understanding of factors contributing to runners' perception of comfort and performance. Another possible avenue is examining the influence of running speed on footwear comfort. It is well-known that running speed can affect biomechanics and foot strike patterns (Breine et al., 2019). Therefore, investigating how different running speeds impact the perception of comfort can provide valuable insights into the dynamic relationship between speed and different footwear. Further research could also explore whether the perceived ease of running in novel shoes is associated with an improved running economy. Understanding the relationship between perceived exertion and running economy could provide valuable insights into runners' responses to minimal shoes and shoes with AFT. This investigation has the potential to shed light on whether individuals positively or negatively respond to the use of minimal shoes and shoes with AFT based on their subjective exertion.

Conclusion

Overall, this thesis provides novel data relevant to the understanding of running shoes and footwear comfort. There was little association between running footwear comfort and biomechanics, with individuals perceiving their shoes as the most comfortable. Overall, familiarity with habitual shoes is generally regarded as positive. Furthermore, the perception of novel footwear was characterised by both positive and negative views. Shoes with AFT were perceived as 'bouncy', whereas minimalist shoes were perceived as 'light'. Both novel footwear were perceived as fast and quick by some runners. Lastly, this thesis highlights the role of comfort in runners' footwear preference, as well as price. Ultimately, this research paves the way for a more holistic understanding of running footwear and provides valuable insights that can inform the development of future shoe designs and enhance the overall running experience for runners.

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Appendix

Appendix One – Ethics approval

The University of Waikato
Private Bag 3105
Gate 1, Knighton Road
Hamilton, New Zealand

Human Research Ethics Committee
Roger Moltzen
Telephone: +64021658119
Email:humanethics@waikato.ac.nz

15 January 2021

Kim Hebert-Losier
Te Huataki Waiora School of Health
By email: kim.hebert-losier@waikato.ac.nz

Dear Kim

HREC(Health)2020#83 : Comfort and perceptions of recreational runners wearing new footwear

Your application for HREC(Health)2020#83 was considered on 15 December 2020 by the University of Waikato Human Research Ethics Committee (Health). We understand from your application that the purpose of your project is to explore the perceptions and comfort of recreational runners wearing two different novel footwear compared to their own: Nike Vaporfly 4% and Saucouny Endorphin Racer 2 (racing flats), while monitoring self-selected running speeds and select biomechanical measures.

There were no issues with the application and we are now pleased to provide formal approval for your project.

Please contact the committee by email (humanethics@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.

Regards,

____

Emeritus Professor Roger Moltzen MNZM
Chairperson
University of Waikato Human Research Ethics Committee

Appendix Two – Chapter Two supplementary material

<u>Comfort visual analogue scale (VAS)</u>

^ Experimental shoes only

^ Predicted comfort – *How comfortable do you think running in these shoes will be? (based on looking, holding, feeling)*

Not comfortable at all **Most comfortable imaginable**

Acute comfort – *How comfortable do you think running in these shoes will be? (based on having the shoes on)*

Not comfortable at all **Most comfortable imaginable**

Slow comfort – *Consider your overall comfort in these shoes when running at the slower (comfortable) speed*

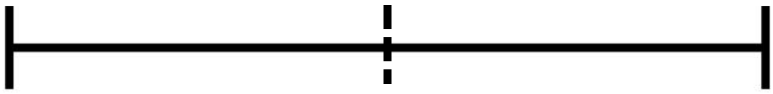
Not comfortable at all **Most comfortable imaginable**

Fast comfort – *Consider your overall comfort in these shoes when running at the faster (5 km) speed*

Not comfortable at all **Most comfortable imaginable**

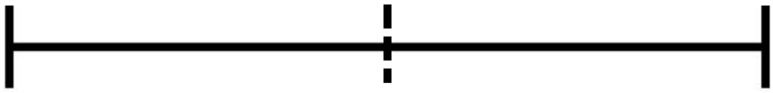
Shoe properties visual analogue scale (VAS) after slow and fast running

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



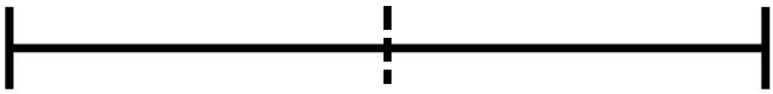
Heel not cushioned at all **Ideal** **Heel too cushioned**

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



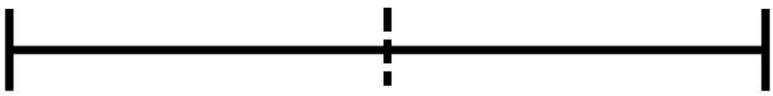
Forefoot not cushioned at all **Ideal** **Forefoot too cushioned**

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



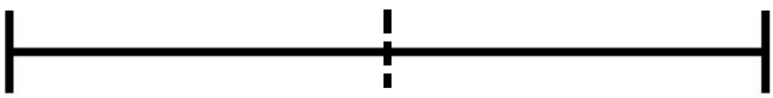
Forefoot not flexible at all **Ideal** **Forefoot too flexible**

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



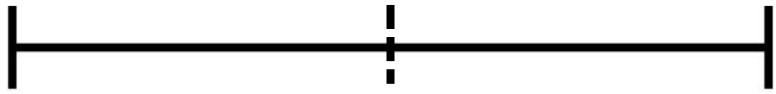
Shoe not stable at all **Ideal** **Shoe too stable**

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



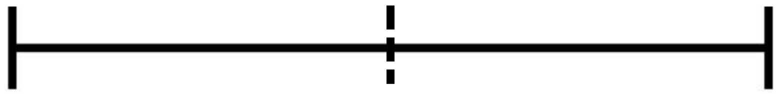
Shoe not stiff at all **Ideal** **Shoe too stiff**

Technical and supporting features – *Consider the overall technical and supporting features of the shoe (arch, motion control, rigid heel counter, supportive tensioned upper, etc.). How do you feel?*



No features at all **Ideal** **Too many features**

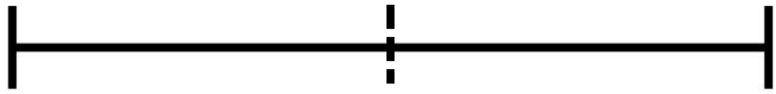
Shoe weight – *Consider the overall weight of the shoe. How do you feel?*



Shoe too light **Ideal** **Shoe too heavy**

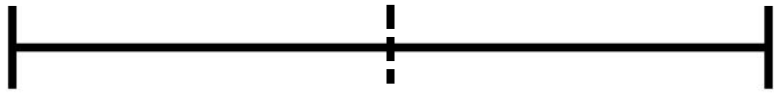
Overall running experience visual analogue scale (VAS) after slow and fast running

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



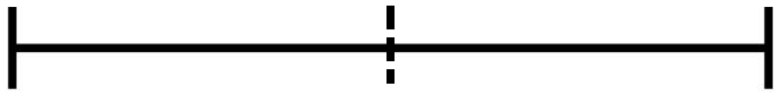
Very bad **Neutral** **Very good**

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



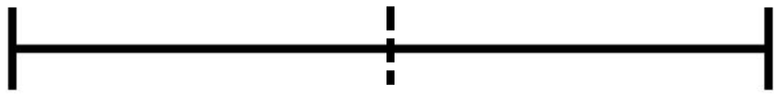
Much harder **Neutral** **Much easier**

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



Much worse **Neutral** **Much improved**

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



Much lower risk **Neutral** **Much higher risk**

POST ALL SHOE CONDITIONS

Ranking

Overall, which shoe was the most comfortable when running at the slower (comfortable) speed?

1. _________________________ (most comfortable)
2. _________________________
3. _________________________ (least comfortable)

Overall, which shoe was the most comfortable when running at the faster (5-km) speed?

1. _________________________ (most comfortable)
2. _________________________
3. _________________________ (least comfortable)

Overall, which shoe do you think you would perform the best in under a race situation?

1. _________________________ (best performance)
2. _________________________
3. _________________________ (worst performance)

Overall, in which shoe do you think your injury risk would be lowest?

1. _________________________ (lowest risk of injury)
2. _________________________
3. _________________________ (highest risk of injury)

Table S1. Effect sizes and confidence levels [lower, upper] of differences in biomechanical measurements.

Variable	Distance	OWN/FLAT	FLAT/VP4	VP4/OWN
Overall Speed (m/s)	1.1 km	0.14 [-0.24,0.54]	0.06 [-0.10,0.22]	0.20 [-0.20,0.60]
	400 m	0.27 [0.03,0.51]	0.15 [0.00,0.31]	0.10 [-0.16,0.36]
Optojump measurements				
Speed (m/s)	1.1 km	**0.37 [0.11,0.64]**	0.05 [-0.21,0.30)	**0.28 [0.06,0.50]**
	400 m	0.04 [-0.31,0.39]	0.12 [-0.16,0.41]	0.10 [-0.15,0.36]
Cadence (steps/minute)	1.1 km	**0.35 [0.13,0.58]**	**0.28 [0.03,0.50]**	0.09 [-0.11,0.29]
	400 m	0.16 [-0.01,0.33]	0.15 [-0.01,0.29]	0.02 [-0.17,0.20]
Step length (cm)	1.1 km	0.20 [-0.10,0.50]	0.09 [-0.18,0.36]	0.25 [0.05,0.45]
	400 m	0.15 [-0.22,0.52]	0.23 [-0.12,0.59]	0.10 [-0.10,0.29]
Flight time (s)	1.1 km	0.25 [0.02,0.48]	0.01 [-0.25,0.23]	0.22 [-0.09,0.52]
	400 m	0.05 [-0.23,0.35]	0.16 [-0.07,0.39]	0.11 [-0.14,0.36]
Contact time (s)	1.1 km	**0.49 [0.29,0.69]**	0.22 [-0.024,0.47]	0.27 [-0.026,0.56]
	400 m	0.09 [-0.21,0.39]	0.02 [-0.18,0.21]	0.13 [-0.17,0.43]
Propulsive phase (%)	1.1 km	0.35 [-0.11,0.81]	**0.92 [-0.41,1.43]**	**0.53 [0.21,0.86]**
	400 m	0.41 [-0.13,0.94]	**1.18 [0.63,1.74]**	**0.84 [0.34,1.33]**
k_{vert} (kN/m)	1.1 km	**0.34 [0.17,0.51]**	**0.21 [0.03,0.39]**	0.17 [-0.01,0.34]
	400 m	0.11 [0.03,0.20]	0.10 [0.02,0.17]	0.03 [-0.05,0.11]
k_{leg} (kN/m)	1.1 km	**0.19 [0.04, 0.33]**	**0.15 [-0.02,0.29]**	0.03 [-0.11,0.17]
	400 m	0.09 [-0.04,0.21]	0.05 [-0.04,0.14]	0.03 [-0.09,0.15]
Duty factor (%)	1.1 km	**0.37 [0.15,0.58]**	0.09 [-0.16,0.34]	0.25 [-0.05,0.55]
	400 m	0.01 [-0.30,0.32]	0.12 [-0.11,0.35]	0.13 [-0.15,0.42]
2D camera data				
Foot strike angle (°)	1.1 km	**0.47 [0.23,0.70]**	**0.56 [0.14,0.97]**	0.01 [-0.34,0.36]
	400 m	**0.59 [0.14,1.04]**	**0.89 [0.43,1.36]**	0.25 [-0.24,0.75]
IMU sensor data				
TRA (g)[a]	1.1 km	0.51 [-0.05,1.08]	0.10 [-0.25,0.45]	0.33 [-0.21,0.87]
	400 m	0.27 [-0.25,0.79]	0.43 [-0.13,1.00]	0.01 [-0.64, 0.83]

Notes. Significant differences during post-hoc comparisons ($p \leq 0.05$) indicated in **bold**. [a] Missing data from 4 participants. **RUN-CAT weighted average of four measures, where 100 represents ideal. *Abbreviations.* 2D, two-dimensional. FLAT, Saucony Endorphin Racer 2 road racing flat. IMU, inertial measurement unit. k_{leg}, leg stiffness. k_{vert}, vertical stiffness. OWN, runners own habitual running shoes. RUN-CAT, running shoe comfort assessment tool. TRA, tibial resultant acceleration. VAS, visual analogue scale. VP4, Nike Vaporfly 4%.

Table S2. P-values from t-test

Variable	Distance	OWN/FLAT	FLAT/VP4	VP4/OWN
Overall Speed (m/s)	1.1 km	0.450	0.453	0.320
	400 m	0.034	0.060	0.457
Optojump measurements				
Speed (m/s)	1.1 km	**0.008**	0.714	**0.016**
	400 m	0.830	0.379	0.409
Cadence (steps/minute)	1.1 km	**0.004**	**0.031**	0.369
	400 m	0.064	0.049	0.862
Step length (cm)	1.1 km	0.181	0.509	0.018
	400 m	0.421	0.189	0.308
Flight time (s)	1.1 km	0.039	0.937	0.158
	400 m	0.678	0.172	0.364
Contact time (s)	1.1 km	**0.000**	0.082	0.076
	400 m	0.533	0.867	0.397
Propulsive phase (%)	1.1 km	0.130	**0.000**	**0.003**
	400 m	0.127	**0.000**	**0.001**
k_{vert} (kN/m)	1.1 km	**0.011**	**0.020**	0.446
	400 m	0.164	0.202	0.575
k_{leg} (kN/m)	1.1 km	**0.001**	**0.039**	0.081
	400 m	0.185	0.245	0.591
Duty factor (%)	1.1 km	**0.002**	0.376	0.145
	400 m	0.954	0.381	0.495
2D camera data				
Foot strike angle (°)	1.1 km	**0.001**	**0.009**	0.959
	400 m	**0.010**	**0.000**	0.301
IMU sensor data				
TRA (g)[a]	1.1 km	0.072	0.629	0.306
	400 m	0.495	0.087	0.339

Table S3. Effect sizes and confidence levels [lower, upper] of differences in VAS measurements.

Characteristics	**OWN/FLAT**	**FLAT/VP4**	**VP4/OWN**
Comfort VAS			
Predicted	--	0.44 [-0.16,1.03]	--
Acute	**1.20 [0.44,2.00]**	**0.77 [0.10,1.43]**	0.31 [-0.46,1.07]
Slow speed	**1.08 [0.37,1.79]**	**0.68 [0.00,1.36]**	0.27 [0.24,0.79]
Fast speed	0.66 [0.02,1.29]	0.25 [-0.48,0.98]	0.32 [-0.15,0.78]
Shoe properties			
Heel cushioning*	**1.59 [0.62,2.57]**	**2.60 [1.21,4.01]**	**1.22 [0.12,2.32]**
Forefoot cushioning*	**0.87 [0.09,1.64]**	**1.07 [0.50,1.64]**	0.46 [-0.27,1.19]
Forefoot flexibility*	0.33 [-0.24,0.91]	**1.35 [0.34,2.38]**	**1.00 [0.10,1.90]**
Stability*	0.56 [-0.06,1.18]	0.30 [-0.43,1.03]	0.21 [-0.58,1.00]
RUN-CAT **	**0.95 [0.12,1.77]**	0.31 [-0.44,1.06]	**0.63 [0.05,1.22]**
Stiffness*	0.10 [-0.46,0.66]	**1.34 [0.28,2.40]**	**1.44 [0.34,2.55]**
Technical features*	0.38 [-0.06,0.82]	**1.63 [0.58,2.67]**	**1.23 [0.37,2.09]**
Weight*	**1.88 [0.58,3.18]**	**0.81 [0.16,1.48]**	0.66 [-0.13,1.45]
Overall running experience VAS			
Pleasure/displeasure	0.83 [0.06,1.60]	0.46 [-0.24,1.17]	0.36 [-0.19,0.90]
Easiness/hardness	0.52 [-0.11,1.14]	0.28 [-0.32,0.88]	0.27 [-0.20,0.74]
Performance (worse/improved)	0.12 [-0.48,0.72]	0.24 [-0.36,0.84]	0.11 [-0.34,0.55]
Injury risk (lower/higher)	**1.27 [0.50,1.27]**	0.58 [-0.18,1.34]	**0.82 [-0.02,1.66]**

Notes. Significant difference during post-hoc comparisons ($p \leq 0.05$) are in **bold**. **RUN-CAT weighted average of four measures, where 100 represents ideal. *Abbreviations.* FLAT, Saucony Endorphin Racer 2 road racing flat. OWN, runners own habitual running shoes. RUN-CAT, running shoe comfort assessment tool. VAS, visual analogue scale. VP4, Nike Vaporfly 4%.

Table S4. P values from t-test for subjective measures

Characteristics	**OWN/FLAT**	**FLAT/VP4**	**VP4/OWN**
	Comfort VAS		
Predicted	**--**	0.136	--
Acute	**0.001**	**0.016**	0.416
Slow speed	**0.001**	**0.038**	0.287
Fast speed	0.034	0.488	0.172
	Shoe properties		
Heel cushioning*	**0.000**	**0.000**	**0.009**
Forefoot cushioning*	**0.017**	**0.000**	0.194
Forefoot flexibility*	0.241	**0.002**	**0.013**
Stability*	0.064	0.403	0.595
RUN-CAT **	**0.012**	0.400	**0.028**
Stiffness*	0.724	**0.002**	**0.001**
Technical features*	0.088	**0.000**	**0.001**
Weight*	**0.000**	**0.010**	0.077
	Overall running experience VAS		
Pleasure/displeasure	0.022	0.175	0.187
Easiness/hardness	0.090	0.354	0.258
Performance (worse/improved)	0.691	0.413	0.633
Injury risk (lower/higher)	**0.000**	0.112	**0.036**

Table S5. Correlation 95% confidence intervals [lower, upper] between comfort measures and subjective and biomechanical measures.

	Predicted comfort	***Acute comfort***	***Slow comfort***	***Fast comfort***	***RUN-CAT***
Comfort VAS					
Predicted comfort	1.000	--	--	--	--
Acute comfort	[-0.094, 0.709]	1.000	--	--	--
Slow comfort	[-0.210, 0.645]	**[0.455, 0.822]**	1.000	--	--
Fast comfort	[-0.102, 0.705]	**[0.254, 0.732]**	**[0.509, 0.844]**	1.000	--
Shoe properties VAS					
Heel cushioning*	[-0.032, 0.749]	**[0.207, 0.708]**	**[0.216, 0.712]**	[-0.176, 0.457]	[-0.210, 0.429]
Forefoot cushioning*	**[0.133, 0.805]**	**[0.394, 0.796]**	**[0.183, 0.695]**	[-0.068, 0.540]	[-0.046, 0.555]
Flexibility*	[-0.373, 0.528]	[-0.243, 0.400]	[-0.506, 0.115]	[-0.248, 0.396]	[-0.417, 0.224]
Stability*	[-0.558, 0.337]	[-0.279, 0.368]	[-0.020, 0.573]	[-0.207, 0.432]	**[0.263, 0.736]**
Stiffness*	[-0.368, 0.533,]	[-0.395, 0.249]	[-0.156, 0.482]	[-0.190, 0.446]	[-0.128, 0.496]
Technical features*	**[0.123, 0.802]**	[-0.040, 0.618]	[-0.216, 0.432]	[-0.244, 0.409]	[-0.404, 0.248]
Weight*	[-0.292, 0.590]	[-0.133, 0.499]	[0.075, 0.640]	[-0.232, 0.418]	[-0.120, 0.509]
RUN-CAT**	[-0.451, 0.467]	**[0.131, 0.666]**	**[0.447, 0.819]**	**[0.516, 0.846]**	1.000
Overall running experience VAS					
Pleasure/ displeasure	**[0.0349, 0.768]**	**[0.249, 0.734]**	**[0.404, 0.804]**	**[0.600, 0.880]**	**[0.503, 0.844]**
Easier/ harder	**[0.073, 0.783]**	**[0.085, 0.645]**	**[0.284, 0.751]**	**[0.570, 0.869]**	**[0.314, 0.765]**
Performance (worse/improved)	[-0.105, 0.704]	[-0.163, 0.476]	[-0.167, 0.473]	**[0.165, 0.691]**	**[0.078, 0.642]**
Injury risk (lower/higher)	[-0.443, 0.465]	**[-0.755, -0.293]**	**[-0.753, -0.289]**	**[-0.64, -0.077]**	**[-0.762, -0.309]**
Biomechanical measures					

Overall speed	[-0.418, 0.489]	[-0.201, 0.437]	[-0.252, 0.392]	[-0.109, 0.517]	[-0.323, 0.568]
Speed	[-0.432, 0.475]	[-0.220, 0.420]	[-0.326, 0.322]	[-0.049, 0.553]	[-0.363, 0.284]
Cadence	**[-0.775, -0.052]**	[-0.520, 0.095]	[-0.425, 0.215]	[-0.460, 0.173]	[-0.433, 0.206]
Step length	[-0.320, 0.571]	[-0.131, 0.493]	[-0.276, 0.371]	**[0.032, 0.607]**	[-0.314, 0.334]
Flight time	[-0.363, 0.537]	[-0.20, 0.441]	[-0.264, 0.382]	[-0.054, 0.550]	[-0.285, 0.362]
Contact time	[-0.253, 0.618]	[-0.308, 0.340]	[-0.312, 0.336]	[-0.449, 0.187]	[-0.284, 0.362]
Propulsive phase	[-0.550, 0.346]	[-0.574, 0.019]	[-0.505, 0.115]	[-0.406, 0.237]	[-0.410, 0.232]
k_{vert}	[-0.743, 0.022]	[-0.439, 0.198]	[-0.413, 0.229]	[-0.300, 0.347]	[-0.430, 0.209]
k_{leg}	[-0.668, 0.170]	[-0.460 0.174]	[-0.372, 0.274]	[-0.409, 0.234]	[-0.382, 0.263]
Duty factor	[-0.320, 0.571]	[-0.299, 0.349]	[-0.215, 0.425]	[-0.448, 0.188]	[-0.298, 0.350]
Foot strike angle	[-0.440, 0.469]	[-0.094, 0.521]	[-0.171, 0.462]	[-0.224, 0.418]	[-0.109, 0.510]
TRA	[-0.797, 0.090]	[-0.565, 0.142]	[-0.544, 0.173]	[-0.559, 0.151]	[-0.326, 0.419]

Notes. Meaningful correlations and statistically significant ($|r| \geq 0.30$, *moderate,* $p \leq 0.05$) are **bold**. * midpoint (50 mm) represents ideal, 0 mm indicates an absence of the property and 100 mm indicates too much of a property. † midpoint (50 mm) represents ideal, 0 mm indicates too much of a property and 100 mm indicates the absence of a property **RUN-CAT weighted average of four measures, where 100 represents ideal. *Abbreviations.* k_{leg}, leg stiffness. k_{vert}, vertical stiffness. RUN-CAT, running shoe comfort assessment tool. TRA, tibial resultant acceleration. VAS, visual analogue scale.

Table S6. P values for correlations between comfort measures and subjective and biomechanical measures of data from 18 participants.

	Predicted comfort	*Acute comfort*	*Slow comfort*	*Fast comfort*	*RUN-CAT*
Comfort VAS					
Predicted comfort	--	--	--	--	--
Acute comfort	0.112	--	--	--	--
Slow comfort	0.264	**0.000**	--	--	--
Fast comfort	0.120	**0.001**	**0.000**	--	--
Shoe properties VAS					
Heel cushioning*	0.067	**0.002**	**0.001**	0.352	0.473
Forefoot cushioning*	**0.014**	**0.000**	**0.003**	0.117	0.091
Flexibility*	0.691	0.606	0.200	0.628	0.527
Stability*	0.571	0.770	0.066	0.459	**0.001**
Stiffness*	0.674	0.632	0.267	0.399	0.225
Technical features*	**0.016**	0.029	0.483	0.592	0.613
Weight*	0.446	0.232	0.017	0.545	0.204
RUN-CAT**	0.988	**0.007**	**0.000**	**0.000**	--
Overall running experience VAS					
Pleasure/displeasure	**0.037**	**0.001**	**0.000**	**0.000**	**0.000**
Easier/harder	**0.025**	**0.015**	**0.000**	**0.000**	**0.000**
Performance (worse/improved)	0.123	0.307	0.317	**0.004**	**0.017**
Injury risk (lower/higher)	0.955	**0.000**	**0.000**	**0.017**	**0.000**
Biomechanical measures					
Overall speed	0.854	0.439	0.645	0.263	0.260
Speed	0.912	0.511	0.990	0.094	0.796
Cadence	**0.031**	-0.159	0.490	0.345	0.454
Step length	0.520	0.231	0.756	**0.032**	0.947
Flight time	0.656	0.420	0.699	0.100	0.798
Contact time	0.349	0.916	0.939	0.390	0.800
Propulsive phase	0.601	0.065	0.197	0.576	0.560
k_{vert}	0.062	0.427	0.545	0.877	0.467
k_{leg}	0.200	0.346	0.747	0.564	0.697
Duty factor	0.521	0.871	0.490	0.393	0.865

Foot strike angle	0.941	0.158	0.339	0.523	0.186
TRA	0.096	0.212	0.275	0.228	0.785

Notes. Meaningful correlations and statistically significant ($|r| \geq 0.30$, *moderate,* $p \leq 0.05$) are **bold**. * midpoint (50 mm) represents ideal, 0 mm indicates an absence of the property and 100 mm indicates too much of a property. † midpoint (50 mm) represents ideal, 0 mm indicates too much of a property and 100 mm indicates the absence of a property **RUN-CAT weighted average of four measures, where 100 represents ideal. *Abbreviations.* k_{leg}, leg stiffness. k_{vert}, vertical stiffness. RUN-CAT, running shoe comfort assessment tool. TRA, tibial resultant acceleration. VAS, visual analogue scale.