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Physiology and Training of Marathon Runners from Recreational to World-Class

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All you need is the courage to believe in yourself
and put one foot in front of the other.

Kathrine Switzer

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II. Acknowledgements

First and foremost, I want to express my heartfelt gratitude to my thesis supervisor, Prof. Dr. Henning Wackerhage, for his invaluable support and encouragement throughout my doctoral studies. His guidance and trust allowed me the perfect balance of direction and freedom to develop this project. Furthermore, he demonstrated a great understanding of my situation and goals, always offering valuable advice when needed. His commitment to clear and thorough research and scientific writing will remain a constant guiding principle in my future pursuits. I would also like to extend my sincere thanks to Dr. Martin Schönfelder, I am grateful for his continuous support, especially in navigating the German bureaucracies of the university system. Also, appreciation goes out to additional members of the exercise biology team, including Daniel Appelhans, whose coaching perspective enriched our collaborative research.

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A profound thank you goes to my family and friends, who have been by my side throughout the different stages of my life, despite the physical distances between Germany and the USA. To my mom and dad, I am immensely grateful for their unwavering support, and encouragement, and for paving the way for me to pursue my passions. This is the greatest gift I could ever receive, and I will forever cherish it. To the Menter family, thank you for providing balance and helping me stay focused on the bigger picture.

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This accomplishment would not have been possible without the incredible contributions of all these remarkable individuals. From the depths of my heart, thank you!

Munich, 28.04.2024 Melanie Knopp

III. Foreword

This dissertation is publication-based and comprised of two peer-reviewed scientific articles that collectively enhance our understanding of marathon running and performance. These articles explore a range of topics, from understanding the physiological factors that predict marathon performance to investigating various training methods.

In discussions with my supervisor, we decided the following is the best way to structure this dissertation. Of note, we decided that further elaboration of methods and materials beyond what is published in the original manuscripts is not necessary and will only lead to redundancy.

Throughout this dissertation, I mainly use the active voice, in line with current scientific writing style recommendations such as by Nature. Furthermore, this dissertation is written in US English, incorporating the appropriate punctuation conventions.

As you read through, I hope you find this dissertation interesting and helpful in understanding marathon running better.

IV. Conflict of Interest

I am an employee of adidas AG.

V. Abstract

Marathon running is experiencing contrasting trends. An influx of recreational runners slows average performances, while the elites are breaking world records. This PhD presents two studies that investigate these disparities, by analyzing physiological and training factors in both recreational and elite marathon runners.

The recent surge in road running world records has partially been contributed to advancements in footwear technology. These advancements have been shown to improve the running economy of recreational runners, although the degree of benefit varies from person to person. The main beneficiaries of such technologies, world-class athletes, have only been analyzed using race times. Therefore, the first study investigates the impact of advanced footwear technology on the running economy in seven world-class Kenyan and seven amateur European male runners in a standard laboratory setting. The study involved a $\dot{V}O_2$peak assessment followed by submaximal steady state running economy trials with different advanced footwear and traditional racing flats, supplemented by a systematic search and meta-analysis. Results show amateur runners exhibited a more significant average improvement in running economy using advanced footwear technology (4.4 ± 3.2%) than the world-class group did (0.2 ± 4.7%) when compared to traditional running flats. Additionally, substantial inter- and intra-subject variability was revealed, with performance changes in both world-class road runners, ranging from an 11.4% benefit to an 11.3% drawback, and in amateurs, ranging from a 9.7% benefit to a 1.1% drawback, in running economy of advanced footwear technology compared to a flat. The post-hoc meta-analysis, through Hedge's g, confirms a significant medium benefit with an effect size of -0.58 of advanced footwear technology on running economy compared to traditional flats. This research demonstrates that advanced running shoes could work differently for every runner and calls for personalized approaches by coaches and relevant organizations to ensure optimal performance.

For recreational runners, training factors influence marathon performance. The diversity of marathon training strategies complicates controlled scientific studies, often leading to reliance on subjective, opinion-based training plans. While evidence-informed and results-proven approaches offer new ways to approach training based on scientific analysis, they have not been extensively applied to recreational runners' plans. The second study of this research addresses this gap by scientifically analyzing 92 sub-elite training plans, focusing on the last 12 weeks before a marathon and categorizing plans based on weekly running volume. Results show average weekly distances of 105 km, 58 km, and 44 km for high, middle, and low volume plans, with a pyramidal intensity distribution across zones. While this method has obvious limitations, such as the challenge of verifying the effectiveness of these training plans, this analysis offers tailored marathon training guidance, effectively linking scientific research with practical application.

Overall, this research provides new insights into training and footwear technology, which are poised to transform training and performance strategies for marathon runners at all levels.

VI. Zusammenfassung

Die neuesten Entwicklungen im Marathon zeigen eine gegensätzliche Entwicklung zwischen den Leistungen von Amateur- und Eliteläufern auf. Während die Durchschnittsleistungen bei Amateurläufern sinken, werden bei den Eliteläufern im Marathon Weltrekorde gebrochen. Diese Dissertation beinhaltet zwei Studien, die diese Unterschiede näher betrachten, indem physiologische und trainingsbezogene Faktoren sowohl bei Amateur- als auch bei Eliteläufern im Marathon analysiert werden.

Der jüngste Anstieg der Straßenlauf-Weltrekorde ist teilweise auf Fortschritte in der Schuhtechnologie zurückzuführen. Diese Fortschritte in der Technologie hat auch Verbesserungen in der Laufökonomie von Amateurläufern gezeigt. Dabei variiert die Auswirkung stark je Athlet. Diejenigen, die am meisten von solchen Technologien profitieren, Weltklasse-Athleten, wurden bisher nur anhand von Wettkampfergebnissen analysiert. Daher untersucht die erste Studie die Auswirkungen fortschrittlicher Schuhtechnologie auf die Laufökonomie von sieben Weltklasse-Läufern aus Kenia und sieben Amateurläufern aus Europa in einem standardisierten Laborumfeld. Die Studie beinhaltete eine $\dot{V}O_2$peak-Bewertung, gefolgt von submaximalen Laufökonomie-Tests mit verschiedenen fortschrittlichen Schuhen und herkömmlichen Wettkampf-Flats. Dies wird ergänzt durch eine systematische Suche und Metaanalyse. Die Ergebnisse zeigen eine größere durchschnittliche Verbesserung bei den Amateurläufern in der Laufökonomie beim Einsatz von fortschrittlicher Lauftechnologie (4,4 ± 3,2% Durchschnitt ± Standardabweichung) als bei Elite-Läufern (0,2 ± 4,7% Durchschnitt ± Standardabweichung) im Vergleich zu herkömmlichen Flats. Zusätzlich wird eine erhebliche inter- und intraindividuelle Variabilität festgestellt, mit Leistungsänderungen sowohl bei Weltklasse-Läufern als auch bei den Amateuren. Bei den Weltklasse-Läufern erstrecken sich die Reaktionen auf die Laufökonomie durch fortschrittlichen Schuhtechnologie im Vergleich zu einem Flat in einem Bereich von -11,3% Nachteil bis zu einem 11,4% Vorteil, während die Auswirkungen bei den Amateuren in einem Bereich zwischen -1,1% Nachteil und 9,7% Vorteil liegen. Die ergänzende Metaanalyse bei der Anwendung von Hedge’s g bestätigt einen signifikanten mittleren Vorteil mit einer Effektgröße von -0,58 beim Einsatz fortschrittlicher Schuhtechnologie für die Laufökonomie im Vergleich zu herkömmlichen Flats. Diese Forschung zeigt, dass fortschrittliche Schuhtechnologie unterschiedliche Auswirkungen auf Elite-Läufer hat und unterstreicht somit die Notwendigkeit eines individualisierten Ansatzes von Trainern und relevanten Organisationen, um die optimale Performance der Athleten zu gewährleisten.

Bei Amateurläufern beeinflussen weitere Trainingsfaktoren die Marathonleistung erheblich. Die Vielfalt der Marathon-Trainingsstrategien erschwert kontrollierte wissenschaftliche Studien, was oft zu subjektiven Gestaltungen von Trainingsplänen führt. Während evidenzbasierte und ergebnisbewährte Ansätze neue und effektive Wege bieten, das Training auf der Grundlage wissenschaftlicher Analysen zu gestalten, wurden diese noch nicht systematisch auf den Amateur-Bereich angewendet und analysiert. Die zweite Studie dieser Dissertation befasst sich mit dieser Lücke, indem sie 92 Sub-Elite-Trainingspläne wissenschaftlich analysiert. Dabei wird sich auf die letzten 12 Wochen vor einem Marathon konzentriert und Pläne auf der Grundlage des wöchentlichen Laufvolumens kategorisiert. Die Ergebnisse zeigen in den Plänen mit den Laufvolumen niedrig, mittel und hoch eine durchschnittliche wöchentliche Trainings-Distanz von 44 km, 58 km und 105 km auf. Dabei beinhalten die Pläne eine pyramidale Verteilung der Intensitätszonen über den Vorbereitungszeitraum. Obwohl diese Methode offensichtliche Einschränkungen hat, wie die Überprüfung der Wirksamkeit, bietet diese Analyse individuelle Marathon-Trainingsanleitungen und verbindet effektiv wissenschaftliche Forschung mit praktischer Anwendung.

Insgesamt bietet diese Forschung kritische, evidenzbasierte Einblicke in Training und Schuhtechnologie, die darauf ausgerichtet sind, Trainings- und Leistungsstrategien für Marathonläufer auf allen Leistungsniveaus zu transformieren.

VII. List of Publications

First Author Publications:

Knopp, M., Muñiz-Pardos, B., Wackerhage, H., Schönfelder, M., Guppy, F., Pitsiladis, Y., Ruiz, D. Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-analysis Results. Sports Med. 2023;53(6):1255-1271. https://doi.org/10.1007/s40279-023-01816-1

Knopp, M., Appelhans, D., Schönfelder, M. *et al.* Quantitative Analysis of 92 12-Week Sub-elite Marathon Training Plans. *Sports Med - Open* 10, 50 (2024). https://doi.org/10.1186/s40798-024-00717-5

1. Introduction

1.1 Marathon Running: Past, Present, and Trends

The marathon, a 42.195-kilometer race, remains a challenging test of individual endurance that has captivated athletes and enthusiasts alike. It originates from the ancient Greek tale of Pheidippides, who ran from Marathon to Athens to deliver news of their victory at the Battle of Marathon before collapsing and dying (Lucas, 1976). The beginning of the modern Olympics in 1896, marked the introduction of the Olympic marathon race as a men-only event (Maron and Horvath, 1978). The Boston marathon, first held in 1897, became the first non-Olympic marathon road race (Maron and Horvath, 1978). However, it was not until 1972, 75 years later, that women were allowed to participate in the Boston Marathon, with an additional 12 years passing before the inaugural Olympic marathon for women was organized in 1984 (Burfoot, 2007).

In recent years, the marathon's popularity has soared, attracting both recreational and world-class runners with global participation growing by almost 50% from 2008 to 2018, reaching 1.1 million participants in 2018 (Fig. 1, Andersen and Nikolova, 2021). Major world marathons in New York City, Boston, and Berlin have seen parallel participation increases in recent years (Knechtle et al., 2020; Nikolaidis et al., 2018; Reusser et al., 2021), with the average marathon finishing time in 2019 recorded as 4:32:49 h:min:s (Fig. 1, Andersen and Nikolova, 2021; Rizzo, 2021). This time represents the slowest average finish time since 1986, reflecting an increase in both the number of participants and the inclusion of a broad spectrum of recreational runners (Andersen and Nikolova, 2021; Rizzo, 2021).

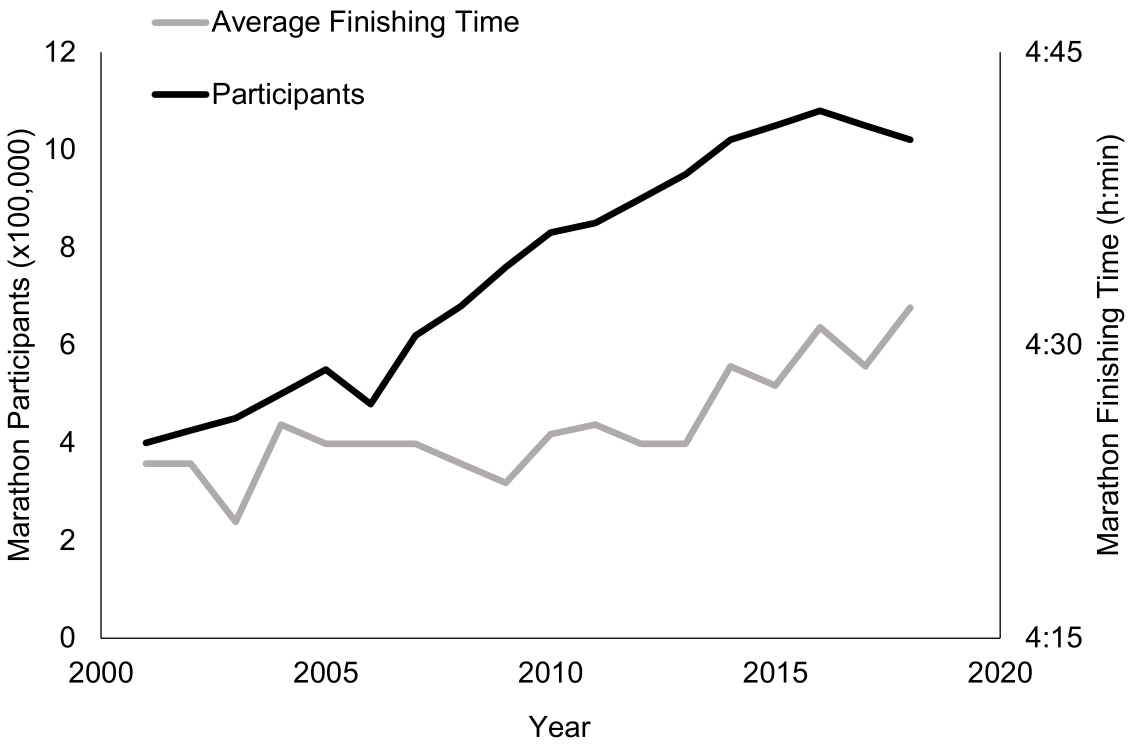

Fig. 1 Participation trends (black line) and average marathon finish time regardless of age or gender (grey line) in marathon running from 2001 to 2018 as recreated from Andersen's State of Running 2019 and marathon statistics research (Andersen, 2021; Andersen and Nikolova, 2021).

Another notable trend is that world-class athletes have set numerous world records in long-distance events, particularly marathons and half-marathons (Muñiz-Pardos et al., 2021). The current male marathon world record, set in October 2023 by Kelvin Kiptum, is 2:00:35 h:min:s, while the female counterpart, set in September 2023 by Tigist Assefa, is 2:11:53 h:min:s (World Athletics, 2023a, b). Analysis of top road race times from 2001 to 2019, shows the most significant improvement occurred between 2017-2019 compared to any other three-year period analyzed (Goss et al., 2022). This trend is not limited to the race winners; the top 100 runners of nearly every analyzed group, regardless of gender, ran faster across various events during this period (Goss et al., 2022).

Within this field of world-class athletes, Kenyan elite runners dominate middle and long-distance events, with their success and record-breaking achievements attracting significant research interest (Tucker et al., 2015; Jones et al., 2021; Muñiz-Pardos et al., 2021). Analysis of the top 20 running performances for males and females in both middle- (800 m, 1500 m, 3000 m) and long-distance events (5000 m, 10,000 m, 5 km, 10 km, half marathon, and marathon from August 2016 to August 2021) shows that Kenyan athletes accounted for 42% of the top performances, underscoring their dominance (Fig. 2, World Athletics, 2021).

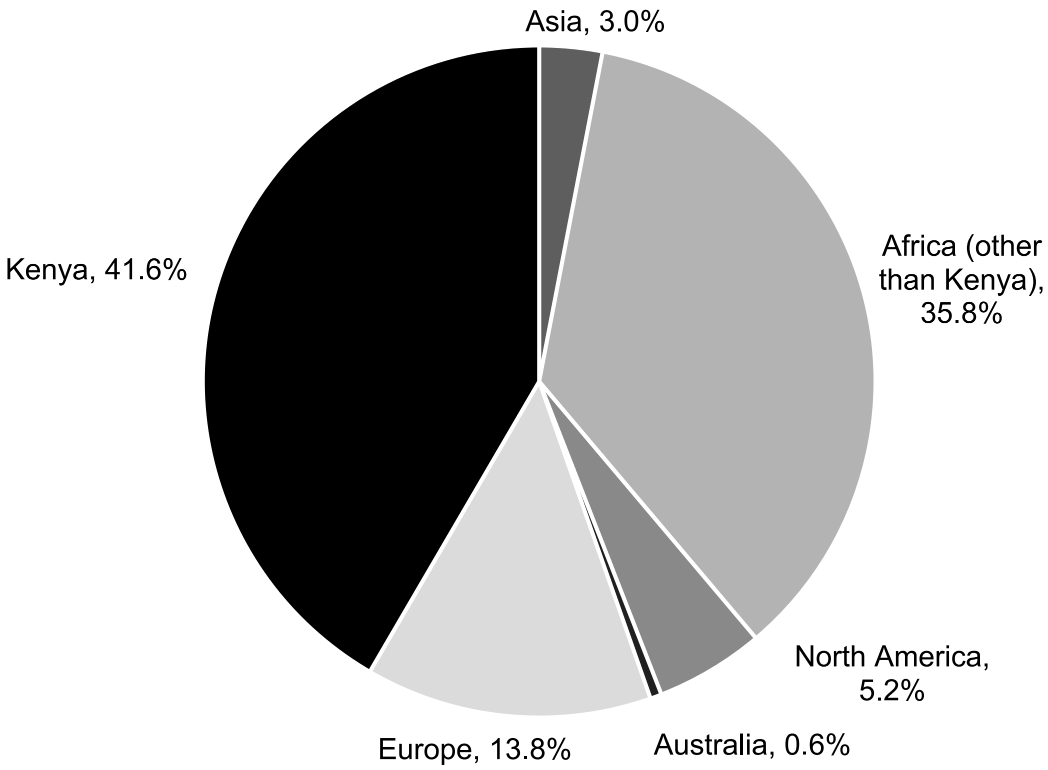

Fig. 2 Geographic distribution of top 20 running performances in middle- and long-distance events (800 m, 1500 m, 3000 m, 5000 m, 10,000 m, 5 km, 10 km, half marathon, and marathon) from August 2016 – August 2021 (World Athletics, 2021)

1.2 Physiological Components of Marathon Running

Unravelling the factors behind endurance running success is difficult, with research over the past century into elite athletes and their achievements revealing a wide-ranging array of elements that collectively shape athletic success in endurance running (Fig. 3). Central to this are physiological attributes such as peak aerobic capacity, metabolic capacity of exercising muscles, anaerobic threshold, and running economy (Sjödin and Svedenhag, 1985; Joyner, 1991; Coyle, 2007; Foster and Lucia, 2007; Joyner and Coyle, 2008). Beyond this, biomechanics (Kyröläinen et al. 2001;

Williams, 2007; Barnes and Kilding, 2015a), psychology (Venturini and Giallauria, 2022), nutrition (Sjödin and Svedenhag, 1985; Coyle, 2007; Joyner et al., 2020), training techniques (Conley et al., 1981; Sjödin and Svedenhag, 1985; Joyner et al., 2020), tactical race planning (Joyner and Coyle, 2008; Venturini and Giallauria, 2022), and external factors like climate and terrain (Sjödin and Svedenhag, 1985; Coyle, 2007; Venturini and Giallauria, 2022), alongside cutting-edge technologies (Joyner et al., 2020), and genetic predisposition (Joyner, 1991; Joyner and Coyle, 2008; Venturini and Giallauria, 2022), may play pivotal roles in endurance running.

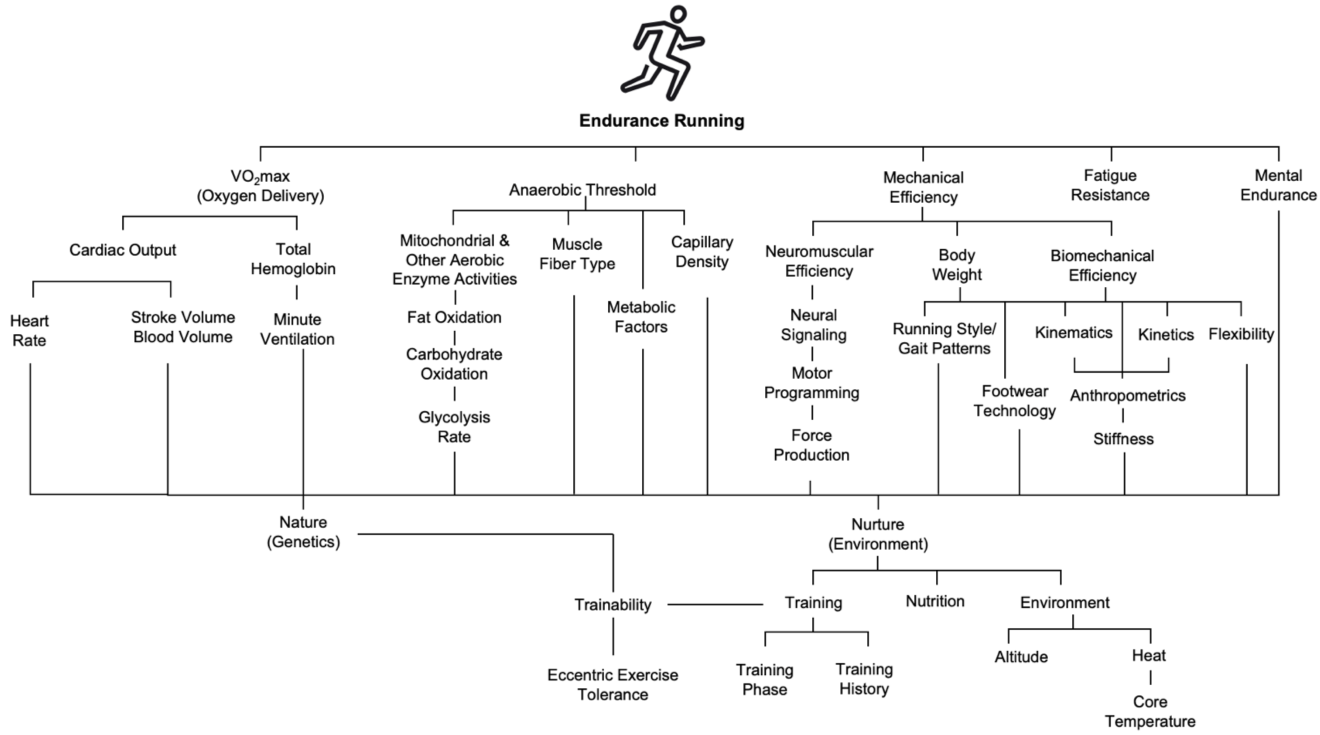

Fig. 3 – Diagram illustrating the factors influencing endurance running and marathon performance. Adapted and combined from schematics presented in Saunders et al., 2004a; Joyner and Coyle, 2008; Jones et al., 2011; Barnes and Kilding, 2015a; and Wackerhage (unpublished).

One of the earliest analyses of world records was conducted by A.V. Hill in 1925. His research focused on physiological factors such as energy stores, oxygen demand, oxygen debt, and types of fatigue in relation to athletic performance. This work laid the foundation for the decades of research since. Subsequent studies have established key physiological determinants of marathon performance, including (1) an athletes' cardiorespiratory capacity, (2) the metabolic capacity of their exercising muscles, and (3) their running economy (Barnes and Kilding, 2015a; Conley et al., 1981; Coyle, 2007; Foster and Lucia, 2007; Joyner, 1991; Joyner and Coyle, 2008; Joyner et al., 2020; Sjödin and Svedenhag, 1985; Venturini and Giallauria, 2022). Given they determine performance, these factors also offer predictive insights over the marathon (di Prampero et al., 1986; Joyner, 1991). In 1986, di Prampero et al. proposed calculating marathon performance speed by combining maximum oxygen uptake ($\dot{V}O_2max$), its maximal sustainable fraction, and the energy cost of running per unit distance (di Prampero et al., 1986). This approach highlights the interaction between $\dot{V}O_2max$ and its fractional utilization in sustaining aerobic and anaerobic metabolism (i.e. performance volume of oxygen uptake ($\dot{V}O_2$)), while efficiency defines the speed (i.e. performance velocity) achievable at a given energy expenditure (di Prampero et al., 1986; Joyner and Coyle, 2008).

1.2.1 Peak Aerobic Capacity ($\dot{V}O_2max$)

During endurance running, the working muscles require a constant resynthesis of adenosine triphosphate (ATP), to sustain movement. This ATP is primarily generated via oxidative metabolism in the muscle cell’s mitochondria, which elevates the demand for oxygen (Coyle, 1999). In laboratory measurements, the $\dot{V}O_2$ consumption per time during exercise represents the bodies’ ability to use oxygen for energy production. While oxygen consumption rises, heart rate, ventilation, and stroke volume also increase to keep up with the demand (Santisteban et al., 2022). As exercise intensity continues to increase $\dot{V}O_2$ reaches a plateau known as $\dot{V}O_2max$ (Shephard et al., 1968). At this stage, increasing exercise intensity higher does not lead to increased oxygen consumption primarily because the working muscles face limitations in oxygen delivery (Coyle, 1999). This restriction arises from several factors. Central factors, include pulmonary ventilation, diffusion across the pulmonary capillary membrane, cardiac output, and hemoglobin mass. Peripheral factors involve skeletal muscle blood flow and the diffusion of oxygen from the circulation into the muscle (Coyle, 1999). Consequently, $\dot{V}O_2max$ indicates the highest rate at which ATP can be resynthesized through aerobic pathways and serves as a limit to exercise tolerance (Jones, 2006). $\dot{V}O_2max$ can be expressed in absolute terms (L/min) or, given the impact of body mass on running performance, expressing $\dot{V}O_2max$ relative to body mass (mL/kg/min) is most relevant to distance running (Jensen et al., 2001; Joyner, 2017). Interestingly, recent studies have indicated that maximal aerobic metabolism can decline during a 5-8-minute performance bout in a laboratory setting. This decline is attributed to reduced stroke volume, accelerated muscle fatigue from decreased blood and oxygen delivery, and increased anaerobic metabolism (González-Alonso and Calbet, 2003; Mortensen et al., 2005). This suggests that the maximum rate of aerobic ATP resynthesis during an intense exercise bout such as a running race is dynamic and should be considered when discussed in the context of a marathon.

Endurance sports like cycling, running, and cross-country skiing require high $\dot{V}O_2max$ levels, with Norwegian cyclist Oskar Svendsen holding the record for the highest recorded $\dot{V}O_2max$ at 97.5 mL/kg/min (KORR Medical Technologies Inc., 2023). Marathon runners, however, typically have lower $\dot{V}O_2max$ values, reflecting the distinct physiological demands of their sport. In marathons, runners generally maintain a pace below their $\dot{V}O_2max$, operating instead at about 75-85% $\dot{V}O_2max$ (Joyner and Coyle, 2008), with the shorter 10-kilometer race demanding closer to 90-100% of $\dot{V}O_2max$, and the shortest long distance road running event, the 5-kilometer race, is generally completed close to $\dot{V}O_2max$ (Bassett and Howley, 2000; Costill et al., 1973).

A study on recreational marathon runners found varying $\dot{V}O_2max$ values based on their finishing times (Fig. 4). Runners finishing in 2.5-3 hours had an average $\dot{V}O_2max$ of 63.3 mL/kg/min, those in the 3.5-4 hour bracket averaged 53.2 mL/kg/min, and those over 4.5 hours averaged 46.5 mL/kg/min (Gordon et al., 2017). In contrast, elite male endurance athletes typically have $\dot{V}O_2max$ values between 70-85 mL/kg/min, while elite women's values are about 10% lower due to physiological differences such as lower hemoglobin concentrations and higher levels of body fat (Durstine et al., 1987; Pate et al., 1987; Pollock, 1977; Saltin and Astrand, 1967).

In endurance running in general, research indicates a negative correlation between $\dot{V}O_2max$ and marathon times, especially in recreational runners, with $\dot{V}O_2max$ accounting for about 59% of performance variance (Billat et al., 2001; Costill et al., 1971). However, this correlation weakens among elite athletes with a narrower $\dot{V}O_2max$ range, suggesting other factors consequentially influence endurance running performance (Conley and Krahenbuhl, 1980; Lucia et al., 2006; di Prampero et al., 1986; Venturini and Giallauria, 2022). Interestingly, East African runners often excel in marathons despite having comparatively lower $\dot{V}O_2$max values, measuring values around 61.9 mL/kg/min (Weston et al., 2000) to 73.8 mL/kg/min (Lucia et al., 2006), indicating other performance determinants are contributing to this groups performances in distance running (Santos-Concejero et al., 2015; Weston et al., 2000).

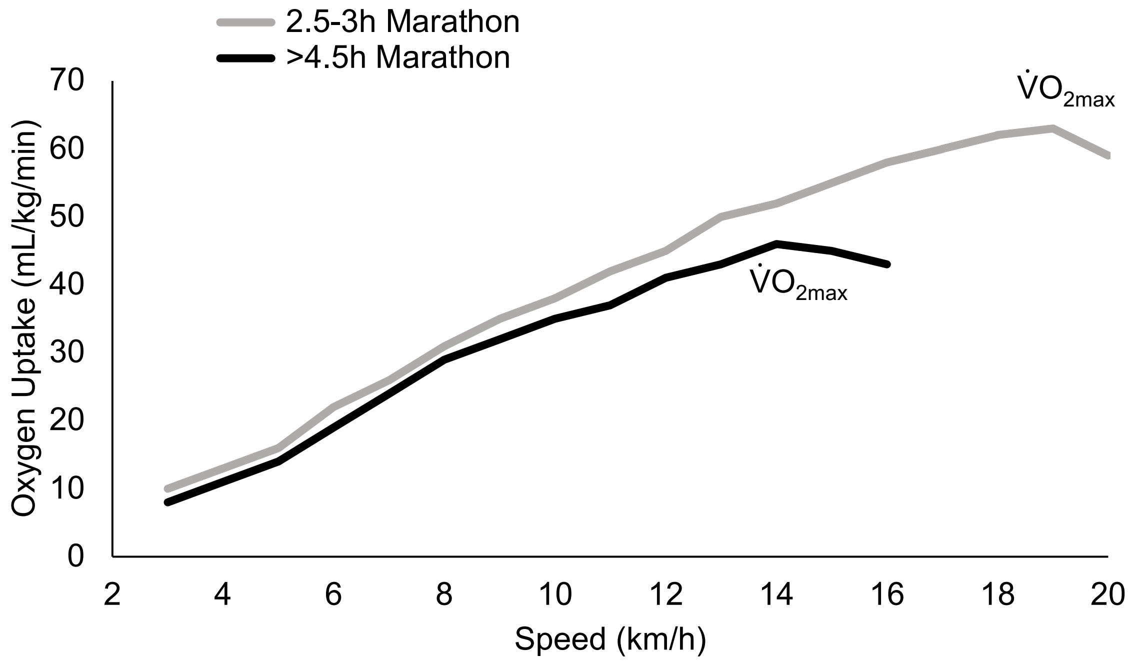

Fig. 4 – Representational oxygen uptake values with incremental speeds during standardized laboratory cardiopulmonary exercise testing showing $\dot{V}O_2$max differences between less trained >4.5-hour marathon finishers and their more highly trained 2.5-3-hour counterparts. Adapted from data presented in (Gordon et al., 2017).

1.2.2 Metabolic Capacity of the Exercising Muscles

The second main physiological factor is encompassed by discrepancies in understanding and terminology but is currently often denoted as fractional utilization of maximum (Joyner, 1991, 2017; Jones et al., 2021; Santisteban et al., 2022). Essentially, this metric is the metabolic capacity of exercising muscles, signifying the highest exercise intensity sustainable before muscle function declines. Within the field of cardiorespiratory physiology, this is referred to as the fractional utilization of maximum and indicates the sustained percentage of $\dot{V}O_2$max that can be maintained over a defined period, such as a marathon (Bassett and Howley, 2000; Impellizzeri et al., 2005; Jones et al., 2021; Joyner and Coyle, 2008; Joyner et al., 2020). On a cellular level, this indicates the highest exercise intensity before lactate production surpasses removal, leading to a rapid rise in blood lactate during exercise and is sometimes called the lactate inflection point or the anaerobic threshold (Billat, 1996; Santisteban et al., 2022). This threshold initiates the neutralization of lactic acid through the bicarbonate buffering system, leading to changes in the subject's ventilatory patterns, manifesting as an increase in the volume of carbon dioxide consumption per time during exercise ($\dot{V}CO_2$) relative to $\dot{V}O_2$ (Vasquez Bonilla et al., 2023). This alteration is crucial for all gas exchange-based methods of anaerobic threshold detection (Beaver et al., 1986; Binder et al., 2008).

For marathon runners, the goal is to enhance their ability to run at higher speeds while producing less lactate. Endurance training plays a key role in this by increasing muscle lactate transport capacity, promoting a higher proportion of type I (slow-twitch) skeletal muscle fibers, and with it an increase of mitochondria (versus the highly glycolytic type II fast-twitch fibers). These adaptations are crucial for minimizing blood lactate accumulation during prolonged exercise (Lundby and Robach, 2015; Pilegaard et al., 1994). Enhanced mitochondrial function, allows for more efficient oxidation of pyruvate at any given glycolysis rate, resulting in lower lactate production (Holloszy and Coyle, 1984). Additionally, this adaptation shifts muscle metabolism from carbohydrate reliance to more efficient energy sources, facilitating higher running speeds or power outputs while conserving glycogen. Furthermore, increased capillary density in trained muscles is also believed to play a role in extending the duration of exercise at intensities beyond the anaerobic threshold (Coyle et al., 1988).

Studies have demonstrated a strong correlation between the metabolic capacity of exercising muscles and long-distance running performance (Bassett, 2002; Costill et al., 1973; Davis, 1985; Farrell et al., 1979; Föhrenbach et al., 1987; Noakes et al., 2001; Santisteban et al., 2022; Sjödin and Schele, 1982; Wackerhage et al., 2022). Reports suggest elite athletes can sustain 80-95% of their $\dot{V}O_2max$ with minimal increases in blood lactate during extended activities like marathons (Fig. 5, Bassett, 2002; Jones et al., 2021; Joyner and Coyle, 2008; Pate and O'Neill, 2007; Poole et al., 2016). In contrast, runners with around 4-hour marathon times typically sustain about 60% of their $\dot{V}O_2max$ (Fig. 5, Bassett and Howley, 2000; Sjödin and Svedenhag, 1985). This highlights the substantial differences in endurance capabilities between elite and recreational runners.

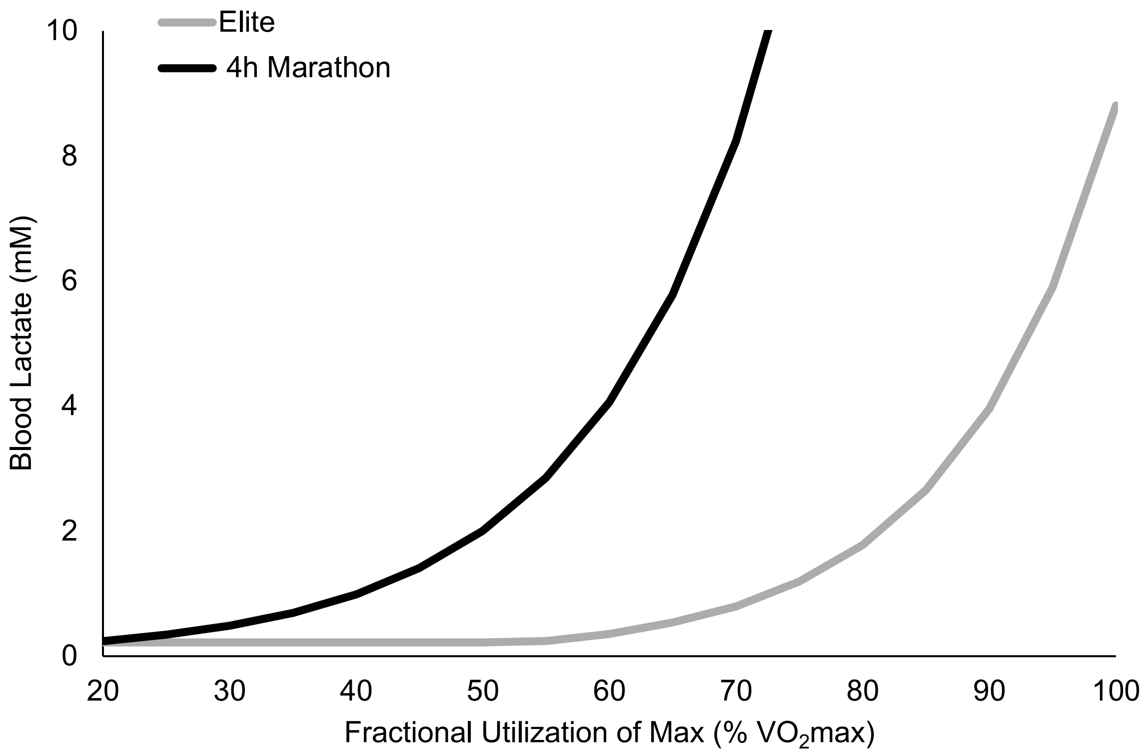

Fig. 5 - Representational blood lactate levels of elite and 4-hour marathon runners at varying exercise intensities. As seen, elite athletes can run at a much higher intensity before their lactate exponentially increases. However, 4-hour marathon runners reach this point at a much lower effort as a percentage of their $\dot{V}O_2max$. Adapted from data presented in (Bassett, 2002; Bassett and Howley, 2000).

1.2.3 Running Economy

Running economy, also known as running efficiency, is the third physiological factor notably impacting endurance performance. Due to the absence of practical direct calorimetric methods, measuring instantaneous rates of heat and work production during endurance exercise is challenging. The most feasible way to estimate actual metabolic energy production and ATP turnover is through measures of oxygen consumption with indirect calorimetry during an endurance performance bout (Joyner and Coyle, 2008; Scott, 2000; Webb et al., 1988). Consequently, running economy refers to the oxygen cost of running at a given high but submaximal speed (Joyner et al., 2020). Athletes with superior running economy demonstrate a lower $\dot{V}O_2$ at the same steady-state speed than runners with poor economy. This efficiency allows athletes to use a lower percentage of their $\dot{V}O_2max$ for a given velocity, thereby conserving glycogen and reducing anaerobic metabolism reliance during endurance competitions (Jones, 2006; Saunders et al., 2004a). Among elite runners with similar $\dot{V}O_2max$ levels, running economy can account for as much as 65.4% of the variation observed in a 10 km race performance (Conley and Krahenbuhl, 1980). Notably, the oxygen cost of endurance running (mL/kg/min) at a specific speed can vary by 30-40% among individuals with similar performance capacities (Conley and Krahenbuhl, 1980; Farrell et al., 1979; Joyner, 1991; Sjödin and Svedenhag, 1985).

Running economy encompasses metabolic, cardiorespiratory, biomechanical, and neuromuscular factors (Barnes and Kilding, 2015a; Saunders et al., 2004a). Metabolic efficiency pertains to the optimal use of available energy for enhanced performance and is affected by factors like core temperature, muscle fiber type, and substrate utilization (Barnes and Kilding, 2015a). Cardiorespiratory efficiency involves reducing work output during processes associated with oxygen transport and utilization. It is influenced by factors such as $\dot{V}O_2max$, heart rate, and minute ventilation (Barnes and Kilding, 2015a; Daniels, 1985; Saunders et al., 2004a). By enhancing these two factors, a runner will increase oxygen utilization, subsequently increasing energy production relative to a given work output, thus improving running economy (Barnes and Kilding, 2015a). Additionally, neuromuscular and biomechanical characteristics indicate how the neural and musculoskeletal systems work together to convert muscle power into physical movement, ultimately affecting athletic performance (Anderson, 1996; Barnes and Kilding, 2015a). While no universally applicable biomechanical pattern exists for efficient movement in all runners, research has highlighted that various biomechanical traits affect efficiency (Barnes and Kilding, 2015a). For example, anthropometric dimensions such as closer mass distribution to the torso and shorter Achilles moment arms, influence running economy (Bourdin et al., 1993; Cavanagh and Kram, 1985, 1989; Pate et al., 1992; Scholz et al., 2008; Taylor et al., 1982; Williams and Cavanagh, 1987). Additionally, specific gait patterns such as running with preferred stride length, stride rate, and foot strike pattern also play a role

(Barnes and Kilding, 2015b; Cavagna et al., 2005; Cavanagh and Williams, 1982; Di Michele and Merni, 2014; Morgan et al., 1994a; Morgan and Martin, 1986; Nilsson and Thorstensson, 1987; Svedenhag and Sjodin, 1984; Tartaruga et al., 2012). Finally, optimal kinematic and kinetic lower and upper body patterns that minimize wasteful vertical motion also impact running economy (Cavanagh et al., 1977; Cavanagh and Williams, 1982; Chang and Kram, 1999; Farley and McMahon, 1992; Heise and Martin, 2001; Kram and Taylor, 1990; Tartaruga et al., 2012; Williams and Cavanagh, 1987). Neuromuscular efficiency also plays an important role, particularly among athletes with similar physiological attributes. The neuromuscular system translates cardiorespiratory capacity into efficient mechanics and can be categorized into two main factors. First, those that enhance neural signaling and motor programming for running, such as the timing and amplitude of muscle activity before and during ground contact. Second, those that improve muscle force production, such as enhancing leg stiffness and utilizing stored elastic energy, all of which consequently affect performance (Barnes and Kilding, 2015a; Bonacci et al., 2009). It is worth noting, that while adjusting one of these factors may improve running economy in one athlete, it may not have the same effect in another due to inherent individual variations in physiological and biomechanical traits (Barnes and Kilding, 2015a). Finally, we must also acknowledge that some of these factors can be affected by training, adding another layer of complexity to understanding running economy and its role in improved endurance exercise performance (Saunders et al., 2004a).

The conventional method for assessing running economy entails measuring $\dot{V}O_2$ while running at a constant speed on a treadmill in a laboratory setting until a physiological steady state is reached (Barnes and Kilding, 2015a; Saunders et al., 2004b). Studies typically use bouts of 3 to 15 minutes at speeds below the ventilatory or lactate threshold (Morgan et al., 1989), as above this threshold, a slow component increase of $\dot{V}O_2$—which refers to the gradual rise in oxygen uptake during prolonged, submaximal exercise, beyond the initial steady state, indicating a shift in muscle recruitment and energy metabolism—is evident and could affect the results (Jones et al., 2003). To make running economy comparable between individuals, typically $\dot{V}O_2$ is interpolated to a standard running velocity and expressed relative to body mass (mL/kg/min) or as the total volume of oxygen required to run one kilometer relative to body mass (mL/kg/km) (Barnes and Kilding, 2015a; Foster and Lucia, 2007). In this context, various terms like “cost”, “oxygen cost”, “energy cost,” and “requirement” have been used to describe the relationship between oxygen consumption and running velocity (Daniels, 1985).

Given the variation in protocols, gas-analysis equipment, data analysis techniques, and differences in maximal aerobic capacity, it is difficult to determine what constitutes good, average, and poor running economy in existing studies (Barnes and Kilding, 2015a). Furthermore, the interindividual variation in running economy must also be acknowledged with controlled studies involving moderately trained to elite subjects showing variations in running economy of 1.3% to 5% at speeds between 12 to 18 km/h (Barnes et al., 2013b; Barnes and Kilding, 2015a; Brisswalter and Legros, 1994; Morgan et al., 1994b; Morgan et al., 1990; Morgan et al., 1991; Pereira and Freedson, 1997; Pereira et al., 1994; Saunders et al., 2004b; Williams et al., 1991). Considering these limitations, representative $\dot{V}O_2$ values for male and female runners at varying ability levels can be found in Table 1 (Fig. 6). Building on previous studies of elite marathon performance, previous research examining the physiological demands of running a 2-hour marathon, at a race pace of 21.1 km/h, has found that a 59 kg runner would need a running economy of 67 mL/kg/min (Jones et al., 2021). One group in particular, East African runners, have gained international recognition for their exceptional running economy, with numerous studies attributing this phenomenon to their specific anthropometric characteristics, such as smaller body size, thinner lower legs, and a shorter Achilles tendon moment arm (Foster and Lucia, 2007; Scholz et al., 2008; Larsen and Sheel, 2015; Lucia et al., 2006; Mooses and Hackney, 2017; Mooses et al., 2015; Santos-Concejero et al., 2017).

TABLE 1. Normative data on running economy for male and female runners across different skill levels. Table adapted from Barnes and Kilding, 2015a.

Runner Classification	Speed (km/h)	Running Economy (mL/kg/min)	
		Male mean (range)	Female mean (range)
Recreational	12	42.2 (40.4 - 45.3)	43.2 (38.5 - 48.1)
Highly Trained	16	50.6 (40.5 - 66.8)	54.5 (46.2 - 61.9)
Elite	16	47.9 (43.2 - 53.4)	48.9 (45.1 - 55.8)

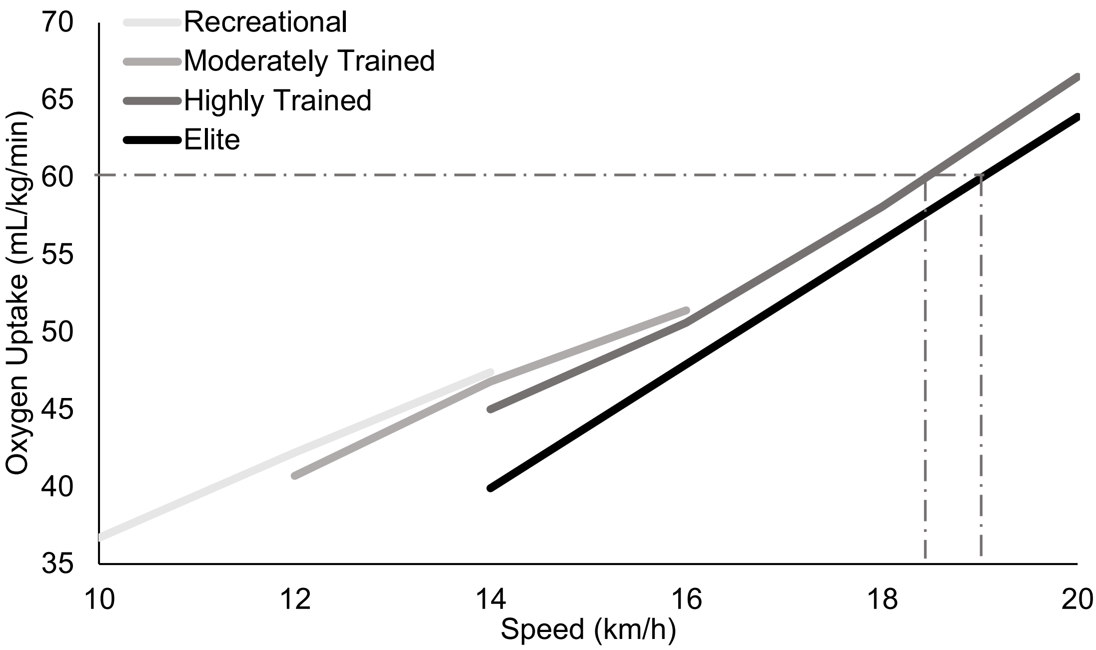

Fig. 6 – Oxygen uptake values at different speeds representing normative running economy data for male runners of varying ability. The dashed lines portray the effect of better running economy on performance where, at the same oxygen uptake of 60 mL/kg/min, elite runners achieve faster running speeds than their highly trained counterparts. Adapted from data presented in (Barnes and Kilding, 2015a).

1.2.4 Additional Factors to Consider for Marathon Performance

Beyond the three main physiological factors mentioned about, other elements—including fatigue resistance, genetics, environmental factors, nutrition, sex differences, age, and origin—also influence success in marathon performance (Fig. 3, Alvero-Cruz et al., 2020; Casado et al., 2021; El Helou et al., 2012; Jones et al., 2021; Venturini and Giallauria, 2022).

1.2.4.1 Fatigue Resistance

Recent research on marathon performance has alluded to fatigue resistance as a potential fourth key factor, suggesting the metabolic capacity of exercising muscles and running economy may not stay constant over the duration of a marathon (Jones et al., 2021). Fatigue resistance considers how these factors deteriorate over time (Joyner and Coyle, 2008). Although its specific physiological basis is not fully understood, professional endurance events like marathons, where athletes operate at or above 85% of $\dot{V}O_2max$, require exceptional fatigue resistance under conditions that induce substantial anaerobic metabolism (Hawley et al., 1997; Joyner and Coyle, 2008).

1.2.4.2 Genetics

The role of genetics in elite athletic performance, including in power, endurance, and speed disciplines is substantial (Joyner and Coyle, 2008; Tucker et al., 2013; Yaghoob Nezhad et al., 2019; John et al., 2020; Ma et al., 2013; Puthucheary et al., 2011). Research over the past two decades has linked certain genes, such as ACTN3 and ACE, to athletic abilities. ACTN3 influences type II muscle fibers crucial for power sports, while ACE is associated with cardio-respiratory efficiency in endurance athletes (Cambien et al., 1992; John et al., 2020; Rigat et al., 1990; Tiret et al., 1993; Williams et al., 2000; Yang et al., 2009; Yang et al., 2003; Davids and Baker, 2007; Guth and Roth, 2013). However, athletic success is not determined by single genes but rather by the complex interaction of multiple genetic and environmental factors that continue to be researched (John et al., 2020).

1.2.4.3 Environmental Factors

Marathon performance is also influenced by external factors including course topography, environmental factors, and race strategies (Hoogkamer et al., 2017). Flatter courses like the Berlin marathon typically yield faster times (Díaz et al., 2019). Environmental factors, such as temperature, humidity, radiant heat, wind speed, and direction, play a pivotal role in marathon performance (Díaz et al., 2019). Thermoregulation is also crucial during running due to high metabolic rates and heat production. Extreme temperatures can impede race times and increase the risk of hyperthermia and dehydration (Hoogkamer et al., 2017; Jones et al., 2021; Venturini and Giallauria, 2022). Clean air is essential for peak performance, as particulate pollution affects the airways of runners and reduces marathon performance (Marr and Ely, 2010; Zoladz and Nieckarz, 2021). Additionally, running in a sheltered position or drafting can enhance performance by reducing energy expenditure and psychological stress associated with pace management (Zouhal et al., 2015; Hoogkamer et al., 2019). Having several runners set the pace may improve race times, although this is often regulated (Venturini and Giallauria, 2022). In general, maintaining a uniform pace with minimal speed changes throughout the race contributes to faster overall performance (Díaz et al., 2019).

1.2.4.4 Nutrition

Nutrition is vital for marathon performance, with a focus on body mass, anthropometry, and efficient carbohydrate utilization for ATP production during the race (Burke et al., 2019). Additionally, proper hydration is also essential to counteract electrolyte losses due to sweating, which is especially important in high temperature environments during exercise (Burke et al., 2019).

Having high carbohydrate availability, through pre-race meals and in-race consumption, enhances endurance performance by sparing stored glycogen and reducing the oxidative demand of glycemic substrate (Burke et al., 2017; Burke et al., 2019; Smith et al., 2010). Elite athletes strategically consume carbohydrates, through sports drinks or gels, during the marathon to sustain carbohydrate oxidation, which helps maintain a high respiratory exchange ratio and low $\dot{V}O_2$ levels (Burke et al., 2019; Clark et al., 2019). In hot conditions, pre-race hyperhydration or cooling strategies may help alleviate thermal challenges and fluid deficits (Goulet et al., 2007; van Rosendal and Coombes, 2012). Evidence-based performance supplements like caffeine and nitrate may also offer additional advantages (Burke, 2008; Burke et al., 2019; Southward et al., 2018; Spriet, 2014). Ultimately, the aim of race nutrition is to effectively address factors that may lead to fatigue or suboptimal performance, particularly as the event progresses and nears its conclusion (Burke and Hawley, 2018).

1.2.4.5 Sex Differences

Certain physiological differences between men and women runners impact their performance in running events. Men generally exhibit higher $\dot{V}O_2max$ values, attributed to greater muscle mass, heart size, higher hemoglobin concentration, and lower body fat. As a result, their marathon times are approximately 10-12% faster than women (Hunter et al., 2015; Joyner, 2017; Pate and O'Neill, 2007). While $\dot{V}O_2max$ is a key determinant explaining sex differences in marathon performance, there is conflicting evidence on the role of metabolic capacity of exercising muscles and running economy (Joyner, 2017; Venturini and Giallauria, 2022). Moreover, there are potential influences of sex differences in thermoregulation, although their impact on performances remains uncertain (Joyner, 2017). There is also speculation about sex differences in field depth and pacing strategies, possibly affecting common sense, planning, and risk-taking during a race (Deaner et al., 2015; Hunter et al., 2015; Joyner, 2017). Nonetheless, most of these factors lack sufficient data on elite women athletes in comparison to their men counterparts, indicating the need for more comprehensive elite data collection, with a particular focus on gathering additional information on women athletes (Joyner, 2017).

1.2.4.6 Age

Age is another factor that affects marathon performance (Venturini and Giallauria, 2022). As individuals age, their maximum heart rate decreases, resulting in a reduction of peak maximum oxygen consumption, with the highest values among elite marathoners typically achieved at 27 years for men and 29 years for women (Lara et al., 2014). Surprisingly, peak marathon performance is usually around the age of 35 due to an improved running economy, compensating for declining $\dot{V}O_2max$ (Tanaka and Seals, 2008). Moreover, the psychological profile of elite runners evolves over time, marked by increased emotional stability, high motivation, and unwavering mental vigor, boosting performance in later years (Parker, 2011). These diverse age-related factors collectively influence marathon runners’ performance trajectories (Venturini and Giallauria, 2022).

1.2.4.7 Origin

Numerous factors contribute to the success of East African distance runners, particularly Kenyan and Ethiopian athletes (Larsen, 2003; Larsen and Sheel, 2015; Tucker et al., 2015; Wilber and Pitsiladis, 2012). Their dominance is attributed to a blend of cultural, physiological, anthropometric, genetic, environmental, and psychological elements. For instance, among the Kalenjin and Arsi tribes that produce many of these elite runners, early aerobic training during childhood, coupled with distance running as a primary mode of transport shapes their advantageous physiology (Billat et al., 2003; Larsen et al., 2004; Onywera et al., 2006; Saltin et al., 1995b; Scott et al., 2003). Adhering to the traditional diets of these tribes, which have historically been low in fat and high in carbohydrates, also supports their performance in middle- and long-distance running events (Onywera et al., 2004). Their somatotypes, with Kenyans often having ectomorphic characteristics, offer biomechanical and metabolic advantages (Billat et al., 2003; Larsen et al., 2004; Saltin et al., 1995b). For example, Kenyan anthropometrics ideal for endurance performance include slender and long legs, high flexibility, short calcaneal tubers, and long Achilles tendons. These athletes also exhibit low body fat, a higher percentage of type I muscle fibers, and an advantageous oxidative enzyme profile, all beneficial for endurance performance (Saltin et al., 1995a; Venturini and Giallauria, 2022). Moreover, living at moderate altitudes for millennia may provide genetic and phenotypical benefits. These include relatively high hemoglobin and hematocrit levels, which enable consistent high-intensity training at altitude and translate into exceptional performance at lower elevations (Billat et al., 2003; Larsen, 2003; Larsen et al., 2004; Onywera et al., 2006; Prommer et al., 2010; Saltin et al., 1995b; Yang et al., 2007). Additionally, strong motivation, driven by socioeconomic rewards and societal recognition, further fuels their dedication (Onywera et al., 2006). Finally, the rich tradition of distance running excellence in Kenya and Ethiopia continues to nurture future champions (Wilber and Pitsiladis, 2012). Together, these factors contribute to the remarkable achievements of East African marathoners in the world of endurance running (Joyner, 2017; Larsen, 2003; Millet et al., 2012).

1.3 Advancements in Running Footwear Technology Impacting Biomechanical Factors of Marathon Performance

Recent advancements in long-distance running footwear technology, such as improvements in weight, cushioning, and longitudinal bending stiffness, have significantly influenced biomechanical elements of marathon performance and athlete’s mechanical efficiency (Burns and Tam, 2020; Hoogkamer et al., 2019; Hoogkamer et al., 2017; Jones et al., 2021; Hoogkamer et al., 2016; Nigg et al., 2020; Stefanyshyn and Fusco, 2004; Worobets et al., 2014). The introduction of these innovative shoes has led to remarkable improvements in race times, with researchers proposing multiple underlying mechanisms for these advancements (Hoogkamer et al., 2019; Nigg et al., 2020; Rodrigo-Carranza et al., 2021). Featuring a curved stiff midsole component and a 40 mm stack height made of compliant, resilient, and lightweight foam, these shoes have been designed to optimize running economy by minimizing energy loss (Fig. 7) (Muñiz-Pardos et al., 2021; Nigg et al., 2020).

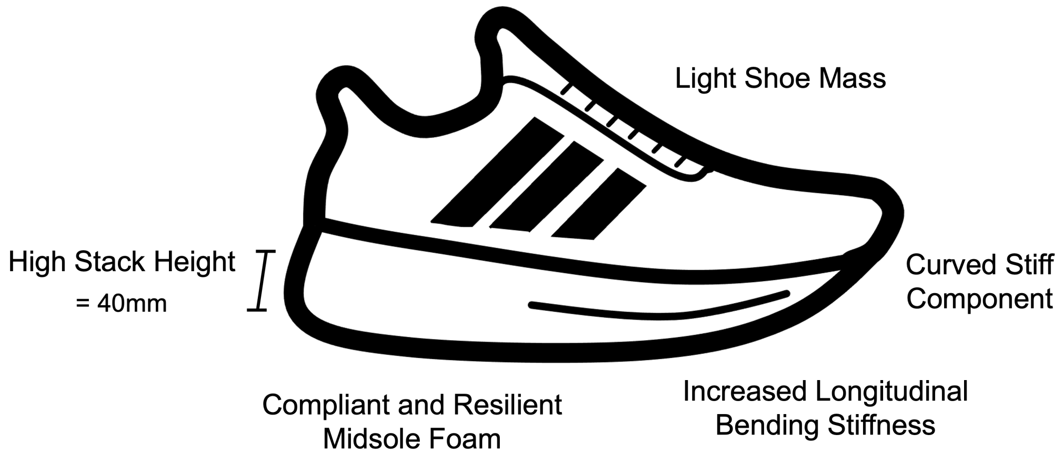

Fig. 7 – Schematic illustration of advanced footwear technology and characteristics that make them different from traditional racing flats. These innovative shoes consist of a curved stiff element in the midsole of the shoe increasing the longitudinal bending stiffness, as well as a high midsole stack height made up of a resilient, compliant, and lightweight foam (Nigg et al., 2020; Venturini and Giallauria, 2022).

The first proposed effect revolves around reduced shoe weight, with a 1% decrease in oxygen consumption for every 100-gram reduction in shoe mass (Franz, et al., 2012; Hoogkamer et al., 2016; Nigg et al., 2020). Innovations in compliant, resilient, lightweight foam maintain lightness while delivering high energy return, lowering energy expenditure per step via passive elastic recoil (Hoogkamer et al., 2016; Nigg et al., 2020; Venturini and Giallauria, 2022; Worobets et al., 2014). Moreover, increased stack height benefits runners with additional cushioning from the innovative foam (Muñiz-Pardos et al., 2021; Venturini and Giallauria, 2022). This concept stems from a biomechanical model that establishes a relationship between limb length and the energy expended during movements in terrestrial animals (Pontzer, 2005, 2007b). In the context of running, this model computes the rate of muscle force generation by considering effective limb length, the angle of limb movement during ground contact, and the energy spent on limb motion (Pontzer, 2007a). Although shoe sole height is adapted according to foot size, this adaptation is non-linear, leading to a disproportionately greater increase in lower leg length for individuals with shorter stature (Lucia et al., 2006). This alteration has been proposed to potentially enhance running efficiency (Muñiz-Pardos et al., 2021). Additionally, the heightened midsole stack height allows for a curved plate design to fit within the height of the midsole and still be surrounded by foam, increasing longitudinal bending stiffness and facilitating a teeter-totter effect on the running mechanics (Fig. 8, Nigg et al., 2020). This proposed interaction transforms stored energy in the forefoot into a reactive force during take-off and occurs when a runner's center of pressure overcomes the bending point of the curved structure causing the reaction force to act on the heel perpendicular to the stiff element providing leverage during push-off (Farina et al., 2019; Nigg et al., 2020). Furthermore, increasing stiffness minimizes energy loss in the metatarsophalangeal joint (Stefanyshyn and Nigg, 2000; Day and Hahn, 2019).

While the precise impact of new shoe technologies is still being explored, they collectively contribute to about a 4% improvement in running economy, disrupting the evolution of marathon performance times (Hoogkamer et al., 2018; Muñiz-Pardos et al., 2021). Researchers suggest that recent world record performances may owe more to changes in external factors like shoe technology than solely to the athletes' physiology (Goss et al., 2022).

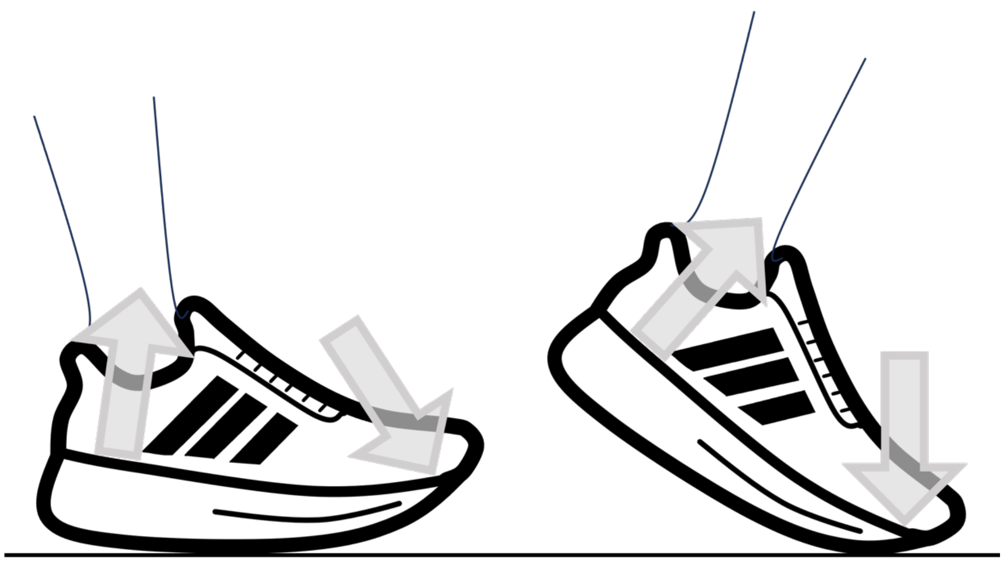

Fig. 8 – Schematic illustration of the proposed teeter-totter mechanism facilitated by advanced footwear technology. In this illustration, the runner's force is exerted on the front part of the shoe, generating a corresponding reaction force at the heel of the foot during the early/mid stance and push-off phases. Modified from Nigg et al., 2020.

1.4 Marathon Training

Beyond the foundational physiological factors that influence performance, training variables have emerged as strong predictors of marathon running success (Bale et al., 1986; Billat et al., 2003; Bale et al., 1985; Hagan et al., 1981; Hagan et al., 1987; Slovic, 1977). Notably, factors such as volume of easy runs, training pace, training load (consisting of both volume and intensity), deliberate short-interval practice, and tempo runs have been shown to predict marathon performance (Alvero-Cruz et al., 2020; Casado et al., 2021). For example, the contrast between elite marathoners and their less experienced counterparts is evident, as the former consistently showcase the capability to cover longer distances at faster speeds during their training sessions (Bale et al., 1986; Billat et al., 2003; Gomez-Molina et al., 2017). While the impact of training on physiological performance factors is evident, delving into such variables holds special significance for the growing community of non-competitive runners. For marathon events, training variables are not only convenient and cost-effective to track compared to metabolic testing, typically reserved for elite athletes, but they also serve as a powerful means to gauge marathon success, especially beneficial for sub-elite runners (Tanda, 2011).

Preparing for a marathon involves diverse training strategies, which include runs of various lengths and intensities, as well as nutritional and recovery techniques. These elements are tailored over months and continuously adjusted through periodization and tapering (Wackerhage and Schoenfeld, 2021). This complexity challenges controlled studies to figure out the best training methods, meaning there is limited scientific guidance available for long-distance runners and their coaches (Midgley et al., 2007). Consequently, many current marathon training plans rely on subjective opinions, only occasionally supplemented by evidence-based recommendations.

To tackle this challenge, experts have come up with new ways of generating and utilizing evidence in training plans. For example, Wackerhage and Schoenfeld (2021) have suggested evidence-informed training plans, where only some of the decisions are based on evidence whereas the rest is based on subjective best practice. Another idea is results-proven practice, where experts carefully gather and study training data from elite athletes who have attained top-tier outcomes (Haugen et al., 2022). While these plans lack direct comparisons or controls to determine causation, they provide insight into how an elite athlete's training plan contributed to their outstanding results. Researchers like Haugen and his team have done important studies using this approach, covering different racing distances (Haugen et al., 2021; Haugen et al., 2022; Haugen et al., 2019). This information can be used to write training plans for athletes trying to attain similar goals. The concept of results-based practice could also be applicable to sub-elite athletes, by quantitatively analyzing the training plans of marathon runners who have achieved certain target times.

1.5 Research Gaps and Aims

The evolving marathon landscape has seen growing engagement from recreational runners, as indicated by the decrease in average performance of marathon races, while at the same time the elites are breaking world records at an unprecedented rate (Andersen and Nikolova, 2021; Muñiz-Pardos et al., 2021). However, amid this transformation, the challenge persists in translating scientific research into practical advantages for runners, highlighting the difference between scientific insights and their real-world application.

Among the mentioned physiological predictors, running economy, has recently gained increasing attention due to a surge in world records coinciding with advancements in footwear technology (Muñiz-Pardos et al., 2021). Prior research has compared the running economy of non-elite runners wearing different shoe technologies under controlled laboratory settings (Burns and Tam, 2020; Hoogkamer et al., 2019; Hoogkamer et al., 2017; Jones et al., 2021; Hoogkamer et al., 2016; Nigg et al., 2020; Stefanyshyn and Fusco, 2004; Worobets et al., 2014). However, there is a notable gap in understanding the variability in running economy among the main beneficiaries of these technological advancements, world-class athletes. This unexplored area presents an opportunity for further research to comprehensively understand the impact of new footwear technologies on world-class athletic performance.

Alongside the physiological factors, training parameters have emerged as crucial predictors of marathon performance, especially for recreational runners who typically lack elite athletes’ access to extensive physiological testing (Tanda, 2011). Marathon preparation involves diverse, evolving strategies, making it difficult to conduct controlled studies to determine the best training techniques. This leads to a reliance on opinion-based marathon training plans with only limited evidence-based guidance. Addressing this need, experts are exploring evidence-informed and results-proven practices, focusing on analyzing elite athletes’ training plans to guide similar performance goals (Wackerhage and Schoenfeld, 2021; Haugen et al., 2021; Haugen et al., 2022; Haugen et al., 2019). However, applying these practices to sub-elite athletes, through quantitative analysis of their training plans, remains an unexplored area.

The aim of this study is to fill some of the aforementioned gaps in relation to advanced footwear technology and marathon training.

Aim 1 is to analyze the variability in physiological response in terms of running economy on a laboratory treadmill in advanced footwear technology compared to a traditional racing flat in world-class Kenyan distance runners (Half Marathon mean time: 59:30 min:sec) versus European amateur runners. Another goal of this research, based on the obtained results, is to confirm the observed variability and determine the overall effect of advanced footwear technology in comparison to previously published literature. To accomplish this, we systematically conduct an electronic search of relevant studies and perform a meta-analysis.

This aim is addressed in Study 1: “Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-Analysis Results”.

Aim 2 is to systematically and quantitatively analyze the final 12 weeks of 92 sub-elite marathon training plans. This research details recommendations on volume, intensity, training types, and periodization for recreational runners. Despite limitations like the subjective nature of this analysis and the absence of data regarding training plan effectiveness, this study identifies commonalities and patterns in these plans. These findings provide valuable information for the development of effective sub-elite marathon training plans.

This aim is addressed in Study 2: “Quantitative Analysis of 92 12-Week Sub-Elite Marathon Training Plans”.

2. Publications

This section presents the two first-authored published manuscripts that make up this cumulative dissertation. The first publication delves deeper into the parameters of running economy and investigates how recent advancements in footwear technology have influenced it in both world-class and amateur athletes participating in marathon races. This research revealed a wide range of responses in running economy to different footwear among both world-class Kenyan and amateur European road runners. Furthermore, a meta-analysis demonstrated a significant advantage of advanced footwear technology over traditional running flats, as observed in the previously conducted research studies.

The second publication shifts the focus to amateur or recreational runners and explores an additional aspect of marathon performance relevant to this population: training factors. This publication bridges the gap between science and best practice recommendations by systematically and quantitatively analyzing published subjective sub-elite marathon training plans. It synthesizes the resulting recommendations for comparison with relevant research and serves as a starting point for hypothesis testing.

In addition to discussing the content of the publications, this section will also include a statement outlining the authors' contributions, the abstract of each study, and the original publications. All publications are open-access articles published under the Creative Commons Attribution License (CC BY 4.0), which permits utilization, sharing, modification, distribution, and reproduction in any medium or form, given that the original work is properly cited, a link to the Creative Commons license is included, and any alterations are clearly indicated. To view a copy of this license, please visit http://creativecommons.org/licenses/by/4.0/. Table 2 provides a summary of the two articles published as part of this dissertation.

TABLE 2. List of publications defining this dissertation

Study	Title	Authors	Journal	Date of Publication
I	Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-Analysis Results	Knopp, M. Muñiz-Pardos, B. Wackerhage, H. Schönfelder, M. Guppy, F. Pitsiladis, Y. Ruiz, D.	Sports Medicine	2 March 2023
II	Quantitative Analysis of 92 12-Week Sub-Elite Marathon Training Plans	Knopp, M. Appelhans, D. Schönfelder, M. Seiler, S. Wackerhage, H.	Sports Medicine – Open	2 May 2024

2.1 Publication I: Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-Analysis Results

Authors:

Melanie Knopp, Borja Muñiz-Pardos, Henning Wackerhage, Martin Schönfelder, Fergus Guppy, Yannis Pitsiladis, Daniel Ruiz

Published In:

Sports Medicine

Journal Impact Factor:

This paper was published in 2023 in *Sports Medicine*. At the time of publication, *Sports Medicine* had a 2022 journal impact factor of 9.8 and a five-year impact factor of 12.6.

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2 March 2023

Citation:

Knopp, M., Muñiz-Pardos, B., Wackerhage, H. *et al.* Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-analysis Results. *Sports Med* 53, 1255–1271 (2023). https://doi.org/10.1007/s40279-023-01816-1

2.1.1 Authors' Contributions

An international collaboration involving adidas AG (Athlete Science, adidas Innovation), the Technical University of Munich (Chair of Exercise Biology, Department of Sport and Health Sciences), University of Zaragoza (Faculty of Health and Sport Sciences), Heriot Watt University (Institute of Life and Earth Sciences), and University of Brighton (School of Sport and Health Sciences) conducted this study. The manuscript's first author is Melanie Knopp, who, along with Daniel Ruiz, conceived and designed the research. Melanie Knopp, Daniel Ruiz, and additional colleagues carried out the data collection. Melanie Knopp, Daniel Ruiz, Borja Muñiz-Pardos, Henning Wackerhage, Martin Schönfelder, Fergus Guppy, and Yannis Pitsiladis performed the data analysis. The statistical analysis was conducted by Melanie Knopp and Fergus Guppy. All authors participated in the interpretation of the experiment's results. Melanie Knopp drafted the manuscript, and all authors contributed to its final version, reviewed it, and approved the final manuscript.

2.1.2 Abstract

Background

Advanced footwear technology improves average running economy compared to racing flats in sub-elite athletes. However, not all athletes benefit as performance changes vary from a 10% drawback to an 14% improvement. The main beneficiaries from such technologies, world-class athletes, have only been analyzed using race times.

Objective

The aim of this study was to measure running economy on a laboratory treadmill in advanced footwear technology compared to a traditional racing flat in world-class Kenyan (mean Half Marathon time: 59:30 min:s) versus European amateur runners.

Methods

Seven world-class Kenyan and seven amateur European male runners completed a $\dot{V}O_2$peak assessment and submaximal steady state running economy trials in three different models of advanced footwear technology and a racing flat. To confirm our results and better understand the overall effect of new technology in running shoes, we conducted a systematic search and meta-analysis.

Results

Laboratory results revealed large variability in both world-class Kenyan road runners, ranging from a 11.3% drawback to a 11.4% benefit, and amateur Europeans, ranging from a 9.7% benefit to a 1.1% drawback in running economy of advanced footwear technology compared to a flat. The post-hoc meta-analysis revealed an overall significant medium benefit of advanced footwear technology on running economy compared to traditional flats.

Conclusions

Variability of advanced footwear technology performance appears in both world-class and amateur runners, suggesting further testing should examine such variability to ensure validity of results and explain the cause as a more personalized approach to shoe selection might be necessary for optimal benefit.

2.1.3 Original Publication

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ORIGINAL RESEARCH ARTICLE

Variability in Running Economy of Kenyan World-Class and European Amateur Male Runners with Advanced Footwear Running Technology: Experimental and Meta-analysis Results

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Abstract

Background Advanced footwear technology improves average running economy compared with racing flats in sub-elite athletes. However, not all athletes benefit as performance changes vary from a 10% drawback to a 14% improvement. The main beneficiaries from such technologies, world-class athletes, have only been analyzed using race times.

Objective The aim of this study was to measure running economy on a laboratory treadmill in advanced footwear technology compared to a traditional racing flat in world-class Kenyan (mean half-marathon time: 59:30 min:s) versus European amateur runners.

Methods Seven world-class Kenyan and seven amateur European male runners completed a maximal oxygen uptake assessment and submaximal steady-state running economy trials in three different models of advanced footwear technology and a racing flat. To confirm our results and better understand the overall effect of new technology in running shoes, we conducted a systematic search and meta-analysis.

Results Laboratory results revealed large variability in both world-class Kenyan road runners, which ranged from a 11.3% drawback to a 11.4% benefit, and amateur Europeans, which ranged from a 9.7% benefit to a 1.1% drawback in running economy of advanced footwear technology compared to a flat. The post-hoc meta-analysis revealed an overall significant medium benefit of advanced footwear technology on running economy compared with traditional flats.

Conclusions Variability of advanced footwear technology performance appears in both world-class and amateur runners, suggesting further testing should examine such variability to ensure validity of results and explain the cause as a more personalized approach to shoe selection might be necessary for optimal benefit.

Key Points

- Running economy of world-class Kenyan and amateur European runners with next-generation long-distance running shoes that contain advanced footwear technology varies greatly, with a range from a 11.4% benefit to a 11.3% detriment.
- Meta-analysis results reveal an overall statistically significant medium benefit of advanced footwear technology on running economy when compared with traditional racing flats and confirmed the variability we report when examining the performance benefits of advanced footwear technology.
- Our results suggest a more personalized approach to new footwear technology.

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1 Introduction

Kenyan elite runners win many international track and road distance races, which has stimulated research into the causes of this success [1–6]. When examining the geographical distribution of the top 20 running performances for male and female athletes in both middle- and long-distance events (800 m, 1500 m, 3000 m, 5000 m, 10,000 m, 5 km, 10 km, half-marathon, and marathon) in the past 5 years (since the last Olympic cycle: 5 August, 2016 to 29 August, 2021), 41.6% have been achieved by Kenyan athletes [7]. Such running performances depend on three main physiological factors: (1) an athletes' maximal oxygen uptake ($\dot{V}O_2$max), (2) their fractional utilization of $\dot{V}O_2$max or the ability of an athlete to sustain a high percentage of their $\dot{V}O_2$max for long periods of time, and (3) their running economy [8–11]. Previous research examining the uniqueness specifically of Kenyan or other elite East African runners has suggested that of these, it is running economy that is particularly unique in this population [6, 10, 12]. Various studies have further attributed this especially to the anthropometric characteristics of East Africans with smaller body size, thinner lower legs, and a greater Achilles tendon moment arm with a shorter forefoot length [1, 10, 12–14].

Running economy can be defined as the ability to move efficiently in terms of energy demand while running at a specified submaximal velocity and can be measured as the rate of oxygen uptake per kilogram body weight and minute ($\dot{V}O_2$ in mL O_2/kg/min) at that speed [10, 11, 15, 16]. Previous work has reported that among elite runners with similar $\dot{V}O_2$max levels, running economy can account for 65.4% of the variation observed in a 10-km race performance [17]. Running economy is affected by many factors including anthropometric, biomechanical, metabolic, neuromuscular, and cardiorespiratory efficiency [11]. One element that has gained interest in recent years is an athlete's mechanical efficiency being affected by different footwear characteristics such as weight, cushioning, and longitudinal bending stiffness, all of which are included in recent technological advances in long-distance running shoes [18–21]. Previously published work has attributed the improvements of performance of such advanced footwear technology to various mechanisms [20, 22]. The advances in shoe technology themselves have been designed to maximize running economy while minimizing energy loss and consist of a curved stiff element component and a high midsole stack height made of a compliant, resilient, and lightweight foam (Fig. 1). The curved rigid element increases the longitudinal bending stiffness of the shoe and thereby creates a mechanism with a teeter-totter effect on the running mechanics, which occurs when a runner's center of pressure overcomes the bending point of the curved structure and causes the reaction force to act on the heel perpendicular to the stiff element providing leverage during push-off [20, 23]. The high midsole stack height enhances this mechanism and allows for a more curved plate to be inserted into the midsole [20]. The compliant, resilient, lightweight foam material for the midsole ensures that the shoe weight remains light while still having a soft foam with a high-energy return as these have all been suggested to also affect performance [18–20].

The impact of advanced footwear technology on running events is reflected in the progression of world records, with every male and female world record starting from 5 km to the marathon broken by athletes wearing different versions of these shoes since their release [24]. Previous research completed on such footwear technology in the field quantifies this impact on performance, with data from the Strava fitness app on more than a million marathon and half-marathons revealing that shoes containing this new technology could improve race performance in sub-elite athletes, as individuals ran 4–5% faster in advanced footwear technology than runners wearing an average racing flat [25]. Similarly, Rodrigo-Carranza et al. showed that in a sub-cohort of top-100 men's marathon performances from 2015 to 2019 that completed races in both advanced footwear technology and traditional flats, 29 of 40 athletes (72.50%) improved their

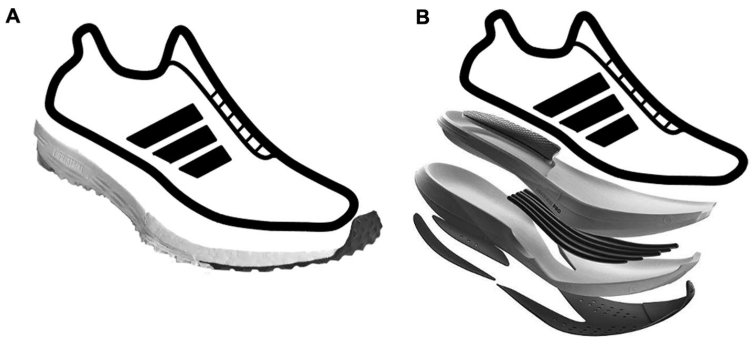


Fig. 1 Schematic of different long-distance running shoes, including **A** a traditional racing flat, which is classically low to the floor with relatively thin soles with the focus here being to keep the shoes lightweight, and **B** advanced footwear technology, which consists of a curved stiff element in the forefoot of the shoe, as well as a high midsole stack height made up of a resilient, compliant, and lightweight foam

performance with this type of footwear [26]. This is also supported by various laboratory-based running economy studies comparing advanced footwear technology to traditional racing flats in sub-elite athletes, suggesting that the design of these shoes reduces the energy cost of running on average by about 2.7–4.4%, thereby benefiting overall running performance [15, 27–30].

While previous studies have compared the running economy of non-elite runners wearing different shoe technologies in relatively controlled laboratory settings [15, 27–30], no study has examined the variability in running economy of the main beneficiaries (i.e., world-class athletes). Knowing this, the primary aim of this study was to answer the research question: how does the variability in physiological response in terms of running economy on a laboratory treadmill in advanced footwear technology compare to a traditional racing flat in world-class Kenyan distance runners (half-marathon mean time: 59:30 min:s) versus European amateur runners? Based on the obtained results, we decided to systematically search the literature for similar relevant studies and conducted a post-hoc meta-analysis to confirm the found range of variability, and better understand the overall effect of advanced footwear technology.

2 Materials and Methods

2.1 Participants

Fifteen subjects volunteered to participate in this study and were classified as either world class or amateur. Runners with current or recent injuries that prevented them from training were excluded, as well as those uncomfortable with running on a treadmill. Shoe size was also part of the inclusion criteria because of shoe cost considerations. One participant dropped out as he struggled to run on a treadmill, meaning 14 participants were finally included for analysis in this study.

The world-class cohort comprised seven male world-class Kenyan runners (mean ± standard deviation, age: 22.7 ± 3.2 years, height: 1.7 ± 0.05 m, mass: 59.9 ± 4.8 kg, body mass index: 19.7 ± 0.6 kg/m^2, $\dot{V}O_2$peak: 75.9 ± 3.5 mL/kg/min) (Table 1) [31]. These runners were recruited through sponsorship deals with collaborating companies and were all professional road racing athletes who had an official mean personal record for the half-marathon of 59:30 ± 0:48 min:s, and a 10-km personal best of 27:33 ± 0:41 min:s. The amateur cohort consisted of seven well-trained male amateur European runners, who at the time of measurement were training daily, (mean ± standard deviation, age: 28.1 ± 4.2 years, height: 1.8 ± 0.03 m, mass: 72.1 ± 7.0 kg, body mass index: 21.9 ± 1.8 kg/m^2, $\dot{V}O_2$peak: 62.3 ± 5.1 mL/kg/min) and volunteered to take part in this research (Table 1). All participants gave written informed consent to being a part of this study after they understood the experimental procedures, potential injury risks, and possible benefits.

2.2 Shoes

Throughout the experimental protocol, analyzed shoe conditions included a commercially available traditional racing shoe (FLAT) used by the subjects regularly for their own training, as well as three different commercially available models of AdvFootTech (1–3) that differed in their geometry and weight (Table 2). As all athletes were the same shoe size, everyone tested in UK 8.5 (US 9/EU 42 2/3).

2.3 Experimental Protocol

This study comprised two laboratory visits occurring on separate days, with a 24-h pause for recovery, at the adidas Sports Science Research Laboratory in Herzogenaurach, Germany located close to sea level at an altitude of 300 m (Fig. 2). During the first session, we collected $\dot{V}O_2$peak and baseline measurements. In the subsequent session, we measured running economy in different footwear conditions at either 75% (world class) or 70% (amateur) of the corresponding velocity to the measured $\dot{V}O_2$peak, (v$\dot{V}O_2$peak) [32]. We chose the 75/70% of v$\dot{V}O_2$peak as this was a submaximal speed related to speeds these subjects would use when running at a marathon pace.

To ensure consistency and avoid any confounding effects of circadian rhythm [33], we tested participants at the same time of day and encouraged them to match their diet, sleep, and training patterns prior to each session. Furthermore, to ensure the athletes felt comfortable being in a foreign

Table 1 Participant descriptive and physiological characteristics for each of the measured cohorts

Variable	World class $n = 7$	Amateur $n = 7$	p-value
Age (years)	22.7 ± 3.2	28.1 ± 4.2	0.020*
Height (cm)	174.3 ± 4.9	181.4 ± 2.6	0.008*
Weight (kg)	59.9 ± 4.8	72.1 ± 7.0	0.003*
$\dot{V}O_2$peak (mL/kg/min)	75.9 ± 3.5	62.3 ± 5.1	< 0.001*
$\dot{V}O_2$peak (L/min)	4.53 ± 0.43	4.49 ± 0.48	0.870
v$\dot{V}O_2$peak (km/h)	22.3 ± 0.6	18.8 ± 1.2	< 0.001*

Data shown are mean ± standard deviation

$\dot{V}O_2peak$ maximal oxygen uptake, $v\dot{V}O_2peak$ velocity at $\dot{V}O_2peak$, Student's t test

*Significance ($p < 0.05$)

Table 2 Descriptive characteristics of the AdvFootTech and FLAT

Shoe label	Mass (g)	Forefoot stack height (mm)	Rearfoot stack height (mm)	Heel-to-toe drop (mm)	Energy return (%)	Stiff element?
AdvFootTech 1	225	31.5	39	8.5	High	Yes
AdvFootTech 2	210	29.5	39.5	10	High	Yes
AdvFootTech 3	196	31	39.5	8.5	High	Yes
FLAT	197	19	24	5	Low	No

NShoe characteristics based on size UK 8.5/US 9

Energy return classification: low: < 70%; medium: 70–80%; high: > 80%

AdvFootTech advanced footwear technology, *FLAT* traditional racing flat

environment and understood all that was asked of them, their coach as well as manager traveled with them and helped with testing. This favored a clearer communication between the research team and the athletes.

2.3.1 Visit 1

In this preliminary visit, we collected physiological baseline and anthropometric measurements. Throughout the whole experiment, all treadmill sessions were conducted in the same standardized laboratory chamber (mean ± standard deviation, temperature: 25.5 ± 1.1 °C, humidity: 60.2 ± 8.8%, pressure: 980.7 ± 4.9 mBar) on a HP Cosmos motorized treadmill (Venus 200/75; h/p/cosmos sports and medical GmbH, Nussdorf-Traunstein, Germany) set at a 1% gradient to mimic the energetic cost of running outdoors [34]. Given that some runners were not accustomed to treadmill running or using a $\dot{V}O_2$peak protocol, we familiarized subjects during a 15-min session on the treadmill with increasing speeds. Once they felt comfortable running on a treadmill, we fitted each athlete with a heart rate monitor (Polar H7; Polar Electro Oy, Kempele, Finland) and face mask (7450 Series V2 Mask; Hans Rudolph, Inc., Shawnee, KS, USA), connected to the MetaMax 3B portable cardiopulmonary gas exchange measuring device (CORTEX Biophysik GmbH, Leipzig, Germany). We then collected respiratory parameters from the subjects using an automated breath-by-breath method, via the measurement and evaluation software, MetaSoft Studio (CORTEX Biophysik GmbH, Leipzig, Germany). Before each testing session, we calibrated this system according to the manufacturer's instructions [35, 36].

To assess maximal aerobic capacity, athletes completed a $\dot{V}O_2$peak ramp test using an incremental speed protocol with a continuous 1% incline. For this, athletes ran in the new pairs of the traditional racing FLAT test condition. For the world-class athletes, this test started at 10 km/h for 2 min and increased progressively at 1 km/h/min until volitional exhaustion. Amateurs completed the same protocol starting at 8 km/h. During this test, we verbally encouraged all athletes to ensure a maximal output was reached.

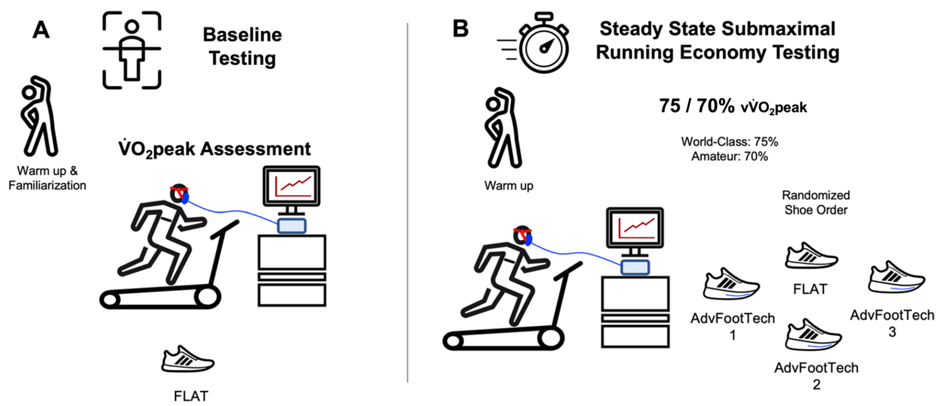


Fig. 2 Illustration of the methods protocol of the present study. **A** For visit 1, we collected baseline information of the subjects, which included conducting a maximal oxygen uptake ($\dot{V}O_2$peak) assessment. **B** On the second day of testing, we then assessed the running economy of both traditional racing flat (FLAT) and different advanced footwear technology (AdvFootTech) models. *v$\dot{V}O_2$peak* velocity at *$\dot{V}O_2$peak*

Upon completion, two experienced exercise physiologists detected and agreed upon ventilatory thresholds and $\dot{V}O_2$peak values. For all cardiorespiratory data, we cleaned the breath-by-breath raw data by removing outlying data points that were more than two standard deviations away from the mean of a seven-breath window. After these outliers were removed, data were smoothed further by taking a moving seven-breath average. The $\dot{V}O_2$max value was recorded as the highest cleaned and smoothed value during the test. As we did not repeat a verification test to confirm these values, the highest recorded $\dot{V}O_2$ value will be defined as a '$\dot{V}O_2$peak' [37]. The measured v$\dot{V}O_2$peak (km/h) was also recorded and used to prescribe the running speed for the running economy tests during visit 2. Ventilatory threshold data as well as previously recorded personal bests of each athlete were used to ensure the selected speeds were sufficient in obtaining testing data that are relevant to racing and would not be affected by fatigue.

2.3.2 Visit 2

During visit 2, we assessed running economy for each of the different shoes at 75% of v$\dot{V}O_2$peak (17.0 ± 0.4 km/h) for world-class athletes and 70% (13.1 ± 1.0 km/h) for amateur athletes. When subjects arrived, they first completed a 6-min standardized warm-up in the FLAT. This was then followed by a 12-min break during which we prepared the equipment for the test that consisted of 6-min bouts with a 12-min rest between bouts. Before each new treadmill trial, athletes changed their shoes for the next bout. The last 30 s of this break were recorded on the treadmill to obtain resting values.

From the recorded measurements, we calculated running economy, oxygen cost of transport, and energetic cost using the Péronnet and Masicotte equation expressed in mL/kg/min, mL/kg/km, and W/kg, respectively, from the $\dot{V}O_2$ data during the 60-s period from minute 4 to 5 of each test [38].

2.4 Data and Statistical Analysis

All data analysis and statistical tests were performed using RStudio [39]. Statistical analyses of the data were performed using the R package 'stats' (version 4.0.0) in RStudio [39, 40] using the traditional level of significance ($p < 0.05$). Power and sample size calculations were performed using the R package 'pwr' (version 1.3-0) in RStudio also using the traditional level of significance ($p < 0.05$), 80% power, and four different groups for the four different shoes. We conducted a Student's *t* test on the descriptive characteristics to analyze population differences between the measured world-class and amateur athletes. Additionally, an analysis of variance test with repeated measures and a Bonferroni post-hoc correction were conducted on the steady-state physiological data [41, 42].

2.5 Systematic Review and Meta-analysis

To confirm the found range of variability with the previously published literature, and better understand the overall effect of advanced footwear technology, we conducted a systematic electronic search of relevant studies and a related meta-analysis.

For this retrospective systematic literature search, Scopus, SPORT-Discus, PubMed, Web of Science, and Footwear Science databases were searched using the terms "Racing Shoes" and "Running Shoes + Running Economy" through 21 November, 2021. Inclusion criteria for this review were studies that (1) examined the running performance effect of different versions of advanced footwear technology for road running compared to a traditional racing flat control condition; and (2) measured the running economy (mL/kg/min) of this comparison. Additional secondary outcome measures including oxygen cost of transport (mL/kg/km) and energetic cost (W/kg) were also analyzed to provide a bigger picture of the effects of such new technology on running performance. These results were then pooled using Hedge's *g* for a standardized effect size [43] and the inverse heterogeneity (IVhet) model using the Epigear Meta XL software (version 5.3) [44]. We further analyzed outcomes of the meta-analysis using a *z*-score for significance, Cochran's *Q* statistic for heterogeneity, and I-squared for inconsistency [45] and assessed the risk of bias using the Cochrane Risk of Bias Instrument for RCTs (RoB 2) [46].

3 Results

3.1 Running Economy

From the available dataset ($n = 14$), for running economy there was a significant difference between shoe types in the amateur athletes ($F(3) = 8.308$, $p = 0.001$) where running economy in the advanced footwear technology was significantly lower than in the FLAT. Compared to the FLAT shoe, amateur athletes saw running economy improved by 3.5 ± 3.7% ($p_{Bonferroni} = 0.042$) with AdvFootTech 1, 4.6 ± 2.7% ($p_{Bonferroni} = 0.005$) with AdvFootTech 2, and 5.0 ± 3.4% ($p_{Bonferroni} = 0.002$) with AdvFootTech 3 (Fig. 3B, Table 3), with no significant differences between the three advanced footwear technology conditions.

Both the world-class and amateur athletes showed a large inter-individual variability with individual trials

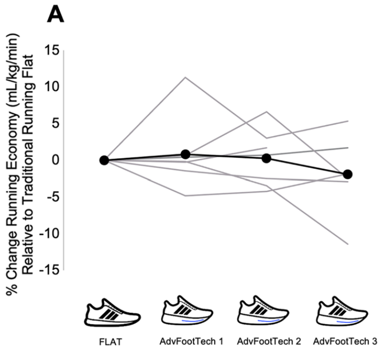


Fig. 3 Percentage change in steady-state running economy oxygen consumption (mL/kg/min) relative to a traditional running flat (FLAT) in different shoe conditions for both **A** world-class and **B** amateur populations. These shoes include a FLAT on the far left as well as three different advanced footwear technology (AdvFootTech) conditions. Here, a negative percentage change indicates less oxygen consumption at a given speed and therefore a better running economy

showing a ± 11.4% variation in performance (Fig. 3). When examining the individual advanced footwear technology conditions for the world-class population, the inter-individual range in overall performance changes of all included subjects vary by 14.6% on average for the different shoes. A similar pattern is also seen in the amateur population where values here range from a 9.7% benefit to a 1.1% drawback for advanced footwear technology when compared to the flat for a narrower inter-individual total range of 10.8% (Fig. 3B). For this population, the individual advanced footwear technology range in performance changes was narrower than that of the world-class population for an average of a 9.5% difference between the maximum and minimum percent change per shoe. Via a time and running economy interaction analysis, we ensured the shoe order did not have a significant effect on the described results (world-class: $p = 0.61$; amateur: $p = 0.67$).

In Table 3, we present the results for running economy, oxygen consumption, and percentage change in running economy in the advanced footwear technology models compared to a traditional running flat for both the world-class and amateur cohorts. Here, we compare the different shoes among cohorts, stratifying the data according to the amateur or world-class athlete results, as well as global effects comparing all tested subjects.

3.2 Systematic Review Study Characteristics

From the initial search that resulted in 929 studies, 30 were selected for a full-text analysis after excluding by duplicates, title, and abstract, and five studies were finally included after fulfilling the inclusion criteria (Fig. 4). All examined studies were randomized crossover trials investigating a range of recreational to highly trained runners with a combined average measured $\dot{V}O_2$peak of 67.1 ± 8.2 mL/kg/min. All studies examined a steady-state running analysis on a treadmill with different advanced footwear technology shoes compared to traditional racing flats, with Hébert-Losier et al. also including participants' own shoes and spray painting the others to blind participants to model details [27]. Of the five studies, Barnes and Kilding was the only experiment to also include a female cohort [15]. Examined footwear conditions of the studies included in the meta-analysis are described in Table 4, please note data of shoe conditions irrelevant for this study, such as track spikes, were excluded in the meta-analysis [15]. When repeated conditions were used for the meta-analysis comparison, the corresponding conditions were divided by the number of repeated comparisons to ensure no double counting of effects. The testing was conducted at a variety of different speeds either between 14 and 18 km/h or in the case of Hébert-Losier et al., at different speeds relative to $\dot{V}O_2$peak [27]. Hereby, we decided to subgroup the analysis based on the speed at which physiological variables were measured according to the protocols. We included four different speed categorizations starting with a very low speed that included 60% of v$\dot{V}O_2$peak where the speed was 11.0 ± 0.6 km/h; the low speed category included those conditions measured at 14 km/h for both men and women or 70% of v$\dot{V}O_2$peak with a speed of 12.9 ± 0.7 km/h; the medium-speed category included 16 km/h for men, 15 km/h for women, and 80% of v$\dot{V}O_2$peak with a speed of 14.7 ± 0.8 km/h; finally, the high-speed category included 18 km/h for men, and 16 km/h for women.

Considering the risk of bias assessment of the included studies, all studies had some concerns for the category of bias arising from period and carryover effects, given the unknown effect of the physiological starting point between the trials and what carryover or how long a carryover might be with regard to running in advanced footwear technology. The overall risk of bias across all studies was of some concern owing to the similarities in the protocol of the study and the period and carryover effects.

Table 3 Steady-state physiological results for each of the different AdvFootTech and FLAT models separated between the world-class and amateur cohorts as well as statistical findings of the whole combined sample

Variable	World class (mean ± SD)				Among world-class subjects	Amateur (mean ± SD)				Among amateur subjects	Combined sample		
	$n=7$					$n=7$					Main effect shoes within subjects	Main population effect between subjects	Interaction effect within subjects
	FLAT	AdvFootTech 1	AdvFootTech 2	AdvFootTech 3	Repeated-measures ANOVA	FLAT	AdvFootTech 1	AdvFootTech 2	AdvFootTech 3	Repeated-measures ANOVA			
Running economy (mL O_2/kg/min)	54.5 ± 2.0	54.9 ± 1.6	54.7 ± 2.8	53.5 ± 3.1	$F=0.743$ $p=0.541$	47.7 ± 2.6	$46.1 \pm 3.2^{\dagger}$ $p_{Bonf}=0.043$	$45.5 \pm 2.1^{\dagger}$ $p_{Bonf}=0.004$	$45.3 \pm 1.9^{\dagger}$ $p_{Bonf}=0.002$	$F=8.308$ $p=0.001$*	$F=3.360$ $p=0.030$*	$F=46.608$ $p<0.001$*	$F=1.741$ $p=0.177$
Oxygen cost of transport (mL O_2/kg/km)	192.3 ± 8.1	193.8 ± 6.6	192.9 ± 11.8	188.7 ± 9.1	$F=0.875$ $p=0.474$	220.2 ± 12.3	$212.3 \pm 5.0^{\dagger}$ $p_{Bonf}=0.047$	$209.9 \pm 8.8^{\dagger}$ $p_{Bonf}=0.006$	$208.9 \pm 10.4^{\dagger}$ $p_{Bonf}=0.003$	$F=7.511$ $p=0.002$*	$F=4.245$ $p=0.012$*	$F=20.757$ $p<0.001$*	$F=2.478$ $p=0.077$
Energetic cost (W/kg)	19.4 ± 0.7	19.6 ± 0.6	19.5 ± 1.0	19.0 ± 1.3	$F=0.836$ $p=0.493$	16.9 ± 0.9	$16.2 \pm 1.2^{\dagger}$ $p_{Bonf}=0.018$	$16.0 \pm 0.8^{\dagger}$ $p_{Bonf}=0.002$	$15.9 \pm 0.7^{\dagger}$ $p_{Bonf}=<0.001$	$F=10.007$ $p<.001$*	$F=3.572$ $p=0.024$*	$F=47.887$ $p<0.001$*	$F=1.886$ $p=0.150$
Respiratory exchange ratio	0.92 ± 0.02	0.93 ± 0.02	0.93 ± 0.02	0.90 ± 0.05	$F=1.001$ $p=0.416$	0.91 ± 0.03	$0.88 \pm 0.02^{\dagger}$ $p_{Bonf}=0.029$	$0.88 \pm 0.03^{\dagger}$ $p_{Bonf}=0.016$	$0.88 \pm 0.03^{\dagger}$ $p_{Bonf}=0.005$	$F=6.518$ $p=0.004$*	$F=2.741$ $p=0.058$	$F=4.935$ $p=0.048$*	$F=1.663$ $p=0.193$
Heart rate (bpm)	158.4 ± 8.8	157.7 ± 8.5	157.3 ± 10.1	155.6 ± 11.2	$F=0.919$ $p=0.453$	160.3 ± 5.9	157.2 ± 7.2	160.1 ± 6.5	158.8 ± 7.5	$F=1.527$ $p=0.242$	$F=1.542$ $p=0.221$	$F=0.278$ $p=0.609$	$F=1.072$ $p=0.373$
% Change in running economy to traditional running FLAT	0.0 ± 0.0	0.8 ± 5.0	0.3 ± 3.9	− 1.9 ± 5.6	$F=0.74$ $p=0.543$	0.0 ± 0.0	$-3.5 \pm 3.7^{\dagger}$ $p_{Bonf}=0.042$	$-4.6 \pm 2.7^{\dagger}$ $p_{Bonf}=0.005$	$-5.0 \pm 3.4^{\dagger}$ $p_{Bonf}=0.002$	$F=7.969$ $p=0.001$*	$F=3.579$ $p=0.023$*	$F=4.170$ $p=0.066$	$F=2.039$ $p=0.126$

AdvFootTech advanced footwear technology, *ANOVA* analysis of variance, *FLAT* traditional racing flat, *SD* standard deviation

*Significant difference ($p<0.05$)

†Shoes with value significantly different to the FLAT

Fig. 4 Flow chart showing study selection. Adapted from the PRISMA flow diagram [60]

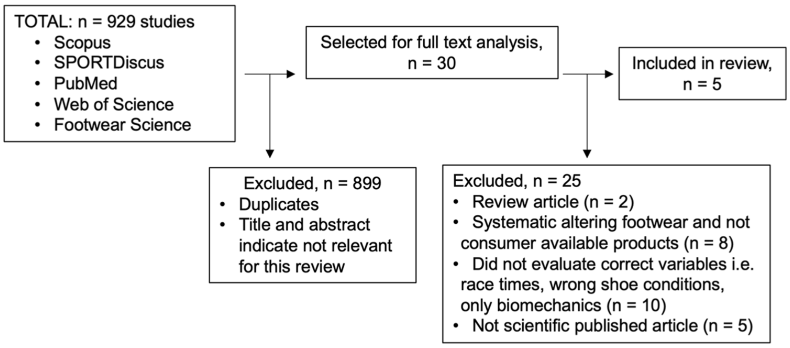


Table 4 Descriptive characteristics of shoe products included in the meta-analysis

Shoe label	Mass (g)	Forefoot stack height (mm)	Rearfoot stack height (mm)	Heel-to-toe drop (mm)	Midsole material	Stiff element?
AdvFootTech 1	225	31.5	39	8.5	n/a	Yes
AdvFootTech 2	210	29.5	39.5	10	n/a	Yes
AdvFootTech 3	196	31	39.5	8.5	n/a	Yes
AdvFootTech 4 [15, 27–29]	195	21	31	10	PEBA	Yes
AdvFootTech 5 [30]	196	32	40	8	PEBA	Yes
AdvFootTech 6 [30]	210	27	35	8	n/a	Yes
AdvFootTech 7 [30]	207	24	34	10	TPU	Yes
AdvFootTech 8 [30]	213	30	35	5	EVA	Yes
AdvFootTech 9 [30]	207	33	38	5	n/a	Yes
AdvFootTech 10 [30]	213	31	39	8	PEBA	Yes
AdvFootTech 11 [30]	210	36	40	4	PEBA	Yes
FLAT	197	19	24	5	TPU	No
FLAT 2 [28, 29]	181	15	23	8	EVA	No
FLAT 3 [28]	221	13	23	10	TPU	No
FLAT 4 [15, 29]	224	13	23	10	TPU	No
FLAT 5 [27]	130	13	13	1	TPU	No
FLAT 6 [27]	313 ± 44	n/a	26.0 ± 7.9	9.4 ± 6.7	Varies	No
FLAT 7 [30]	210	21	30	9	EVA	No

Shoe characteristics based on size UK 8.5/US 9 and obtained from original journal articles used in the meta-analysis or measurements conducted from RunningWarehouse.com. FLAT 6 varies (mean ± standard deviation) as it is a combination of the participants own footwear and includes sizes varying from US 8.5 to 12. Missing information (n/a) is because of the confidentiality of midsole material or missing information in the examined studies

AdvFootTech advanced footwear technology, *EVA* ethylene–vinyl acetate, *FLAT* traditional racing flat, *n/a* not available, *PEBA* polyether block amide, *TPU* thermoplastic polyurethane

3.3 Meta-analysis Primary Outcome Measure: Running Economy

The meta-analysis of running economy (mL/kg/min) in all five examined studies comparing different advanced footwear technology to racing flat conditions revealed a statistically significant benefit of advanced footwear technology on running economy measures with an overall medium effect of − 0.58 [mean (95% confidence interval); $g = -0.58$ (− 0.75, − 0.42), $Z = -6.86$ ($p < 0.001$)], where a negative value indicates improved efficiency when running (Fig. 5). When sub-grouped by speed, the analysis showed a small effect [$g = -0.29$ (− 0.87, 0.31)] at very low speeds, a medium effect [$g = -0.58$ (− 0.90, − 0.26)] at low speeds, a medium effect [$g = -0.54$ (− 0.79, − 0.28)] at medium speeds, and a large effect [$g = -0.92$ (− 1.31, − 0.52)] at high speeds. Incorporating the data presented in this study, results are showing an overall medium effect [$g = -0.39$ (-1.01, 0.23)]. When this sub-analysis is further distributed by population, the world-class subgroup showed a small effect [$g = -0.02$ (-0.88, 0.85)], and the amateur subgroup showed a large effect [$g = -0.80$ (-1.70, 0.10)]. In this analysis, no statistically significant heterogeneity, as assessed via Q, was found ($Q = 14.42$, $p = 1.00$) and inconsistency, as assessed using I^2 as an extension of Q, was very low ($I^2 = 0\%$) [45].

3.4 Meta-analysis Secondary Outcome Measures: Oxygen Cost of Transport and Energetic Cost

The meta-analysis of oxygen cost of transport (mL/kg/km) of the three studies that included this data revealed a statistically significant benefit of advanced footwear technology on the oxygen cost of transport measures [mean (95% CI); $g = -0.67$ (-0.87, -0.47), $Z = -6.60$ ($p = < 0.001$), Fig. 6]. Considering the subgroup analysis by speed, a medium effect [$g = -0.58$ (-0.96, -0.20)] was found at low speeds, a medium effect [$g = -0.62$ (-0.95, -0.30)] at medium speeds, and a large effect [$g = -0.92$ (-1.31, -0.52)] at high speeds. Incorporating the data presented in this study, an overall medium effect [$g = -0.47$ (-1.10, 0.16)] was found. Here as well, no statistically significant heterogeneity was found ($Q = 14.03$, $p = 0.99$) and inconsistency was very low ($I^2 = 0\%$) among the examined studies [45].

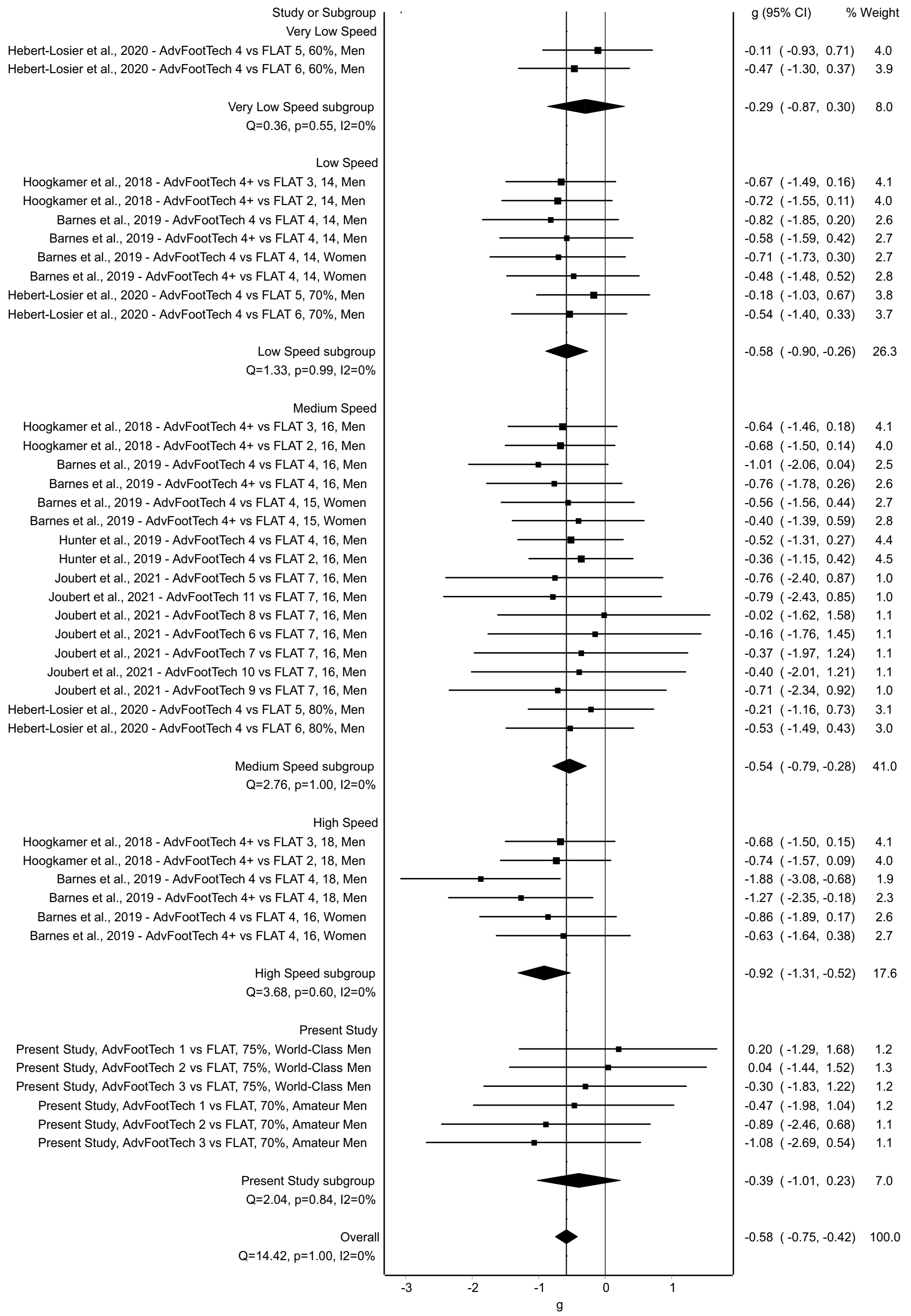
Finally, the meta-analysis of energetic cost (W/kg) of the four studies showed a statistically significant benefit of advanced footwear technology on energetic cost measures [mean (95% CI); $g = -0.54$ (-0.71, -0.37), $Z = -6.28$ ($p = < 0.001$), Fig. 7]. Further examination of the subgroup speed analysis shows a small effect [$g = -0.27$ (-0.86, 0.31)] at very low speeds, a medium effect [$g = -0.53$ (-0.85, -0.21)] at low speeds, a medium effect [$g = -0.55$ (-0.82, -0.27)] at medium speeds, and a large effect [$g = -0.69$ (-1.07, -0.31)] at high speeds. Analysis of the present study shows an overall medium effect [$g = -0.41$ (-1.04, 0.21)]. Again, here, no statistically significant heterogeneity was found ($Q = 8.44$, $p = 1.00$) and inconsistency was very low ($I^2 = 0\%$) between the subgroups [45].

4 Discussion

In this study, we aimed to assess the variability in running economy in advanced footwear technology compared to a traditional racing flat on a treadmill in world-class Kenyan versus European amateur runners at speeds proportional to a marathon pace. Our laboratory results revealed ± 11.4% variability of the running economy of different advanced footwear technology running shoes in world-class Kenyan road runners, while for amateur Europeans, results range from a 9.7% benefit to a 1.1% drawback. The post-hoc meta-analysis revealed an overall statistically significant medium benefit of advanced footwear technology on running economy when compared with traditional flats.

4.1 Running Economy and Running Performance Inter-Individual Variability

The running economy of the measured advanced footwear technology compared to a traditional racing flat of all tested subjects revealed a large inter-subject variability with overall values that ranged from an 11.4% benefit to an 11.3% drawback (Fig. 3). To compare this variation of running economy to other studies, we conducted a systematic literature search. Interestingly, this revealed similar variability in the found research considering the obtained confidence intervals in the conducted meta-analysis (Figs. 5, 6, 7). Hoogkamer et al. examined for the first time advanced footwear technology versus previously established marathon racing flats, all mass neutralized, in high-caliber athletes at three distinct speeds. The results found a range of 1.97–6.26% benefit in energetic cost (W/kg) of the new advanced footwear technology versus flats [28]. A similar study conducted by Barnes and Kilding showed a 1.72–7.15% running economy benefit (mL/kg/min) in highly trained runners in favor of the advanced footwear technology with only trivial-to-small differences between the tested men and women [15]. On average, this study found a 4.2% running economy benefit of advanced footwear technology versus the flat, which decreased to 2.9% when these conditions were weight matched, indicating the effect weight might have on such testing [15]. In an additional study, Hunter et al. found a response range of a 0.0–6.4% improvement in running economy (mL/kg/min) for advanced footwear technology and further suggested that different runners may require individualized shoe stiffnesses to enhance performance [29]. Hébert-Losier et al. examined both running economy and performance during a 3-km time trial and found a variability in running economy (mL/kg/min) of a worsening by a 10.3–13.3% improvement across conditions in recreational runners, and a time trial variability of a worsening by a 4.7–9.3% improvement [27]. To compare seven different models of advanced footwear technology, Joubert et al. conducted running economy tests (mL/kg/min) with trained distance runners and found that when all advanced footwear technology shoes are combined, the responses, as calculated from presented mean and standard deviations as well as described values, ranged from a 1% disadvantage to a 5.3% advantage [30]. An additional group of research studies also conducted a similar analysis by examining race performance measures instead of physiological data obtained in a laboratory. Considering these as well, Guinness et al. examined marathon race performance results from hundreds of elite marathoners who switched to advanced footwear technology and found that 74.5% of


Study or Subgroup
g (95% CI)
% Weight
Very Low Speed
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 60%, Men -0.11 (-0.93, 0.71) 4.0
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 60%, Men -0.47 (-1.30, 0.37) 3.9
Very Low Speed subgroup -0.29 (-0.87, 0.30) 8.0
Q=0.36, p=0.55, I2=0%
Low Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 14, Men -0.67 (-1.49, 0.16) 4.1
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 14, Men -0.72 (-1.55, 0.11) 4.0
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 14, Men -0.82 (-1.85, 0.20) 2.6
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 14, Men -0.58 (-1.59, 0.42) 2.7
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 14, Women -0.71 (-1.73, 0.30) 2.7
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 14, Women -0.48 (-1.48, 0.52) 2.8
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 70%, Men -0.18 (-1.03, 0.67) 3.8
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 70%, Men -0.54 (-1.40, 0.33) 3.7
Low Speed subgroup -0.58 (-0.90, -0.26) 26.3
Q=1.33, p=0.99, I2=0%
Medium Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 16, Men -0.64 (-1.46, 0.18) 4.1
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 16, Men -0.68 (-1.50, 0.14) 4.0
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 16, Men -1.01 (-2.06, 0.04) 2.5
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 16, Men -0.76 (-1.78, 0.26) 2.6
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 15, Women -0.56 (-1.56, 0.44) 2.7
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 15, Women -0.40 (-1.39, 0.59) 2.8
Hunter et al., 2019 - AdvFootTech 4 vs FLAT 4, 16, Men -0.52 (-1.31, 0.27) 4.4
Hunter et al., 2019 - AdvFootTech 4 vs FLAT 2, 16, Men -0.36 (-1.15, 0.42) 4.5
Joubert et al., 2021 - AdvFootTech 5 vs FLAT 7, 16, Men -0.76 (-2.40, 0.87) 1.0
Joubert et al., 2021 - AdvFootTech 11 vs FLAT 7, 16, Men -0.79 (-2.43, 0.85) 1.0
Joubert et al., 2021 - AdvFootTech 8 vs FLAT 7, 16, Men -0.02 (-1.62, 1.58) 1.1
Joubert et al., 2021 - AdvFootTech 6 vs FLAT 7, 16, Men -0.16 (-1.76, 1.45) 1.1
Joubert et al., 2021 - AdvFootTech 7 vs FLAT 7, 16, Men -0.37 (-1.97, 1.24) 1.1
Joubert et al., 2021 - AdvFootTech 10 vs FLAT 7, 16, Men -0.40 (-2.01, 1.21) 1.1
Joubert et al., 2021 - AdvFootTech 9 vs FLAT 7, 16, Men -0.71 (-2.34, 0.92) 1.0
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 80%, Men -0.21 (-1.16, 0.73) 3.1
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 80%, Men -0.53 (-1.49, 0.43) 3.0
Medium Speed subgroup -0.54 (-0.79, -0.28) 41.0
Q=2.76, p=1.00, I2=0%
High Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 18, Men -0.68 (-1.50, 0.15) 4.1
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 18, Men -0.74 (-1.57, 0.09) 4.0
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 18, Men -1.88 (-3.08, -0.68) 1.9
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 18, Men -1.27 (-2.35, -0.18) 2.3
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 16, Women -0.86 (-1.89, 0.17) 2.6
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 16, Women -0.63 (-1.64, 0.38) 2.7
High Speed subgroup -0.92 (-1.31, -0.52) 17.6
Q=3.68, p=0.60, I2=0%
Present Study
Present Study, AdvFootTech 1 vs FLAT, 75%, World-Class Men 0.20 (-1.29, 1.68) 1.2
Present Study, AdvFootTech 2 vs FLAT, 75%, World-Class Men 0.04 (-1.44, 1.52) 1.3
Present Study, AdvFootTech 3 vs FLAT, 75%, World-Class Men -0.30 (-1.83, 1.22) 1.2
Present Study, AdvFootTech 1 vs FLAT, 70%, Amateur Men -0.47 (-1.98, 1.04) 1.2
Present Study, AdvFootTech 2 vs FLAT, 70%, Amateur Men -0.89 (-2.46, 0.68) 1.1
Present Study, AdvFootTech 3 vs FLAT, 70%, Amateur Men -1.08 (-2.69, 0.54) 1.1
Present Study subgroup -0.39 (-1.01, 0.23) 7.0
Q=2.04, p=0.84, I2=0%
Overall -0.58 (-0.75, -0.42) 100.0
Q=14.42, p=1.00, I2=0%
-3
-2
-1
0
1
g

◂**Fig. 5** Forest plot displaying running economy (mL/kg/min) comparisons between advanced footwear technology (AdvFootTech) and traditional racing flats (FLAT) sub-categorized into different speeds. Study labels consist of the study name, the examined AdvFootTech versus FLAT condition where + indicates conditions that are weight matched, the speed either in km/h or as a % of peak, and the examined population. *CI* confidence interval

the men ran faster with an estimate of a 1.4–2.8% improvement in performance, while 71.4% of the women ran faster with an estimate of a 0.6–2.2% performance improvement [47]. Similarly, Senefeld et al. further examined performance and racing shoes in elite racers in four major marathons and found that in a subgroup of athletes with subsequent race performance of a flat then advanced footwear technology, the between-race change in performance for female athletes had a 95% confidence interval range from a 6.9% hindrance to a 13.8% advantage and a 5.4% hindrance to an 11.4% advantage in male athletes, suggesting that observed findings in a laboratory setting translate to real improvements in racing conditions [48]. Finally, Bermon et al. analyzed seasonal best times throughout the years to determine the effect of switching to advanced footwear technology, and found that in half-marathon and marathon races of a subgroup of athletes who competed in the same event with and without these shoes, all athletes (except male half-marathon runners) significantly improved their performance times with calculations on presented data showing that on average the female athletes showed a greater benefit of 1.9% faster in both races when compared with a 0.8% better performance found in the male athletes [49]. Overall, comparable to the present study, the variability in previously published data range from a 13.8% benefit to a 10.3% drawback in an overall change in performance of advanced footwear technology versus traditional racing flats as measured both in the laboratory with steady-state running physiology tests, and in the field examining race times.

Additional results from the five studies included after a retrospective systematic review and meta-analysis revealed that advanced footwear technology had an overall significant medium effect of − 0.58 when compared with a flat in terms of running economy, oxygen cost of transport, and energetic cost, even when accounting for the large individual variability found in these individual studies [15, 27–30]. Interestingly, as revealed via the subgroup analysis, the effect changed with the speed sub-groups where very low speeds showed a small effect and high speeds showed a greater effect, aligning with what has previously been shown in the literature [50]. This suggests that mechanisms involved in the advanced footwear technology might be proportional to the other biomechanical aspects such as changes in stride or gait cycle that alter with speed, with the mechanism reducing the energy required for running bouts proportionally higher when running at higher speeds [51].

Despite the findings of the meta-analysis, it remains important to consider the great inter-individual differences in the response to footwear conditions with individuals in the presented study as well as subjects in previous research showing significant inter-individual differences. Such results suggest possible methodological limitations of measuring the performance of running shoes (e.g., laboratory-based studies, insufficient familiarization protocols), as well as the importance of an individualized approach for athletes considering different biomechanical or anthropometrics that could be contributing to optimize their response to advanced footwear technology.

4.2 Intra-Individual Running Economy Differences in Shoe Conditions

When examining the individual cases, some subjects showed meaningful effects depending on the specific advanced footwear technology shoe being tested, and others were not always trending the same way among all advanced footwear technology models. For example, given the results here, one of the world-class Kenyan runners showed a range from an 11.4% to a 0.2% benefit in the different advanced footwear technology models (Fig. 3A). For the aforementioned athlete, comparing personal best half-marathon times, this individual did indeed improve a sub-1-h half-marathon time by over 1:20 (min:s) in a shoe where this athlete was more economical during testing [52]. However, for another world-class subject who exhibited a running economy range of a 2.5% benefit to a 6.6% drawback for different advanced footwear technology, comparing marathon seasonal best times, this athlete was able to set a new personal record by reducing 2 min off a time already under 2:10 (h:min) in shoes that they, according to our test, should have performed worse in. This further affirms possible limitations of testing shoe performance in this way, particularly with a world-class Kenyan running population where further confounders such as a lack of familiarization to treadmill running and testing conditions might be playing a role.

4.3 Populations Running Economy Differences

When examining in our study the differences in variability ranges between the world-class (an 11.4% benefit to a 11.3% drawback) and the amateur (a 9.7% benefit to a 1.1% drawback) populations, further exploration into the data revealed possible explanations. As we did not measure the running economy of all participants at the same speed, we are unable to conclude how the running efficiency of these two populations compared as a baseline in the same traditional racing flat. However, previously published research established that East Africans have a running economy advantage when compared with their Spanish counterparts [12]. Therefore,

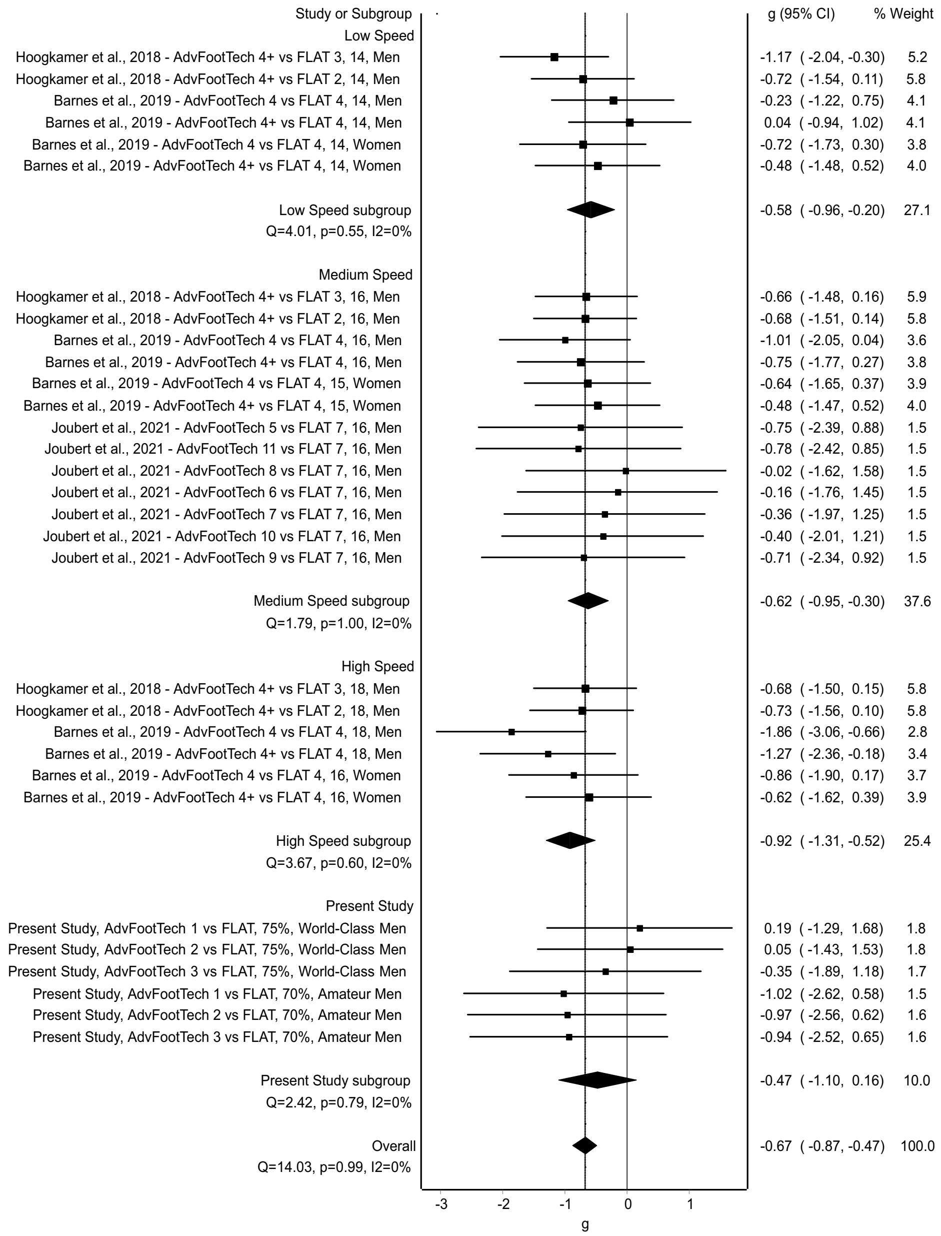


Fig. 6 Forest plot displaying oxygen cost of transport (mL/kg/km) comparisons between advanced footwear technology (AdvFootTech) and traditional racing flats (FLAT) sub-categorized into different speeds. Study labels consist of the study name, the examined AdvFootTech versus FLAT condition where + indicates conditions that are weight matched, the speed either in km/h or as a % of peak, and the examined population. *CI* confidence interval

one consideration could be that our world-class cohort was already more economical when running in the traditional racing flat and therefore would not benefit as much when compared to the amateur European population.

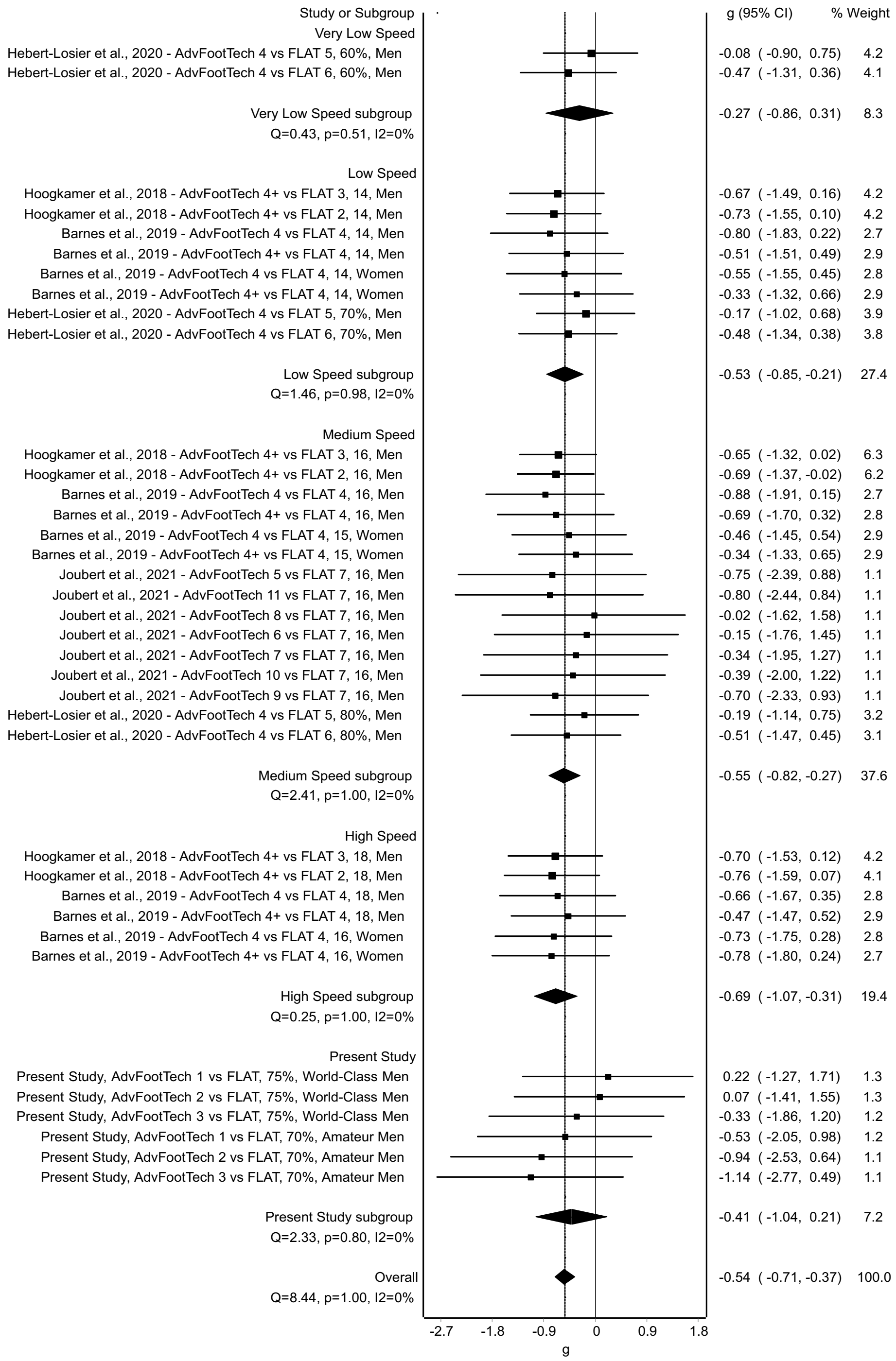
Additionally, regarding the methodology, certain differences between the two populations are also apparent. First, while the relative effort between populations might be comparable, the speed at which they attained such effort differed with the average submaximal velocity for the world-class runners being 17.1 ± 0.4 km/h compared with 13.1 ± 1.0 km/h of the amateurs. These differences could be affecting the percentage benefits of advanced footwear technology in regard to running economy [53]. Moreover, even with a brief warm-up and familiarization session, some world-class runners were not used to running on a treadmill, which as Colino et al. has suggested, changes the mechanics compared with overground running [54, 55]. Furthermore, of note, at the point of testing, the world-class population had already been training in a version of the advanced footwear technology and were therefore familiar with the high-stack height and the feel of running with this technology. In contrast, the amateurs were not regularly running in such shoes outside of the present study. Previous research conducted has suggested injury risks and possible biomechanical changes when transitioning to novel footwear (e.g., minimalist shoes) too quickly, recommending a longer adaptation period [56–58]. Both considerations could have biased the results of the present study.

4.4 Limitations

Several limitations to this study must also be acknowledged. First, we acknowledge the present study is underpowered. As no previous study had been conducted examining a world-class cohort, we had to do power and sample size calculations post-hoc. To start with the amateur cohort, using the smallest found effect size of 0.47 for running economy, sample size calculations revealed that 14 participants should be considered for such an analysis, consistent with the 14 total participants we had recruited at the start of the experiment. Using this same effect size for the amateur cohort, calculations revealed a power of 46.2%. When considering each cohort separately, as with most other studies examining sub-elite populations, we were able to see differences in advanced footwear technology for the amateurs. For the world-class cohort, the effect sizes for running economy of advanced footwear technology shoes compared to the flat varied from 0.04 to − 0.30. Considering this range in effect size, the power calculation here revealed a 5.2% up to a 20.4%. As this signifies our study as being underpowered, we also calculated the necessary sample size that would be needed for the world-class cohort to achieve the desired power of 80%. Based on which effect size, results here revealed 32–1705 participants would be needed, which is a challenge to maintain the high level required in such a large group of participants. This is a common issue that studies using world-class athletes are often underpowered given the singularity and inaccessibility to this sample, resulting rather in case studies or studies with a limited sample size [59]. With the world-class athletes, we must also consider the margin of the examined population, where even a minimal improvement in efficiency can reduce the finishing time over the duration of a marathon and could be the difference between a podium place or not. Furthermore, the results reflect that we must consider the large inter-subject variability and therefore the individuality of the athletes. The question remains of how to detect the marginal changes in an elite population. To further examine this, future studies should also consider examining the test–retest reliability of steady-state running economy laboratory assessments conducted on world-class athletes.

Additional limitations must also be considered owing to the athletes' schedules and availability. More time would have also allowed us to repeat testing measures with the athletes, which would have ensured further reliability of the testing. An additional limitation was that no female athletes were tested within the scope of this study as we only had access to male athletes. Previous results considering both sexes range from only trivial to small differences in laboratory testing to significant differences in performance finishing times for female athletes [15, 48, 49]. Furthermore, it is important to note that because the intention was to test with shoes readily available on the market, it was impossible to blind the participants as to the shoe they were testing. As mentioned, because some athletes were already familiar with and training in versions of these shoes, athletes may have had pre-established opinions that could have influenced the results and the placebo effect cannot be excluded [29]. It must be noted, however, that related research comparing the running economy of different shoes where subjects were blinded to the shoes that were painted in black still revealed similar results [27].

Limitations related to the systematic review and meta-analysis include methodological and characterization variations. For example, some studies manipulated the shoe conditions in terms of weight matching or spray painting for blinding. Additionally, the ambiguity in subject definition related to the caliber of runners makes it difficult to place the results according to populations. Finally, with respect to the described shoe conditions, the specific model or version of a shoe within a franchise was not always clearly labeled, thus we had to make an informed categorization based on the information available.


Study or Subgroup
g (95% CI)
% Weight
Very Low Speed
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 60%, Men -0.08 (-0.90, 0.75) 4.2
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 60%, Men -0.47 (-1.31, 0.36) 4.1
Very Low Speed subgroup -0.27 (-0.86, 0.31) 8.3
Q=0.43, p=0.51, I2=0%
Low Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 14, Men -0.67 (-1.49, 0.16) 4.2
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 14, Men -0.73 (-1.55, 0.10) 4.2
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 14, Men -0.80 (-1.83, 0.22) 2.7
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 14, Men -0.51 (-1.51, 0.49) 2.9
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 14, Women -0.55 (-1.55, 0.45) 2.8
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 14, Women -0.33 (-1.32, 0.66) 2.9
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 70%, Men -0.17 (-1.02, 0.68) 3.9
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 70%, Men -0.48 (-1.34, 0.38) 3.8
Low Speed subgroup -0.53 (-0.85, -0.21) 27.4
Q=1.46, p=0.98, I2=0%
Medium Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 16, Men -0.65 (-1.32, 0.02) 6.3
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 16, Men -0.69 (-1.37, -0.02) 6.2
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 16, Men -0.88 (-1.91, 0.15) 2.7
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 16, Men -0.69 (-1.70, 0.32) 2.8
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 15, Women -0.46 (-1.45, 0.54) 2.9
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 15, Women -0.34 (-1.33, 0.65) 2.9
Joubert et al., 2021 - AdvFootTech 5 vs FLAT 7, 16, Men -0.75 (-2.39, 0.88) 1.1
Joubert et al., 2021 - AdvFootTech 11 vs FLAT 7, 16, Men -0.80 (-2.44, 0.84) 1.1
Joubert et al., 2021 - AdvFootTech 8 vs FLAT 7, 16, Men -0.02 (-1.62, 1.58) 1.1
Joubert et al., 2021 - AdvFootTech 6 vs FLAT 7, 16, Men -0.15 (-1.76, 1.45) 1.1
Joubert et al., 2021 - AdvFootTech 7 vs FLAT 7, 16, Men -0.34 (-1.95, 1.27) 1.1
Joubert et al., 2021 - AdvFootTech 10 vs FLAT 7, 16, Men -0.39 (-2.00, 1.22) 1.1
Joubert et al., 2021 - AdvFootTech 9 vs FLAT 7, 16, Men -0.70 (-2.33, 0.93) 1.1
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 5, 80%, Men -0.19 (-1.14, 0.75) 3.2
Hebert-Losier et al., 2020 - AdvFootTech 4 vs FLAT 6, 80%, Men -0.51 (-1.47, 0.45) 3.1
Medium Speed subgroup -0.55 (-0.82, -0.27) 37.6
Q=2.41, p=1.00, I2=0%
High Speed
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 3, 18, Men -0.70 (-1.53, 0.12) 4.2
Hoogkamer et al., 2018 - AdvFootTech 4+ vs FLAT 2, 18, Men -0.76 (-1.59, 0.07) 4.1
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 18, Men -0.66 (-1.67, 0.35) 2.8
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 18, Men -0.47 (-1.47, 0.52) 2.9
Barnes et al., 2019 - AdvFootTech 4 vs FLAT 4, 16, Women -0.73 (-1.75, 0.28) 2.8
Barnes et al., 2019 - AdvFootTech 4+ vs FLAT 4, 16, Women -0.78 (-1.80, 0.24) 2.7
High Speed subgroup -0.69 (-1.07, -0.31) 19.4
Q=0.25, p=1.00, I2=0%
Present Study
Present Study, AdvFootTech 1 vs FLAT, 75%, World-Class Men 0.22 (-1.27, 1.71) 1.3
Present Study, AdvFootTech 2 vs FLAT, 75%, World-Class Men 0.07 (-1.41, 1.55) 1.3
Present Study, AdvFootTech 3 vs FLAT, 75%, World-Class Men -0.33 (-1.86, 1.20) 1.2
Present Study, AdvFootTech 1 vs FLAT, 70%, Amateur Men -0.53 (-2.05, 0.98) 1.2
Present Study, AdvFootTech 2 vs FLAT, 70%, Amateur Men -0.94 (-2.53, 0.64) 1.1
Present Study, AdvFootTech 3 vs FLAT, 70%, Amateur Men -1.14 (-2.77, 0.49) 1.1
Present Study subgroup -0.41 (-1.04, 0.21) 7.2
Q=2.33, p=0.80, I2=0%
Overall -0.54 (-0.71, -0.37) 100.0
Q=8.44, p=1.00, I2=0%
-2.7 -1.8 -0.9 0 0.9 1.8
g

◂Fig. 7 Forest plot displaying energetic cost (W/kg) comparisons between advanced footwear technology (AdvFootTech) and traditional racing flats (FLAT) sub-categorized into different speeds. Study labels consist of the study name, the examined AdvFootTech versus FLAT condition where + indicates conditions that are weight matched, the speed either in km/h or as a % of peak, and the examined population. *CI* confidence interval

5 Conclusions

Next-generation long-distance running shoes that contain advanced footwear technology result in large inter- and intra-subject variability when measured for changes in running economy in both world-class Kenyan and amateur European runners with overall values that range from an 11.3% hindrance to an 11.4% benefit. Similar variability was also found in the literature as measured both in the laboratory and with real race performance. Additionally, meta-analysis results reveal an overall significant medium benefit of advanced footwear technology on running economy when compared with traditional flats. Such results have important indications. First of all, while testing the performance of shoes with running economy tests has become standard practice, further research should consider other methods that ensure ecological validity, which could include repeated economy tests or field-based tests. Furthermore, performance testing should be standardized to get a better comparison between studies. This is particularly important for the world-class athletes where additional constraints could be affecting their results as well as the acknowledgment that they may already have a better running economy. Second, this study acknowledges that a more personalized approach is necessary and that, when confirmed with additional testing, the inter- as well as intra-subject variability should be considered by stakeholders involved in elite sport. First, among others, it could affect athletes and coaches regarding their shoe selection; sport associations should acknowledge the importance of individualization in sport; shoe manufacturers should consider this when implementing new technology; and governing bodies should consider what impact this might have on the sport, with regard to which magnitude of effect is acceptable and fair.

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Declarations

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Conflict of interest MK and DR are both employees of adidas AG. YP is the founding member of the Sub2 marathon project (http://www.sub2hrs.com). BM-P, FG, HW, and MS have no conflicts of interest that are directly relevant to the content of this article.

Ethics approval This experiment was submitted to the Technical University of Munich Ethics Committee, who advised that formal approval was not required. This study was conducted in accordance with the ethical standards of the Declaration of Helsinki.

Consent to participate All participants gave written informed consent to being a part of this study after they were informed of and understood the experimental procedures, potential injury risks, and possible benefits.

Consent for publication Not applicable.

Data availability Considering the inherent characteristics of this research, the participants of this study did not agree to publicly share the obtained individual data.

Code availability Not applicable.

Author contributions MK and DR conceived and designed the research. MK and DR performed and supported the experiments with the help of additional colleagues. MK, DR, BM-P, HW, MS, FG, and YP analyzed the data. MK and FG conducted the statistical analysis. MK, DR, BM-P, HW, MS, and YP interpreted the results of the experiment. MK drafted the manuscript. DR, BM-P, HW, MS, FG, and YP edited and revised the manuscript.

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2.2 Publication II: Quantitative Analysis of 92 12-Week Sub-Elite Marathon Training Plans

Authors:

Melanie Knopp, Daniel Appelhans, Martin Schönfelder, Stephen Seiler, Henning Wackerhage

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2.2.1 Authors' Contributions

An international collaboration involving adidas AG (Athlete Science, adidas Innovation), the Technical University of Munich (Chair of Exercise Biology, Department of Sport and Health Sciences), and the University of Agder (Faculty of Health and Sport Sciences) conducted this study. Melanie Knopp is the first author of the manuscript. The planning of the review was carried out by Melanie Knopp, Daniel Appelhans, Martin Schönfelder, and Henning Wackerhage. Stephen Seiler developed the method framework for this analysis. Melanie Knopp collected and transcribed the relevant sources. Melanie Knopp and Daniel Appelhans classified the training plans. Data analysis was performed by Melanie Knopp. The interpretation of results involved

Melanie Knopp, Daniel Appelhans, Martin Schönfelder, Stephen Seiler, and Henning Wackerhage. Melanie Knopp drafted the manuscript, and all authors approved the final version.

2.2.2 Abstract

Background

A typical training plan is a mix of many training sessions with different intensities and durations to achieve a specific goal, like running a marathon in a certain time. Scientific publications provide little specific information to aid in writing a comprehensive training plan. This review aims to systematically and quantitatively analyse the last 12 weeks before a marathon as recommended in 92 sub-elite training plans.

Methods

We retrieved 92 marathon training plans and linked their running training sessions to five intensity zones. Subsequently, each training plan was grouped based on the total running volume in peak week into high (> 90 km/week), middle (65-90 km/week), and low (< 65 km/week) training volume plan categories.

Results

In the final 12 weeks before a race, recommended weekly running volume averaged 108 km, 59 km, and 43 km for high, middle, and low distance marathon training plans. The intensity distribution of these plans followed a pyramidal training structure with 15-67-10-5-3%, 14-63-18-2-3%, and 12-67-17-2-2% in zones 1, 2, 3, 4, and 5, for high, middle, and low volume training plans, respectively.

Conclusions

By quantitatively analysing 92 recommended marathon training plans, we can specify typical recommendations for the last 12 weeks before a marathon race. Whilst this approach has obvious limitations such as no evidence for the effectiveness of the training plans investigated, it is arguably a useful strategy to narrow the gap between science and practice.

2.2.3 Original Publication

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Sports Medicine - Open

ORIGINAL RESEARCH ARTICLE

Open Access

Quantitative Analysis of 92 12-Week Sub-elite Marathon Training Plans

Melanie Knopp[1,2*], Daniel Appelhans[1], Martin Schönfelder[1], Stephen Seiler[3] and Henning Wackerhage[1]

Abstract

Background A typical training plan is a mix of many training sessions with different intensities and durations to achieve a specific goal, like running a marathon in a certain time. Scientific publications provide little specific information to aid in writing a comprehensive training plan. This review aims to systematically and quantitatively analyse the last 12 weeks before a marathon as recommended in 92 sub-elite training plans.

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Conclusions By quantitatively analysing 92 recommended marathon training plans, we can specify typical recommendations for the last 12 weeks before a marathon race. Whilst this approach has obvious limitations such as no evidence for the effectiveness of the training plans investigated, it is arguably a useful strategy to narrow the gap between science and practice.

Key points

- This review links science and best practice recommendations by quantitatively analysing 92 publicly available marathon training plans for sub-elite marathon runners.
- Weekly planned running distance in the last 12 weeks before the marathon ranged from 107.7 km for high volume, 58.5 km for middle volume, to 42.9 km for low volume training plans, with the longest run in these plans ranging from 35.2 km for high to 30.9 km for low volume plans.
- Following a five-zone intensity model, training intensity distribution for all volume categories followed a low, middle, and high intensity pyramidal structure with 13.2% in zone 1, 65.6% in zone 2, 15.1% in zone 3, 3.0% in zone 4, and 3.0% in zone 5. Most of the training volume was recommended to be run in zone 2.

Keywords Marathon, Running, Endurance, Recreational athletes, Training guidelines

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Background

Recreational marathon training is popular, attracting individuals of various fitness levels and backgrounds who aspire to complete the iconic 42.2 km race [1–3]. When it comes to training for a marathon, a major challenge is that the training plan is not just one intervention but a complex mix of many interventions such as runs of different intensities and distances as well as nutritional interventions such as carbo-loading, or recovery techniques [4]. This mix of training forms is then applied over months, and it changes with time due to periodisation and tapering [4]. In contrast to a single medical intervention such as a drug treatment, it is practically impossible to investigate in a well-controlled, randomised trial, whether, for example, a specific 3-month marathon training intervention is more effective than a control marathon training intervention. An analysis of the scientific knowledge available for training advice to long-distance runners and coaches reveals limitations. These include a lack of research specifically with trained distance runners and methodological challenges that make it hard to interpret the findings. As a result, the analysis cautions giving training recommendations based on the limited available scientific knowledge [5]. Due to this problem, current marathon training plans are mostly experience-based, occasionally supplemented by evidence-based recommendations such as those related to carbohydrate ingestion.

To address this "evidence problem" of training practice, several researchers have developed new concepts of generating evidence or of utilising evidence for writing training plans. For example, Wackerhage and Schoenfeld have proposed evidence-informed training plans, where some of the decisions are based e.g., on meta-analyses and systematic reviews whereas others are based on subjective best practice [4]. Another notion for elite training plans is the concept of results-proven practice presented by Haugen and colleagues. This approach involves gathering and analysing training plan data from elite athletes who have attained top-tier outcomes [6]. Whilst the lack of comparison and control in these plans means that we cannot determine whether an athlete has won a championship or Olympic medal because of or despite the training plan used, we can infer that the training plan allowed an elite athlete to attain exceptional results. To date, Haugen et al. [6–8] have published results-proven practice reviews on sprinting, middle-distance, and long-distance running that give a practically useful insight into the training strategies of elite athletes. The resultant information obtained from synthesizing training plans from elite athletes can be readily applied in writing training plans for similar athletes. The concept of results-based practice is also applicable for sub-elite athletes, by quantitatively analysing the training plans of marathon runners who have achieved certain target times, such as a sub-4-h marathon. However, such an analysis has not yet been conducted.

This review aims to systematically and quantitatively analyse the last 12 weeks before a marathon as recommended in 92 sub-elite training plans. Whilst there are obvious limitations such as the subjective nature of such an analysis and no data on training plan effectiveness, we argue that the resultant information is useful for writing sub-elite marathon training plans and for testing hypotheses related to best practice training for millions of recreational runners.

Methods

Search Strategy

We obtained the training plans for this analysis from non-peer-reviewed sources, using the search term "marathon training". Each plan that was considered had to incorporate a detailed week-by-week training schedule with the goal to complete a marathon race at the end of the program. Two researchers conducted this search, gathering the top 10 Google search results that were consistently found in both searches and that contained marathon training plans, which included sponsored plans by the world marathon majors, the sporting goods industry, and top running magazines. The same method was applied to the combined top 10 book results, again focusing on those that contained marathon training plans, from both the Amazon United States of America and United Kingdom stores at the time of searching (August 2022) [9, 10]. This process yielded 10 main online sources and 10 main print sources, some of which were accessible online. Among these 20 main sources of marathon training plans, certain sources contained between 1 and 17 distinct training plans targeting various time goals (e.g., ranging from sub-3:00 to sub-5:00 h finishing plans), diverse starting levels (e.g., novice, beginner, intermediate, or advanced), varied focuses (e.g., speed, or endurance), and different time or distance commitments per week. We included all these variations in our analysis, which resulted in 92 sub-elite marathon training plans, presented in Table 1, that we obtained and reviewed for further analysis. We selected this approach to ensure the relevance of our analysis by simulating the search behaviour of the vast number of recreational runners seeking marathon training plans. Two researchers from our team independently conducted this search, and their results were consistent, however, it is essential to acknowledge that search results can be influenced by factors beyond our control, such as geographical location, individual search histories, and search engine algorithm updates. To address this inherent uncertainty, we employed a strategy

Table 1 Overview of included marathon training plans

Plan title [references]	Training plan unit	Volume classification	Distance unit of plan	Plan duration (Weeks)
adidas [39]	Both	Low	km	21
ASICS [40]	Time	Low	mi	16
Boston Marathon—Level 1 [41]	Distance	Low	mi	20
Boston Marathon—Level 2 [42]	Distance	Middle	mi	20
Boston Marathon—Level 3 [43]	Distance	Middle	mi	20
Boston Marathon—Level 4 [44]	Distance	Middle	mi	20
Daniels—Novice [45]	Both	Low	mi	18
Daniels—2Q—Up to 40 mi (64 km) per Week [46]	Both	Low	mi	18
Daniels—2Q—41–55 mi (66–89 km) per Week [47]	Both	Middle	mi	18
Daniels—2Q—56–70 mi (90–113 km) per Week [48]	Both	High	mi	18
Daniels—2Q—71–85 mi (114–137 km) per Week [49]	Both	High	mi	18
Daniels—2Q—86–100 mi (138–161 km) per Week [50]	Both	High	mi	18
Daniels—2Q—101–120 mi (163–193 km) per Week [51]	Both	High	mi	18
Daniels—2Q—120 mi + (193 + km) per Week [52]	Both	High	mi	18
Daniels—4-Week—40 mi (64 km) per Week [53]	Both	Low	mi	26
Daniels—4-Week Cycle—41–55 mi (66–89 km) per Week [54]	Both	Middle	mi	26
Daniels—4-Week Cycle—56–70 mi (90–113 km) per Week [55]	Both	High	mi	26
Daniels—4-Week Cycle—71–85 mi (114–137 km) per Week [56]	Both	High	mi	26
Daniels—4-Week Cycle—86–100 mi (138–161 km) per Week [57]	Both	High	mi	26
Daniels—4-Week Cycle—101–120 mi (163–193 km) per Week [58]	Both	High	mi	26
Daniels—4-Week Cycle—120 + mi (193 km) per Week [59]	Both	High	mi	26
Daniels—18-Week [60]	Both	High	km	18
Daniels—12-Week [61]	Both	High	mi	12
Furman Institute of Running [62]	Both	Low	mi	18
Fitzgerald 20-Week [63]	Both	Low	mi	20
Fitzgerald 80/20—Level 1 [64]	Both	Low	mi	18
Fitzgerald 80/20—Level 2 [65]	Both	Middle	mi	18
Fitzgerald 80/20—Level 3 [38]	Both	High	mi	18
Galloway for Runners and Walkers [66]	Both	Low	mi	30
Hansons—Beginner [67]	Distance	High	km	18
Hansons—Advanced [68]	Distance	High	km	18
Higdon—Advanced 1 [69]	Distance	High	km	18
Higdon—Advanced 2 [70]	Distance	Middle	km	18
Higdon—Boston Bound [71]	Distance	Middle	km	13
Higdon—Intermediate 1 [72]	Distance	Middle	km	18
Higdon—Intermediate 2 [73]	Distance	Middle	km	18
Higdon—Marathon 3 [74]	Distance	Low	km	24
Higdon—Novice 1 [75]	Distance	Low	km	18
Higdon—Novice 2 [76]	Distance	Low	km	18
Higdon—Novice Supreme [77]	Distance	Low	km	30
Higdon—Personal Best [78]	Distance	Middle	km	30
Kastor—Abbott World Marathon Majors [79]	Both	Middle	mi	16
Kastor—20 Week [80]	Distance	Middle	mi	20
Marathon Handbook—3 Hour [81]	Distance	Middle	km	20
Marathon Handbook—3 Month [82]	Distance	Low	km	12
Marathon Handbook—4 Hour [83]	Distance	Middle	km	20
Marathon Handbook—6 Month [84]	Distance	Low	km	24
Marathon Handbook—16 Week [85]	Distance	Middle	km	16

Table 1 (continued)

Plan title [references]	Training plan unit	Volume classification	Distance unit of plan	Plan duration (Weeks)
Marathon Handbook—20 Week Advanced [86]	Distance	Low	km	20
Marathon Handbook—20 Week Advanced 2 [87]	Distance	Middle	km	20
Marathon Handbook—20 Week [88]	Distance	Low	km	20
Marathon Handbook—Couch to Marathon [89]	Distance	Low	km	24
McMillan—3 Month [90]	Both	Low	mi	12
McMillan—Novice [91]	Time	Low	km	12
McMillan—Novice/Intermediate [34]	Both	Low	mi	12
McMillan—Intermediate—Combo Runner [92]	Both	Middle	mi	12
McMillan—Intermediate—Speedster [93]	Both	Middle	mi	12
McMillan—Intermediate—Endurance Monster [94]	Both	Middle	mi	12
McMillan—Intermediate/Advanced—Combo Runner [95]	Both	High	mi	12
McMillan—Intermediate/Advanced—Speedster [35]	Both	High	mi	12
McMillan—Intermediate/Advanced—Endurance Monster [96]	Both	High	mi	12
McMillan—Advanced—Combo Runner [97]	Both	High	mi	12
McMillan—Advanced—Speedster [98]	Both	High	mi	12
McMillan—Advanced—Endurance Monster [99]	Both	High	mi	12
Bank of America Chicago Marathon [100]	Both	Low	mi	18
Nike Run Club [101]	Both	Low	mi	18
Nolan—Beginner [33]	Distance	Low	mi	16
Nolan—Intermediate [102]	Distance	Middle	mi	16
Nolan—Advanced [103]	Distance	Middle	mi	16
Pfitzinger—18 Week—Up to 55 mi (88 km) per Week [104]	Distance	Middle	km	18
Pfitzinger—12 Week—Up to 55 mi (88 km) per Week [105]	Distance	Middle	km	12
Pfitzinger—18 Week—55–70 mi (88–113 km) per Week [106]	Distance	High	km	18
Pfitzinger—12 Week—55—70 mi (88—113 km) per Week [107]	Distance	High	km	12
Pfitzinger—18 Week—70–85 mi (113–137 km) per Week [108]	Distance	High	km	18
Pfitzinger—12 Week—70–85 mi (113–137 km) per Week [109]	Distance	High	km	12
Pfitzinger—18 Week—85 + mi (137 + km) per Week [110]	Distance	High	km	18
Pfitzinger—12 Week—85 + mi (137 + km) per Week [111]	Distance	High	km	12
Runner's World—Advanced—Sub 3:30 [112]	Both	High	mi	16
Runner's World—Intermediate—3:30–4:30 [113]	Distance	Middle	mi	16
Runner's World—Beginner—First Marathon [114]	Both	Low	mi	16
Runner's World—Ultimate—Sub 3:00 [115]	Distance	High	mi	16
Runner's World—Ultimate—Sub 3:15 [116]	Distance	Middle	mi	16
Runner's World—Ultimate—Sub 3:30 [117]	Distance	Middle	mi	16
Runner's World—Ultimate—Sub 3:45 [118]	Distance	Middle	mi	16
Runner's World—Ultimate—Sub 4:00 [119]	Distance	Middle	mi	16
Runner's World—Ultimate—Sub 4:30 [120]	Distance	Low	mi	16
Runner's World—Sub 5:00 [121]	Distance	Low	mi	16
TCS London Marathon—Beginner [122]	Both	Low	mi	16
TCS London Marathon—Improver [33]	Both	Middle	mi	16
TCS London Marathon—Advanced [36]	Both	Middle	mi	17
Women's Health Magazine [123]	Distance	Middle	mi	22
Women's Running [124]	Both	Middle	mi	24

Training plan unit refers to how the training plan is written, either with sessions written based on distance or on time

mi miles, *km* kilometres

of analysing a diverse portfolio of plans from various sources. Nonetheless, we recognize that our search strategy remains a limitation.

Coding of Training Plans

Initially, we transcribed all plans into standardized Excel worksheets with a weekly countdown to the race distributed into days (Monday–Sunday) with each session split into distances. In our transcription, we removed the marathon race itself from the analysis and labelled the last 12 weeks before the race as weeks 11–0. For plans with a Monday race day, such as the Boston Marathon, the week before the race is week zero. Time-based plans were converted to distance using the plan's descriptions and pace calculator. For instance, a 90-min fartlek run session with 11 repetitions of 1-min fast running and 1-min jogging was converted to distance by considering the average goal marathon time of the plan, the fartlek run's description as an easy long run with hard and easy running repetitions and using the corresponding pace calculator to calculate the expected distance. When plans included a range, we used the middle value; for example, we transcribed a 16- to 20-mile-long run as an 18-mile run. Finally, we converted all distance measures into kilometres.

After converting all training plans into this standard format, we classified each part of a training session into one of five exercise intensity training zones for performance based on the model described by both Jamnick et al. and Seiler, with adjustments made to match the training descriptions included in the examined training plans as presented in Table 2 [11, 12]. We opted for the five-intensity training zone model because it blends the physiological reference points of the conventional three-zone model with added practicality, resulting in greater sensitivity and specificity in tailoring training for each athlete [12]. Here, it should be noted that when a training exercise was prescribed to be completed uphill, the intensity zone classification of the training session was increased by one zone. For example, for an uphill workout at a 10 k pace, instead of being in zone 4 representing a level 10 k pace exercise, the classification would be zone 5. Two researchers independently rated and agreed upon the intensity zones for each session, and any discrepancies were resolved by a third researcher (Additional file 1).

Next, we grouped the training plans into low, medium, and high volume categories. Since there were discrepancies in how the different training plans were "self-classified" in terms of beginner, intermediate, and advanced, we reclassified all the training plans based on the weekly running volume in the examined peak week of each plan. Research has suggested that training volume is correlated with marathon race times, so we believed this to be a suitable categorization method given the available data [13–15]. The 'low volume' category included all training plans whose peak week distance was under 65 km, 'middle volume' included those between 65 and 90 km, and 'high volume' those over 90 km. These distances were selected to create groups of similar size. Once categorized, we summarized the collected data quantitatively to determine the recommended training for various marathon levels, considering variables such as distance per week, runs per week, distance per session, longest run, and peak week.

Analysis of Training Plans

We focused on comparing the examined parameters of the coded training plans across the three volume categories (low, middle, and high). To make the plans comparable despite varying durations (ranging from 12 to 30 weeks), we analysed and compared the last 12 weeks leading up to the marathon race. We also conducted additional analyses on the peak week, defined as the highest volume week within the last 12 weeks of each

Table 2 Description of five endurance training intensity zones

Endurance training zone	Heart rate (% of HR_{max})	Rating of perceived exertion (RPE)	Relative to Thresholds	Typical accumulated duration	Example training sessions
Zone 1: Slow Endurance	< 72	1–2 (very light)	< Aerobic	1–6 h	Jogging, Warm-Up, Recovery
Zone 2: Extensive Endurance	73–80	3–4 (light)	Aerobic < Anaerobic	1–3 h	Long Run
Zone 3: Intensive Endurance	81–86	5–6 (moderate)	Aerobic < Anaerobic	50–90 min	Brisk, Half-Marathon, Marathon Pace, Tempo Run
Zone 4: Threshold Training	87–92	7–8 (hard)	~ Anaerobic	30–60 min	10 k Pace, Intervals, Threshold
Zone 5: High Intensity Training	> 93	9–10 (very hard)	> Anaerobic	15–30 min	Speed, Sprints, Mile Pace, 5 k Pace, Fast

Slightly modified from five zone models presented by Jamnick et al. and Seiler to better fit the descriptions accompanying the examined training plans [14, 15]. RPE here uses Borg CR 1–10 scale [125]. Aerobic threshold represents the rise of lactate above baseline, the gas exchange threshold, or the first ventilatory threshold. Anaerobic threshold represents the acceleration of blood lactate accumulation, the respiratory compensation point and/or the maximal lactate steady state

hr hour; *min* minutes, *HR* heart rate, *RPE* rating of perceived exertion plan. For specific variables, we also analysed the progression, which was calculated as the delta from one week to the next and averaged over the relevant duration of the examined training plans. A delta negative value here means the distance, is decreasing from 1 week to the next. Here, we focused on the weeks up to and included the peak week as the build-up phase, while regarding the weeks after peak week as the tapering phase of the plan.

In general, parameters of interest for this analysis were weekly running volume in km, weekly long run distance, longest run included in the whole training plan, number of run sessions per week, distance covered in each session, cross-training, strength-training or rest days, and the intensity distribution in terms of distance covered in each of the five intensity zones per week. Intensity distributions were also converted to weekly percentages and averaged to make them comparable across the different absolute distances covered.

Statistical Analysis

We transcribed the training plans into a Microsoft Excel document and analysed these using RStudio [16, 17]. We conducted statistical analyses using the R packages 'doBy' (version 4.6.16), and 'stats' (version 4.0.0) with a significance level of $p < 0.05$ [16, 18]. We also performed an analysis of variance (ANOVA) test with Tukey post-hoc correction on relevant variables to compare the different classifications of marathon training plans [19].

Results

Training Plan Characteristics

We divided the 92 marathon training plans into 30 high volume (peak weekly volume more than 90 km), 33 medium volume (peak weekly volume 65–90 km), and 29 low volume (peak weekly volume less than 65 km), respectively. The high-volume plans had a median target time of 3:15 h:min for the marathon, with the minimum being 3:00 h:min, the maximum being 3:30 h:min, and only 2 out of 30 training plans indicating a target time. On the other hand, the middle volume plan had a median target time of 3:52 h:min for the marathon, with the minimum being 3:00 h:min, the maximum being 4:30 h:min, and 8 out of 33 plans indicating a target time. Finally, the low volume plan had a median target time of 4:30 h:min for the marathon, with the minimum being 4:00 h:min, the maximum being 5:00 h:min, and only 3 out of 29 plans indicating a target time. There was no significant difference [$F(2,89) = 1.03$, $p = 0.361$] in the duration of the plans in the different groups, the high-volume plans consisted of 17.2 ± 4.8 weeks, the middle volume of 17.8 ± 3.9 weeks, and the low volume plans of 18.9 ± 4.7 weeks.

Analysis of the Last 12 Weeks Before Race

Table 3 displays the average weekly distance, weekly long run, longest run, run sessions, cross training, strength training, rest days, and relative and absolute intensity distribution over the last 12 weeks before race day. The weekly volume (km) for the three different volume groups over the 12 weeks leading up to race week is displayed in Fig. 1, while Fig. 2 illustrates the weekly long run (km) in a comparable way.

Here, high volume plans had higher weekly distances (107.7 ± 38.4 km), longer long runs (27.4 ± 7.1 km), more runs per week (6.8 ± 1.4 runs), and longer distance per session (16.5 ± 4.9 km) than middle and low volume plans. Predictably, low volume plans had shorter long runs (19.9 ± 7.5 km), fewer runs per week (4.1 ± 0.9 runs), shorter distances per session (10.6 ± 3.3 km), and more weekly rest days than high and middle volume plans (2.0 ± 0.9 days).

For the percentage of total weekly distance covered in each intensity zone, there were significant differences in all zones except zone 1. Surprisingly, the training plans varied within each group, indicating far less consensus than we might expect. High (67.5 ± 21.5%) and low (66.7 ± 30.4%) volume plans had significantly higher proportion of their weekly volume in zone 2 compared to the middle volume plans (62.6 ± 26.7%). For zone 3, the middle volume plans had the highest percentage (18.1 ± 16.2%), comparable to the low volume (16.9 ± 22.1%), while the high-volume group had significantly lower (10.2 ± 11.3%). The high-volume plans had significantly more of their weekly distance prescribed in zone 4 (4.6 ± 7.0%), compared to the middle (2.1 ± 5.1%) and low (2.4 ± 6.3%) volume plans. The low volume plans had the lowest percentage of their weekly volume in zone 5 (2.4 ± 4.9%) compared to the high (3.2 ± 3.4%) and middle (3.4 ± 3.6%) volume groups. These differences are presented in Table 3 and Fig. 3A–C.

Additionally, we conducted a detailed analysis of the intensity distribution for each individual training session, rather than solely focusing on the weekly volume. The average intensity distribution for these sessions aligns closely with the combined weekly intensity distribution mentioned earlier. On average, the training sessions exhibit intensity distributions of 17–67–8–4–4%, 17–60–17–2–4%, and 12–66–16–3–3% in zones 1–5 for the high, middle, and low volume groups, respectively.

Table 3 Average training characteristics of last 12 weeks of analysed training plans

Training variable	High volume	Middle volume	Low volume	ANOVA
Weekly Distance (km/week)	107.7 ± 38.4	58.5 ± 17.9	42.9 ± 14.1	F = 622.9
	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Weekly Long Run Session (km)	27.4 ± 7.1	23.0 ± 7.3	19.9 ± 7.5	F = 92.3
	p_{Tukey} = < .001 ‡§	p_{Tukey} = 0.001 §		p = < .001 *
Longest Run	35.2 ± 3.3	32.5 ± 3.8	30.9 ± 4.1	F = 15.2
(km)	p_{Tukey} = .002 ‡§			p = < .001 *
Run Sessions (runs/week)	6.8 ± 1.4	4.9 ± 0.9	4.1 ± 0.9	F = 599.9
	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Distance per Session (km/session)	16.5 ± 4.9	11.8 ± 3.0	10.6 ± 3.3	F = 246.8
	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Cross Training (sessions/week)	0.4 ± 0.7	0.6 ± 0.8	0.6 ± 0.9	F = 7.1
	p_{Tukey} = < .05 ‡§			p = < .001 *
Strength Training (sessions/week)	0.2 ± 0.7	0.3 ± 0.7	0.4 ± 0.7	F = 6.6
	p_{Tukey} = < .001 §			p = .001 *
Rest Day (days/week)	0.1 ± 0.3	1.3 ± 0.7	2.0 ± 0.9	F = 745.6
	p_{Tukey} = < .001 §	p_{Tukey} = < .001 §		p = < .001 *
Zone 1	14.3 ± 20.1	8.6 ± 12.8	4.5 ± 7.4	F = 40.8
(km/week)	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Zone 2	74.8 ± 38.9	35.7 ± 18.4	28.7 ± 16.7	F = 316.8
(km/week)	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Zone 3	10.4 ± 11.9	10.8 ± 9.7	7.4 ± 9.6	F = 11.3
(km/week)	p_{Tukey} = < .001 §	p_{Tukey} = < .001 §		p = < .001 *
Zone 4	5.1 ± 8.1	1.3 ± 3.3	1.2 ± 3.0	F = 63.9
(km/week)	p_{Tukey} = < .001 ‡§			p = < .001 *
Zone 5	3.2 ± 3.2	2.0 ± 2.3	1.0 ± 1.9	F = 66.5
(km/week)	p_{Tukey} = < .001 ‡§	p_{Tukey} = < .001 §		p = < .001 *
Zone 1	14.5 ± 20.5	13.7 ± 19.1	11.5 ± 18.4	F = 2.2
(% of km/week)				p = 0.11
Zone 2	67.5 ± 21.5	62.6 ± 26.7	66.7 ± 30.4	F = 3.7
(% of km/week)		p_{Tukey} = 0.03 §		p = 0.03 *
Zone 3	10.2 ± 11.3	18.1 ± 16.2	16.9 ± 22.1	F = 23.0
(% of km/week)	p_{Tukey} = < .001 ‡§			p = < .001 *
Zone 4	4.6 ± 7.0	2.1 ± 5.1	2.4 ± 6.3	F = 18.3
(% of km/week)	p_{Tukey} = < .001 ‡§			p = < .001 *
Zone 5	3.2 ± 3.4	3.4 ± 3.6	2.4 ± 4.9	F = 6.2
(% of km/week)	p_{Tukey} = 0.02 §	p_{Tukey} = 0.002 §		p = .002 *

Data presented as mean ± standard deviation. Zone classification based on descriptions found in Table 2

*ANOVA Significant difference (p < 0.05)

‡ANOVA Significantly different to middle volume (p < 0.05)

§ANOVA Significantly different to low volume (p < 0.05)

km kilometre, *ANOVA* analysis of variance

Analysis of Peak Week

Results for average weekly distance, weekly long run, longest run, number of run sessions, cross training, strength training, rest days, and the distribution of relative and absolute intensity during the week with the highest weekly volume (peak week) are presented in Table 4.

Focusing on the peak training week of each running volume category, the high-volume training plans reached their peak at week 4.4 on average, while the middle volume group peaked at week 4.0, and the low volume group peaked even closer to race week at week 3.6. The high volume group had the highest weekly distance (132.5 ± 34.5 km), while the middle (75.5 ± 8.5 km) and

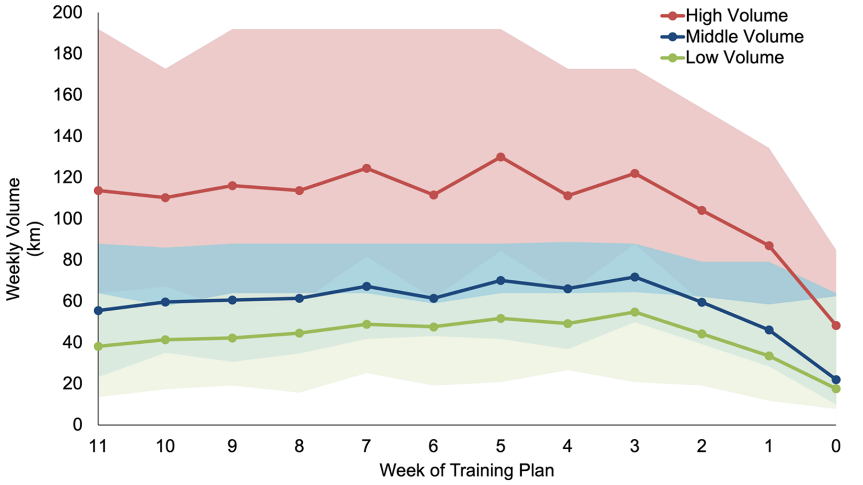

Fig. 1 This line chart displays the weekly volume (in km) of the 12 weeks leading up to the race week, where week 0 refers to the week of the race and excludes the marathon race itself. The chart includes three ribbons indicating the different volume groups analysed: high, middle, and low. The lines in the chart represent the average value of the plans in each group, with the top and bottom of the bands indicating the maximum and minimum values within each group, respectively

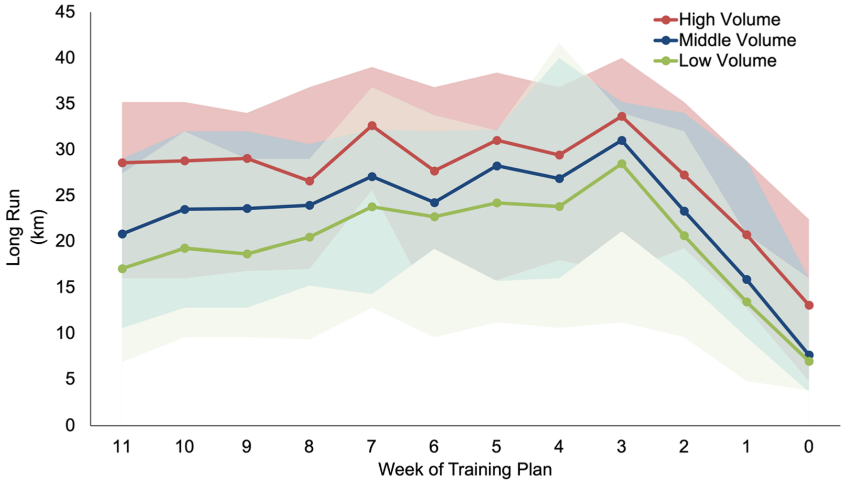

Fig. 2 This line chart displays the weekly long run (in km) of the 12 weeks leading up to the race week, where week 0 refers to the week of the race and excludes the marathon race itself. The chart includes three ribbons indicating the different volume groups analysed: high, middle, and low. The lines in the chart represent the average value of the plans in each group, with the top and bottom of the bands indicating the maximum and minimum values within each group, respectively

low volume (58.6 ± 6.4 km) groups had lower weekly distances. Interestingly, the length of the long run session in peak week was similar for all three groups, at ~ 30–32 km showing that a long run of ~ 30 km in peak week is a common recommendation for all Marathon runners.

We also examined the breakdown of intensity zones for the peak week volume in each group and found

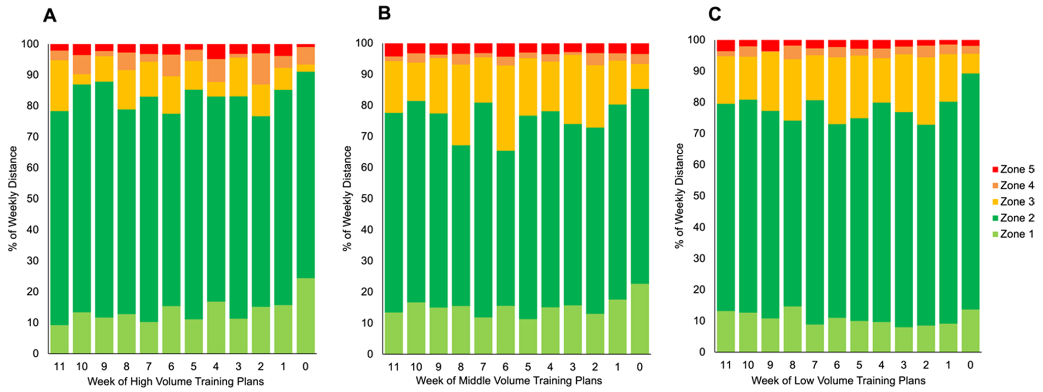

Fig. 3 This bar chart displays the percentage of weekly volume distribution across the five intensity zones during the 12 weeks prior to the race week, where week 0 represents the week of the race with the race itself excluded. The chart is divided into three panels: **A** represents the high volume group, **B** represents the middle volume group, and **C** represents the low volume group. Refer to Table 2 for intensity zone descriptions

there were no statistically significant differences among the three groups.

Progression of Training Plan

To assess the progression changes of different marathon training plans, we analysed the weekly volume difference throughout the entire program. Our findings revealed that during the build-up phase leading up to the peak week, the high-volume plans prescribed an average weekly increase of 3 ± 1 km corresponding to an average of a 5 ± 3% increase from the week before in this phase, followed by a steep decrease of 21 ± 9 km per week or a 22 ± 12% reduction of weekly volume between peak week and race week during the tapering phase. In contrast, the middle volume plans increased by 3 ± 1 km or 7 ± 3% per week during build-up and decreased by 15 ± 6 km or 28 ± 12% per week during the tapering phase. Finally, for the low volume plans, during the build-up phase, the weekly increase was 2 ± 1 km or 9 ± 4%, while the volume decreased by 13 ± 6 km or 31 ± 13% during tapering. Surprisingly, this means that the high-volume plans had a gradual relative weekly change, while the low-volume plans showed more aggressive relative changes from 1 week to the next. Focusing specifically on the taper period following the peak week, all groups showed a particular stark decrease in the last week before the race with an average reduction of 46 ± 17% compared to the previous week for the high-volume plans, 54 ± 16% for the middle volume plans, and 50 ± 24% for low volume plans (Fig. 1).

Discussion

In general, to achieve a target performance and to reduce the risk of detrimental effects of training, effective endurance running plans typically increase the frequency, duration, and intensity of training followed by a taper to maximize performance whilst reducing the possibility of adverse training effects [12]. There are many training plans recommendations that are used by probably millions of marathon runners, but we know little about how a typical marathon training plan recommendation for sub-elite athletes looks like and whether typical recommendations are consistent with current evidence from training intervention trials. The objective of this research was therefore to conduct a quantitative analysis of sub-elite marathon training plans, with a specific focus on the last 12 weeks before the marathon race, to provide a comprehensive overview of current sub-elite marathon training plan recommendations. While such an analysis has not been conducted before, other studies have sought to review the available literature for evidence-based research, study the training behaviour of recreational runners, or analyse elite training results-proven plans to make recommendations for marathon training [5, 6, 12, 20–24].

How do the Recommended Recreational Training Plans Compare to Evidence-Based Research?

In 2007 Midgley et al. [5] concluded that there was little direct scientific evidence to identify the most effective training methods for enhancing long-distance running performance, with even less evidence specifically for the marathon distance. Since then, more work has been

Table 4 Average training characteristics of peak week of analysed training

Training variable	High volume	Middle volume	Low volume	ANOVA
Peak week (week)	4.4 ± 1.4	4.0 ± 1.5	3.6 ± 1.4	F = 2.6 $p = 0.08$
Weekly distance (km/week)	132.5 ± 34.5 p_{Tukey} = < .001 ‡§	75.5 ± 8.5 p_{Tukey} = .005 §	58.6 ± 6.4	F = 104.7 p = < .001*
Weekly Long Run Session (km)	32.2 ± 6.2	31.2 ± 3.1	29.7 ± 4.9	F = 1.9 $p = 0.16$
Cross Training (sessions/week)	0.4 ± 0.7	0.6 ± 0.7	0.6 ± 0.9	F = 0.8 $p = 0.46$
Strength Training (sessions/week)	0.2 ± 0.6	0.3 ± 0.6	0.4 ± 0.7	F = 1.0 $p = 0.37$
Rest Day (days/week)	0.0 ± 0.2 p_{Tukey} = < .001 ‡§	1.2 ± 0.7 p_{Tukey} = < .001 §	1.9 ± 0.8	F = 68.6 p = < .001*
Run Sessions (runs/week)	7.1 ± 1.5 p_{Tukey} = < .001 ‡§	5.1 ± 0.8 p_{Tukey} = .005 §	4.2 ± 0.8	F = 55.8 p = < .001*
Distance per Session (km/session)	20.2 ± 4.1 p_{Tukey} = < .001 ‡§	15.0 ± 1.6	14.3 ± 2.5	F = 35.9 p = < .001*
Zone 1 (km/week)	13.9 ± 20.9	8.7 ± 12.1	5.3 ± 8.9	F = 2.5 $p = 0.09$
Zone 2 (km/week)	100.0 ± 40.3 p_{Tukey} = < .001 ‡§	51.2 ± 16.0	42.7 ± 19.1	F = 39.0 p = < .001*
Zone 3 (km/week)	11.9 ± 7.9	12.2 ± 7.2	8.1 ± 10.6	F = 2.1 $p = 0.13$
Zone 4 (km/week)	4.9 ± 9.0 p_{Tukey} = 0.04 ‡§	1.0 ± 2.6	1.3 ± 3.0	F = 4.4 $p = 0.01$ *
Zone 5 (km/week)	2.0 ± 2.6	2.5 ± 2.9	1.2 ± 2.0	F = 2.2 $p = 0.11$
Zone 1 (% of km/week)	10.9 ± 16.3	11.0 ± 15.3	9.4 ± 15.4	F = 0.1 $p = 0.9$
Zone 2 (% of km/week)	74.2 ± 18.6	67.9 ± 20.5	71.7 ± 30.4	F = 0.6 $p = 0.57$
Zone 3 (% of km/week)	9.9 ± 6.8	16.5 ± 10.4	14.7 ± 21.0	F = 1.9 $p = 0.15$
Zone 4 (% of km/week)	3.2 ± 5.6	1.3 ± 3.2	2.3 ± 5.2	F = 1.3 $p = 0.26$
Zone 5 (% of km/week)	1.7 ± 2.7	3.2 ± 3.6	2.0 ± 3.5	F = 1.8 $p = 0.17$

Data presented as mean ± standard deviation. Zone classification based on descriptions found in Table 2

*ANOVA Significant difference ($p < 0.05$)

‡ANOVA Significantly different to Middle Volume ($p < 0.05$)

§ANOVA Significantly different to Low Volume ($p < 0.05$)

km kilometre, *ANOVA* analysis of variance

published to provide training guidelines for recreational runners and their coaches based on scientific evidence.

Running Training Methods

To improve performance in recreational runners, existing evidence recommends incorporating one to two high-intensity interval training sessions per week along with several sessions of moderate- and low-intensity continuous submaximal running into the training regimen [5, 20]. In the analysed plans, in the last 12 weeks before the marathon race, the high volume plans had an average of 7.8% of weekly volume in zone 4 and 5, while the middle volume plans had 5.5%, and the low volume plans had 4.8% at these intensities (Table 3). Despite the lack of clear understanding regarding the ideal volume and intensity of strength training for improving endurance running performance or preventing injury, it is advised to be included in a training regimen as well.

Another component of a training plan for which there is some empirical evidence is the taper before a race, or the intentional reduction in training volume before competition to improve running performance [25]. The varying tapering techniques used in research studies make it difficult to choose the best recommendation. According to a meta-analysis that investigated the impact of tapering on competitive athletes' performance, the most effective approach to maximize general performance gains is to implement a 2-week taper that involves an exponential reduction of training volume by 41–60%, without any changes to the intensity or frequency of training [26]. Intervention research focusing specifically on a 7-day taper found that the run taper group that reduced their training volume by 85% were 3% faster over a 5-km performance than the control group corresponding to an improved measured running economy [25]. With a focus specifically on the marathon distance, one study analysing the training activities of more than 158,000 recreational marathon runners determined that strict 3-week tapers are associated with better marathon performance compared to relaxed and shorter tapers [27]. In the analysed recreational training plans, peak week was found to be between 3 and 4 weeks out from race week, in line with a longer taper before the marathon race. Looking at the reduction in weekly volume following peak week until the marathon race, the tapers in the analysed plans are more gradual with a 22–31% weekly decrease. Focusing specifically on the last week before the race, the training volume decreases further by an average of 50% compared to the previous week in all plans. Among the three examined groups, the low volume training plans exhibit a shorter taper period, characterized by a peak week that occurs in closer proximity to the race week compared to the other groups.

Training Intensity Distribution

When designing a training plan, one crucial element is the distribution of training intensity across various intensity zones. Here a variety of different models are common including polarized, a pyramidal, and threshold models. Using a 3-zone intensity zone structure, a polarized training plan involves spending a significant percentage of time in zone 1 (75–80%) and in zone 3 (15–20%), with little or no time in zone 2, while a pyramid training plan has 70–80% of the volume in zone 1, with the remaining 20–30% in zone 2 and 3. Finally, when training follows the threshold model, the main focus, and therefore a higher proportion of overall volume, is on zone 2 training [20, 28]. Of these, polarized and pyramid training intensity distributions, that share a similar distribution of around 80% in low-intensity training but differ in how the remaining 20% is distributed, are the most recommended models. However, the evidence is inconclusive as to how best to optimize training [20, 28–30]. Based on these definitions and making it comparable, the last 12 weeks before the marathon of the analysed plans presented in Table 3 consist of a pyramid plan with high, middle, and low volume groups having 82–10–8%, 76–18–6%, and 78–17–5% in zone 1 and 2, zone 3, and zone 4 and 5, respectively. Previous intervention research has indicated that polarized training, with a distribution of 68–6–26% at low-lactate threshold-high intensity respectively, leads to the most significant improvements in various key endurance performance variables for well-trained endurance athletes compared to threshold, high intensity, or high volume training over a 9-week training program [30]. Conversely, a systematic review, which includes both intervention and observational studies, has found that highly trained distance runners tend to follow a pyramidal training intensity distribution approach, which is also related to high levels of performance and significant development of physiological determinants [28]. Another systematic review has analysed pyramidal training, polarized training, and threshold training and concluded that current evidence suggests pyramidal and polarized training to be more effective than threshold training, however among these no single optimal training intensity distribution has been established [29]. Although the inconclusive scientific evidence makes it challenging to recommend only one of these two models, recent research has explored the possibility of periodizing intensity distributions based on the stage of a runner's training cycle. For example, a 16-week pyramidal training plan followed by a 16-week polarized training plan results in the greatest improvement in performance, indicating that this could be a viable method to integrate differences in stimuli from both distributions [31].

How Does the Training Behaviour of Recreational Runners Differ from the Recommended Training Plans?

To compare how established training recommendations align with the actual training behaviour of marathon runners, additional studies that describe these behaviours were considered. Gordon et al. examined the training characteristics of 97 recreational marathon runners including both males and females sub-grouped by different finishing times (2.5–3 h, 3–3.5 h, 3.5–4 h, 4–4.5 h, and > 4.5 h). This study found race speed for a marathon to be correlated with distance covered per training session, and weekly training distance [21]. Comparing these running behaviours, such as distance per week, distance per session, and the longest run of the plan, to the recommendations in the last 12 weeks before the marathon of the analysed plans, the training patterns of the 4–4.5 h group (56.2 km/week) was similar to the middle volume (58.5 km/week), and the > 4.5 h group (43.8 km/week) to the low volume plans (42.9 km/week). Only the weekly distance in the high volume plans of 107.7 km/week differed from the fastest finishing group of 2.5–3 h, which on average ran 91.7 km/week. When training for a marathon, it appears the actual training behaviours of recreational runners correspond well with the recommended most popular training plans for marathon performance [21].

For further analysis, Doherty et al. [22] performed a systematic review, meta-regression, and meta-analysis on 127 cohorts of runners to determine the relationship between training behaviours and marathon race performance. This analysis examined the average weekly running distance, number of weekly runs, maximum weekly running distance, number of runs ≥ 32 km in the pre-marathon training block, average running pace in training, longest run completed, and hours of running per week and found that increases in any one of these training parameters coincided with significant faster marathon finish times [22]. Based on the formulas they created, the marathon finish time calculated from the training recommendations for high volume training plans is 3:04, followed by 3:36 for the middle volume, and 3:50 for the low volume group. These predicted finishing times are faster than those suggested with the plans themselves and those predicted based on training behaviour [22].

How do Training Plans for Recreational Runners and Elite Runners Differ?

To relate the examined recreational training plans analysed in this report to elite populations we compared our findings to the training habits of elite marathon runners. Billat and colleagues examined the training characteristics of top-class and high-level elite marathoners and while the absolute distances of these runners are very different from the plans investigated here, the average intensity distribution revealed 78% of the total weekly distance was run at velocities less than marathon pace, 5% at marathon pace, and 17% greater than their marathon pace, matching a typical polarized training model [23]. While the exact comparison cannot be made due to discrepancies between intensity distribution methods, considering the last 12 weeks before the marathon, the high volume group comes the closest to such a polarized model with an average of 82% of training at less than marathon pace (zone 1 and 2), and 8% greater than marathon pace (zone 4 and 5) while the middle and low volume groups follow a typical pyramid training model.

Additionally, giving further insights into the training behaviour of elite long-distance runners, Haugen and his colleagues published a review integrating scientific literature and results-proven practice to understand the training and development of elite long-distance runners [6]. For marathon runners, this review found the weekly running distance in the mid-preparation period to be between 160 and 220 km per week, again significantly higher than the examined training plans. The intensity distribution of this distance, in line with the last 12 weeks of our examined plans, was made up of ≥ 80% of the total running volume being performed at low intensity (zone 1 and 2), 5–15% at middle intensity (zone 3), and 5–15% at high intensity (zone 4 and 5) inversely related to the middle intensity training [6]. The tapering for these athletes started 7–10 days out from the main competition, whereas for our analysed plans the peak week was around 4 weeks out from the competition, with an additional pronounced decline the last week before the race (Table 4 and Fig. 1) [6].

Finally, research from Karp found that among analysed qualifiers for the United States of America Olympic marathon trials, the large majority of the training was performed at low intensity, with men running 74.8% and women running 68.4% of their weekly distance, at a pace slower than marathon race pace [24]. In more detail, the distribution of training intensity for men and women was 75–10–10–5–3% and 68–13–12–7–5% for intensities below marathon race pace and at marathon race pace, lactate-threshold pace, ≥ 10 k race pace, and ≥ 5 k race pace, respectively [24]. In comparison, the distribution of the last 12 weeks before the marathon data presented here is skewed towards the lower intensities for all volume classifications with 82–10–5–3% for high, 77–18–2–3% for middle, and 78–17–3–2% for low for intensities of zone 1 and 2, zone 3, zone 4, and zone 5, respectively.

Limitations

Although our research has revealed new and potentially valuable insights that could assist coaches, athletes, and recreational runners in improving their training routines, there are several limitations to classifying the training plans in such a way that must be acknowledged. Firstly, it is important to recognize that unlike typical research databases such as PubMed, search outcomes from an Amazon or Google internet search may be impacted by variables outside of our influence, including location, personal search histories, and changes in search engine algorithms. To mitigate this inherent unpredictability, we focused on evaluating a diverse range of plans sourced from various places. Nevertheless, we acknowledge that our approach to searching still has its limitations. Secondly, the classification process involves subjective interpretation, as different training plans were written in various ways, making it necessary to analyse based on subjective decisions to ensure comparability. Moreover, the analyses here are limited to the last 12 weeks before the race, as certain training plans were only written for this duration. Additionally, both the subjective classification of the specific sessions into the five intensity zones and the classification of the training plan itself into low, middle, and high volume are subjective interpretations based on the range of training plans collected and the descriptions of the training sessions themselves.

Most training plans are not developed with a five-zone model in mind, and the intention of specific sessions may not always be apparent. Furthermore, we noticed discrepancies across the analysed training plans with different sources having varying definitions for commonly used phrases. We classified such sessions based on their descriptions in the plan rather than our understanding of the terms. For instance, several plans defined 'steady' runs differently, leading to varying categorizations. When steady was defined as a "purposeful pace … similar to marathon pace that helps to familiarize yourself to speeds you should set off on marathon day" [32], we classified this into zone 3, however for different plans steady runs were defined as the "runs to build the base for the rest of your training where conversations are still possible but only in shorter sentences" [33] or as a "continuous easy-medium pace" [34] which classified the sessions into zone 2. Some plans were also more detailed than others, and this may have affected the classification process. For example, one plan describes in detail a fartlek session starting with 20 min of easy running, then transitioning into 10 repetitions of 1 min hard where "you should be running fast enough that you cannot sustain the pace for more than a few minutes", followed by 1 min at a very easy jog before completing the rest of the run at an easy running pace [35]; whereas another plan just includes 45 min of fartlek running with the explanation that "rather than running a set distance in a set time, you play with different running paces and distances until you feel you've completed the workout" [36]. Additionally, one plan might include 20 different types of sessions included in a plan, while another plan consisting entirely of easy and long runs [37].

Finally, as previously mentioned, another limitation results from converting time-based training sessions into distance-based measures, considering the variability of paces of runners that might intend to follow the plan which will in turn affect the distance covered in a given session. For example, as part of a tempo run, one source includes 30 min in zone 3 [38]. For an advanced goal marathon time of 3:00 h, based on the included pace descriptions, this would mean running this session at a recommended pace of 6:12 min per mile and therefore covering around 4.8 miles. However, for the same exercise, if the goal time is around 4:00 h, the pace for this tempo run would be around 8:10 min per mile meaning this session would cover 3.7 miles. While here for the analysis, we used the information available in the descriptions of the training plans to make the best calculation for how much distance would be covered in sessions written with only a time variable, there may still be considerable variability.

Lessons Learned and Recommendations for Future Training Plans

The limitations identified in this analysis have highlighted significant differences in how training plans are developed and presented for recreational runners, which could potentially cause problems for those attempting to follow such plans. This lack of standardization in training plans makes it difficult to compare different plans, which limits the overall evidence base in this field. It is recommended that future training plans should be developed using consistent language and descriptions to ensure clarity and ease of understanding for those following the plans. By standardizing the language used to describe training sessions, runners can better understand what is expected of them during each session, and researchers can more effectively compare the effectiveness of different training plans. A clear and comprehensive training plan may incorporate the following elements: setting a target marathon time as the desired goal, utilizing a standardized 5-zone model for intensity recommendations, specifying the intended volume for training sessions, indicating the running speed in minutes per kilometre as the intensity measure, and providing information on the training plan structure, whether it is polarized, pyramidal, or follows a different framework. On top of that, this analysis has revealed limits in the existing evidence regarding the best tapering techniques and the optimal training intensity distribution for marathon performance with current research being inconclusive. Additionally, future training recommendations should consider how to optimize marathon preparation for different genders and age groups as well.

While our current study provides valuable insights into marathon training plans, we acknowledge that there are alternative approaches for analysis that could offer additional perspectives. One avenue for future research could involve a more detailed examination of training logs, as opposed to relying solely on pre-written training plans, utilizing a normalization process based on the percentage of the best world performance for a runner's age and gender. Such an approach not only permits a more nuanced evaluation of individual performances and training patterns, but also enables an assessment of effectiveness by correlating it with actual marathon performance outcomes.

Conclusions

The training methods utilized by marathon runners based on best-practice and results-proven recommendations often advance faster than the science of training and performance. By examining and analysing a wide range of recommended plans for recreational runners and integrating best practices with a scientific approach, this research provides valuable insights into creating a marathon training plan. The five most important findings from this analysis include:

1) Typical weekly running volume in the last 12 weeks before a race averages to 108 km for high volume marathon training plans, 59 km for middle volume, and 43 km for low volume.
2) The analysed training plans, in the last 12 weeks before the race, have a pyramidal training intensity organization both in terms of weekly and session distance with 15–67–10–5–3%, 14–63–18–2–3%, and 12–67–17–2–2% of weekly in zones 1–5 distance for high, middle, and low volume respectively, incorporating both high intensity training sessions with continuous submaximal running into the training regimen.
3) By analysing the progression of the different plans during the build-up phase leading up to peak week, the high volume plans had the most gradual relative weekly increase of 5% corresponding here to 3.2 km, whereas the low volume plans showed a more aggressive progression, with a weekly increase of 9% corresponding here to 2.4 km.
4) Peak week analysis revealed that while the distances differed between the three groups, the intensity zone distribution was the same. Given the weekly long run session during peak week was consistent among all groups, there appears to be a consensus that the longest training run for a marathon should be 30–32 km independent of the distance you run per week.
5) All analysed training plans start with a gradual taper 3–4 weeks out from race week with a 22–31% weekly reduction between peak week and race week, with a further 50% reduction in the last week before the race compared to the previous week.

These findings could benefit researchers, athletes, and coaches by providing information on the types and extent of training that is recommended to recreational runners for a marathon. The review applies a unique approach to analysing training recommendations and highlights the distinct features of training methods, volume, and intensity, emphasizing the differences between groups of marathon runners. Although this method has apparent drawbacks, such as the subjective nature of analysing such recommendations, the inconsistency in plan duration, and the inability to measure the effectiveness of such training plans with marathon performance outcomes, it presents a viable solution to the lack of evidence-based training practices being used now. In general, this review provides fresh perspectives on aspects of marathon training that have received limited attention in scientific research and provides beneficial guidance for devising training programs tailored to runners of varying performance levels.

Abbreviations

km	Kilometre
hr	Hour
min	Minute
ANOVA	Analysis of variance
F	F-statistic
p	*p*-Value
10 k	10 Kilometre race
5 k	5 Kilometre race
HR	Heart rate
RPE	Rating of perceived exertion

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40798-024-00717-5.

Additional file 1. This file contains the the coded weekly data used for the analysis of the different marathon training plans including the weekly volume, weekly duration, weekly long run, the intensity distribution both in distance and in time, and the number of rest days planned for each week.

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Author contributions

MK, DA, MS, and HW planned the review. SS developed the framework of the method. MK retrieved and transcribed the relevant sources. MK and DA classified the training plans. MK analysed the data. MK, DA, MS, SS, and HW interpreted the results. MK drafted the manuscript. MK, DA, MS, SS, and HW approved the final version of the manuscript.

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Availability of Data and Materials

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Declarations

Ethical Approval and Consent to Participate
Not applicable.

Consent for Publication
Not applicable.

Competing interests
DA, MS, SS, and HW have no conflicts of interest relevant to the content of this article. MK works at adidas but sees no issues regarding conflicts of interest for this research.

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3. General Discussion

This dissertation contributes to the science of marathon running by exploring both physiological and training aspects for both recreational and world-class athletes. Combined, this research reveals practical applications for optimized individualized performance and paves the way for advancements in the field of marathon science by:

1. Highlighting the importance of personalized strategies in the use of advanced footwear technology, particularly among world-class runners.
2. Providing training guidelines for recreational runners.
3. Effectively connecting theoretical research with practical application, offering tangible benefits for both world-class and recreational marathon runners.

The first study of this dissertation examined the impact of advanced footwear technology on running economy, comparing world-class Kenyan and amateur European male runners. While previous studies have focused on assessing the impact of different shoe technologies on the running economy of non-elite athletes, this study is the first to examine the effects on world-class athletes in a laboratory setting. The research revealed variability in running economy with world-class Kenyan runners' responses ranging from an 11.4% benefit to an 11.3% drawback when using different versions of advanced footwear technology compared to traditional racing flats. European amateurs also showed variability, ranging from a 9.7% benefit to a 1.1% drawback. This variability aligns well with previous research showing performance changes ranging from a 13.8% benefit to a 10.3% drawback when using advanced footwear technology versus traditional racing flats as measured both in the lab and in the field by examining race times. This study was also the first to perform a comprehensive analysis of existing research on this topic through a systematic review and meta-analysis with results being considered in the context of elite runners. The results indicated a medium overall benefit of advanced footwear technology on running economy, but also with notable individual variability, emphasizing the need for personalized shoe choices for optimal performance. Surprisingly, amateurs showed a higher average improvement in running economy with the advanced footwear technology (4.4 ± 3.2%) compared to the world-class cohort (0.2 ± 4.7%). This might be due to their different running speeds, East African runners' superior running economy, treadmill familiarity, and the placebo effect. In addition to the performance benefit coming from these shoes, athletes have also reported feeling fresher and capable of training more in cushioned advanced footwear compared to traditional flats, which could be impacting race performance as well. This study, however, also recognizes limitations, including the small sample size of world-class runners, a common constraint in studying elite populations. Additionally, time restrictions in the athletes' schedule further limited the ability to conduct repeated tests, which might have strengthened the data. In general, this research highlights how individual differences can markedly influence performance outcomes suggesting the importance of informed, individual footwear choices for marathon performance, highlighting also the importance of governing bodies to consider the diverse impacts of advanced footwear technology in marathon running.

The second study in this dissertation represents an alternative approach to marathon training research. To quantitatively summarize training plan recommendations for recreational runners, 92 sub-elite marathon training plans were systematically analyzed. The plans were then categorized based on weekly running volume into high, middle, and low, and the last 12 weeks before the marathon were examined. The findings reveal differences in weekly running volume among the plans, with the high-volume group averaging 108 km per week, more than two and a half times greater than that of the low-volume group at 43 km. All plans have a pyramidal training intensity distribution across both weekly and session distances, incorporating both high-intensity training sessions with continuous submaximal running. In terms of weekly training volume progression, the high-volume plans have the most gradual relative weekly increase per week of 5%, corresponding to 3.2 km, whereas the low-volume plans showed a more aggressive progression of 9% per week, corresponding to 2.4 km. An analysis of peak week revealed while the distances differed between the three groups, the intensity zone distribution was the same. The study reveals that the long run session during peak week is consistently set between 30-32 km across all groups, regardless of their overall weekly running volume. This indicates a strategic choice to not cover the full marathon distance in training, contrary to what one might think. Additionally, it highlights a standardized approach to tapering, with all groups of training plans initiating a gradual reduction in intensity 3-4 weeks out from race week with a 22-31% weekly reduction between peak week and race week, followed by an additional 50% reduction in the final week leading up to the race. While these findings contribute to the theoretical foundation of evidence-based training practices for recreational marathon runners, the study also acknowledges its limitation. These include the subjective nature of plan interpretation and analysis, and the absence of direct effectiveness data that focuses on assessing the best-practice recommendations rather than the results-proven performance. However, this work is still useful as it summarizes current training recommendations for recreational marathon runners.

The implications of this dissertation extend beyond academia to influence the practical aspects of marathon running. These studies pave the way for future research to optimize the use of footwear technology, further refine training strategies, and ultimately enhance marathon performance across various levels of runners.

4. Future Directions

The two studies presented in this dissertation provide valuable insights into two aspects of marathon running: footwear technology and training. By examining footwear technology and training methodologies, these studies not only deepen our understanding of marathon performance but also lay the foundation for future research that has the potential to advance this field.

Sex Disparities

Addressing sex disparities is crucial for comprehensive marathon research. Only limited studies have compared performance responses to advancements in footwear technology between sexes, warranting further investigation. It is crucial to consider shoe grading, as factors like lighter stature and slower relative speeds in female marathoners result in less force exerted on shoes. This could affect the mechanical responses and effectiveness of these technologies. Additionally, most established marathon training plans for recreational runners did not differentiate between male and female-specific recommendations. Given the distinctive physiological demands of running a marathon for each gender and considering the physiological variations associated with hormonal fluctuations during the menstrual cycle in females, future research should focus on tailored training plans that address the specific needs of both sexes.

General Understanding of Responders versus non-Responders

The variability in responses to interventions in this dissertation highlights the need for further investigation into the individual characteristics influencing these outcomes. When examining responses to different footwear on performance, the variability found indicates the need for personalized approaches to achieve similar benefits across subjects. Similarly, exploring the individualization of training plans based on physiological variables could enhance marathon training effectiveness. Future studies should explore customizing training regimens to each athlete's unique physiological profile to maximize their performance. This understanding of responders and non-responders to specific interventions would allow us to fine-tune interventions, providing athletes with tailored strategies for peak performance. Sharing individualized data in publications represents a straightforward yet powerful step towards enriching the collective body of knowledge, ultimately paving the way for personalized performance optimization in the future.

Real-Time Analysis During Marathons

The advent of wearable sensor technology offers new opportunities to gather extensive running data in diverse conditions. Although progress has been made in collecting biomechanical data via inertia measurement units (IMUs), their full potential in race scenarios remains underutilized. Integrating real-time metabolic analysis, including live measurements of oxygen uptake, respiratory exchange ratios, and lactate levels, during actual marathons could provide invaluable insights into athletes' dynamic physiological responses throughout a race. This approach could deepen our understanding of the physiological demands inherent to marathon running. Moreover, the development of innovative wearables that seamlessly integrate with race performance opens exploration into a broad spectrum of factors including nutritional and psychological elements, that could allow us to dissect their respective roles in marathon performance. Ultimately, these insights could be leveraged to refine predictive models for marathon running, aiding race preparation, and informing footwear optimization strategies for the entirety of the race.

Footwear Technology and Performance

The field of advanced footwear technology and its impact on running performance has experienced a surge in research since the launch of such shoes. However, despite numerous proposed mechanisms on how they work, many remain speculative. To gain a comprehensive understanding of how specific shoe characteristics influence marathon performance, future research should systematically evaluate these characteristics and conduct long-term studies on their effects. This endeavor should include a diverse range of runners, from elite to recreational, over extended periods to assess the durability and sustainability of the observed performance improvements. In addition to the conventional running economy tests, alternative metrics should be explored for a more ecologically valid assessment of this footwear's impact. Furthermore, standardizing testing protocols across studies is essential to enable more meaningful cross-study comparisons.

Evidence-Informed Training Recommendations

In marathon running research, there is a lack of evidence that can directly inform the writing of training plans. This can be addressed with various approaches. Longitudinal studies encompassing both elite and sub-elite runners could reveal how training adaptations impact marathon performance over time. However, these studies are difficult to conduct as it is challenging to recruit enough runners to study the effect of well-controlled training plans versus control or placebo on marathon running performance. Alternatively, analyzing changes in the physiological predictors of marathon performance in response to training modifications can help practitioners refine their methods and assess the efficacy of these interventions throughout a training cycle. Additionally, standardizing terminology in training recommendations could significantly improve their accessibility for average runners and enable better comparisons across different training approaches.

In conclusion, this dissertation paves the way for future research that could further enrich our understanding of marathon running and performance.

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Appendix

I. Conference Contributions

Conference Abstract

Knopp, M., Appelhans, D., Schönfelder, M., Wackerhage, H., Systematic Review of 92 Marathon Training Plans. In 28th Annual Congress of the European College of Sports Science; 4 - 7 July 2023; Paris, France.

Conference Talks

Knopp, M., Miles, H., Fritz, J., Alcañiz, A., Fleiter, M., Schweizer, F., Luckfiel, T., Körger, H., Scheurer, H., Schlarb, H., Muñiz-Pardos, B., Wackerhage, H., Schönfelder, M., Pitsiladis, Y., Ruiz, D., Understanding and enhancing elite running performance – Kenyathlon: A multidisciplinary approach. In International Federation of Sports Medicine's 36th World Congress of Sports Medicine; 23-26 September 2021; Athens, Greece.

Knopp, M., Muñiz-Pardos, B., Wackerhage, H., Schönfelder, M., Pitsiladis, Y., Ruiz, D., Physiological Characteristics of World-Class Kenyan Runners – Maximal Aerobic Capacity and Running Economy. In 27th Annual Congress of the European College of Sports Science; 30 August - 2 September 2022; Sevilla, Spain.