motricidade

LETTER TO THE EDITOR

https://doi.org/10.6063/motricidade.42847

# Bridging the gap: integrating physiology, strength and innovation to enable a women's sub-4 minute mile

Ricardo J. Fernandes[1,2], Paulo Colaço[1]

ABSTRACT

This Letter explores the physiological, biomechanical and strategic factors underpinning the possibility of a woman running a mile in under 4 min — a barrier historically viewed as symbolic and physiologically prohibitive. Drawing on recent projections, we examine the interplay between aerobic power, anaerobic work capacity, neuromuscular coordination and mechanical efficiency, highlighting how targeted strength training, tendon stiffness, and reactive force development may contribute to bridging the remaining 7.65 s gap (6.42 in a non-official recently made record). The discussion integrates advancements in pacing strategies, oxygen uptake kinetics and footwear technology, alongside sociocultural and institutional enablers. We argue that individualised long-term development models, supported by data-driven monitoring and sex-specific interventions, are critical to this pursuit. Far from a speculative goal, the sub-4 min mile for women now stands as a strategically actionable target. Today, this endeavour is strongly supported by several scientific studies and concepts, but its realisation will require a convergence of current knowledge with the preparation, training organisation and belief that enabled Bannister's breakthrough in 1954.

KEYWORDS: performance; women; mile; training; stiffness; pacing.

A *Letter to the Editor* in a scientific journal is a concise form of scholarly communication, typically intended to comment on, critique or supplement a recently published work. Such letters offer readers a platform to provide constructive criticism, raise methodological concerns, or propose alternative interpretations of the findings (Bhopal & Tonks, 1994). They may also serve to highlight overlooked literature, present preliminary data, or suggest new hypotheses. Although generally shorter than full-length articles, letters are often peer-reviewed and must conform to the journal's formatting guidelines and standards of scientific rigour. Authors use this format to engage in academic discourse and foster scientific dialogue (Nuzzo, 2023). Some journals also accept letters that are not tied to specific articles, enabling researchers to address broader issues within the field. Overall, *Letters to the Editor* contribute to the self-correcting nature of science by promoting critical reflection and informed debate. In this opinion article, we take the opportunity to comment on a topic recently introduced in a *Letter to the Editor* (Osborne et al., 2025b), which is currently under discussion.

In this context, through the present opinion article, we reflect on the physiological and performance-related considerations underpinning the possibility of a woman running a mile in under 4 min — a landmark achievement of both symbolic and scientific significance. Osborne et al. (2025b) initially outlined the physiological thresholds required to reach such a milestone, suggesting that the barrier could potentially be broken by 2030. Concurrently, the 2038 projection — another forecast proposed by the same authors — appears realistic for runners currently beginning (or soon to begin) structured training, as it allows for an earlier and more individualised developmental approach specifically aimed at breaking the 4 min barrier. In a follow-up commentary, Osborne et al. (2025a) further emphasised the central role

[1]Universidade do Porto, Faculty of Sport, Centre of Research, Education, Innovation and Intervention in Sport – Porto, Portugal.
[2]Universidade do Porto, Porto Biomechanics Laboratory – Porto, Portugal.
*Corresponding author: Universidade do Porto, Faculdade de Desporto, R. Dr. Plácido da Costa, 91 – 4200-450 – Porto, Portugal.
E-mail: ricfer@fade.up.pt

Conflict of interests: nothing to declare. Funding: nothing to declare.
Received: 25th August 2025. Accepted: 24th November 2025.

of anaerobic work capacity, noting that many elite female runners already possess a sufficient critical speed — i.e. the maximal aerobic intensity that can be maintained over time without exhaustion (Fernandes et al., 2013) — yet may lack the anaerobic reserve necessary to sustain the required pace. The interaction between these performance-related determinants forms the conceptual basis for evaluating pacing strategies and guiding training interventions.

Achieving a sub-4 min mile requires sustaining a race pace of 6.71 m/s (~16.8 s per 100 m) over four consecutive laps. To meet this demand, a runner must not only exhibit exceptional aerobic power but also possess the neuromuscular coordination and metabolic flexibility required to sustain high velocities under increasing fatigue. Importantly, anaerobic work capacity is thought to be closely related to lean body mass, which tends to be lower in women (Hill & Smith, 1993). This physiological constraint may be attenuated through structured resistance and plyometric training designed to enhance force production and improve muscle recruitment efficiency (Esteve-Lanao et al., 2008; Pellegrino et al., 2016). Training programs should address not only muscular strength but also tendon stiffness — particularly within the Achilles tendon–aponeurosis complex. Increased tendon stiffness enhances the storage and release of elastic energy, improving running economy. Strength training protocols that incorporate eccentric loading and optimise the stretch-shortening cycle have been shown to induce biomechanical adaptations beneficial to middle-distance running performance, with these mechanical gains being especially impactful when developed from an early age.

We concur that optimising mile-specific training requires a high power-to-weight ratio and that appropriate resistance training may be a key contributing factor. Legendary runners, such as Sebastian Coe, have long emphasised the importance of implementing targeted strength training strategies to achieve these adaptations. Recent research suggests that strength-oriented programs — particularly those incorporating high loads and plyometric exercises — can significantly improve running economy (Llanos-Lagos et al., 2024), even when implemented over relatively short time durations (3-6 months). Among young runners, the combination of heavy resistance and plyometric training has been shown to enhance the reactive strength index and running economy, while also reducing blood lactate concentrations at submaximal speeds (Li et al., 2019). Nevertheless, in female athletes under the age of 18, the limited number of studies precludes definitive conclusions. Still, improvements in running economy, stride length and lactate clearance may enable young women to better maintain speed during glycogen-depleted phases of the race — potentially making sub-4 min mile performances physiologically attainable.

As noted before, incorporating eccentric loading and controlled plyometric training in female runners can enhance tendon stiffness and reactive strength, improving energy return, reducing ground contact time and contributing to greater efficiency during high-speed running (McMahon & Cook, 2024). These adaptations are particularly relevant for events such as the mile, where maintaining mechanical efficiency under fatigue is critical. In adolescent female runners, such training may be especially valuable for mitigating developmental plateaus associated with puberty, which can temporarily limit performance progression due to hormonal shifts and changes in body composition. It has been emphasised that the importance of periodised strength training as a means of optimising stride mechanics, preserving stride length, and improving ground contact dynamics (Blagrove et al., 2018) — all of which are essential for sustaining race pace in the final stages of a middle-distance event.s Within this context, a long-term runner development model that integrates progressive strength, neuromuscular and plyometric training from early adolescence may provide the structural and functional foundation necessary for future breakthroughs in female middle-distance performance.

In addition to musculoskeletal conditioning, several performance-enhancing strategies may contribute to a sub-4 min mile performance. One such approach involves the use of priming or pre-conditioning exercises, consisting of short bouts of high-intensity effort performed shortly before competition. These efforts are designed to accelerate pulmonary oxygen uptake kinetics, enhancing oxygen delivery to working muscles and reducing early reliance on anaerobic metabolism. A faster attainment of maximal oxygen uptake may help spare anaerobic work capacity for the latter stages of the race, enabling more strategic energy distribution across laps (Blagrove et al., 2018). Investigations into time to exhaustion at maximal oxygen uptake pace also offer valuable insights in this regard since this is an effort of a distance around 1 mile (Cardoso et al., 2025). Integrating these strategies from an early stage in the runner's development may foster more efficient oxygen uptake kinetics and establish a higher physiological ceiling for future anaerobic performance.

As running velocity increases, aerodynamic resistance becomes a progressively more significant contributor to the overall energy cost of locomotion. At speeds approaching 6.7 m/s — required to complete a mile in under 4 min — the drag force imposes a non-negligible metabolic demand, especially in the latter stages of the race when fatigue compromises mechanical efficiency. Pacemaking can partially

mitigate this aerodynamic burden by allowing the target runner to draft behind one or more pacers, reducing frontal air resistance. This was notably demonstrated in Faith Kipyegon's 2023 world record, during which she benefited from pacemaking support for over half the distance (Osborne et al., 2025b). Optimising pacing strategies — by extending the duration of assistance, improving positioning or using coordinated dynamic drafting techniques — may generate time savings in the range of 1–2 s. However, this was not sufficient for Faith Kipyegon to achieve the 4 min goal in her recent attempt in June 2025, which took place in a non-official race alongside male pacers until the finish. While seemingly modest, such margins are highly consequential in the context of record-chasing efforts at the elite level. In addition, strategic pace setting may reduce the psychological load associated with solo pacing, allowing the runner to distribute effort more evenly and delay the onset of critical fatigue (Da Silva et al., 2025).

Technological advancements in footwear have significantly transformed middle-distance running performance, with modern spikes that incorporate carbon-fibre plates and high-rebound foams now empirically shown to improve running economy by reducing the energetic cost of locomotion (Ruiz-Alias et al., 2024). These benefits arise from improved force transmission, reduced energy dissipation at ground contact and optimised mechanics throughout the stance phase. Recent findings suggest that female runners may derive even greater advantages — potentially due to sex-specific differences in force application, footstrike mechanics and contact dynamics (Rodrigo-Carranza et al., 2025). Customising footwear properties such as stiffness, stack height, compliance and energy return to align with the biomechanics and target race pace of elite female milers may unlock further performance gains. This process of personalised shoe selection - incorporating both midsole and plate characteristics — could enhance mechanical economy, delay fatigue onset and improve overall race efficiency. In the context of elite middle-distance competition, such marginal advantages may cumulatively translate into critical time savings, particularly under fatigue conditions where biomechanical resilience is paramount.

In parallel, nutritional strategies, particularly the use of ergogenic aids, also merit consideration (Lopes et al., 2023). Supplementation with sodium bicarbonate, beta-alanine and creatine has been demonstrated to enhance buffering capacity, delaying the onset of fatigue during high-intensity efforts (Edge et al., 2006; Richard et al., 2024). Although the effects of these supplements are not strictly additive, their periodized use during key training blocks and competition phases may improve physiological preparedness. An emerging yet underexplored area of interest involves the physiological adaptations observed postpartum: pregnancy induces haematological and cardiovascular changes — such as increased blood volume, stroke volume and haemoglobin mass — that resemble those achieved through prolonged endurance training (Almquist et al., 2022). There is growing speculation that an athlete returning from maternity leave could leverage these adaptations, particularly if supported by structured reconditioning and recovery protocols.

In terms of training design, combining high-volume aerobic work with targeted strength training cycles aimed at developing anaerobic work capacity appears to be a promising strategy for middle-distance runners. Sessions that alternate between high-intensity aerobic interval training and explosive power development may enhance both aerobic power and neuromuscular readiness, creating the dual capacity required to meet the aggressive pacing demands of a sub-4 min mile (Rønnestad & Mujika, 2014). Additionally, integrating technology — such as force plates, motion sensors and wearable monitors — allows for real-time tracking of biomarkers, mechanical output and fatigue indicators, enabling more precise and individualised coaching interventions. From a biomechanical perspective, key determinants of performance include increased leg stiffness, reduced ground contact time and preservation of stride length under fatigue. Motion capture analyses suggest that elite runners minimise vertical oscillation while maximising horizontal propulsion, contributing to superior mechanical efficiency (Moore, 2016). Training exercises that promote reactive strength (e.g. hurdle hops, bounding drills, sprint-assisted running and depth jumps) may help develop the movement patterns necessary to approach these optimal mechanics in competition.

Race strategy must also evolve in response to the physiological and tactical demands of a sub-4 min mile. Traditional approaches such as negative splits or aggressive opening laps may prove unsustainable under current constraints. Instead, an even or slightly positive pacing profile (guided by real-time feedback from pacers or digital display systems) may provide the most efficient use of physiological resources. Advances in research on fatigue thresholds, critical speed and intra-race lactate dynamics could further refine pacing strategies and recovery timing. Equally important is the examination of sociocultural and institutional factors. Investment in female-specific high-performance systems, long-term development models and individualised data-driven coaching frameworks will be essential to close the remaining performance gap. The breaking of the 4 min mile by Roger Bannister in 1954 was not solely an athletic

feat but the result of scientific innovation (for those times), organisational structure and cultural belief (Krüger, 2006). A similar convergence of factors may now be within reach for women. In this context, the pursuit of a sub-4 min mile in female runners has moved from a speculative ambition to a plausible and strategically actionable goal.

Physiological ceilings are being raised, technical barriers lowered, and training systems continuously refined. By integrating strength, science and innovation, coaches and runners can collectively work to bridge the remaining 7.65 s. Whether achieved by 2030 or earlier, this milestone represents not merely a performance objective but a statement of what is possible in women's middle-distance running. In particular, training interventions that increase stiffness in the Achilles tendon–aponeurosis complex may enhance energy storage and return, improving muscular output during running (Albracht & Arampatzis, 2013). These adaptations can lead to improved running economy, with positive effects across both aerobic and anaerobic energy systems. Nonetheless, it remains essential to maintain a high volume of structured aerobic training, as a robust aerobic base continues to be the primary determinant of performance in the 1,500 m. This is exemplified by the current success of Jakob Ingebrigtsen, whose dominance is strongly underpinned by aerobic capacity and efficiency (Le Hyaric et al., 2024).

Although factors such as altitude training, nutrition, warm-up routines, race tactics and footwear can all meaningfully impact performance, systematic and targeted monitoring may be the most decisive tool for long-term progress. By tracking individual responses over time, coaches can identify the most effective strength exercises to enhance the function of elastic structures within the musculoskeletal system. This, in turn, supports improvements in mechanical efficiency, particularly in reducing ground contact time and preserving stride length, which are critical for closing the remaining 7.65 s gap. In parallel, aerodynamic optimisation through environmental monitoring and pacing strategies also offers potential gains. Modelling studies suggest that elite runners using optimised drafting formations can reduce energy cost by up to 6%, particularly when supported by wind-aware pacing or semi-enclosed track configurations. Incorporating pacer rotations and positional coordination could further minimise drag-related losses, providing small but meaningful advantages in record-chasing scenarios.

Ultimately, the possibility of a woman running a mile in under 4 min is no longer constrained by biology alone, but shaped by how knowledge is applied across training, science and support systems. This pursuit demands a shift in mindset: away from the belief that such performances lie beyond female potential and toward evidence-based confidence in what structured individualised preparation can achieve. While many of the physiological, biomechanical and technological conditions are already in place, continued progress will depend on sustained investment in female runner development and a willingness to challenge outdated narratives. As history has shown, breakthrough performances often arise when preparation meets belief. The sub-4 min mile is not simply a barrier to be broken, but a horizon to be redefined — and that redefinition may now be closer than ever.

## REFERENCES


Albracht, K., & Arampatzis, A. (2013). Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. *European Journal of Applied Physiology, 113*(6), 1605–1615. https://doi.org/10.1007/s00421-012-2585-4

Almquist, N. W., Sandbakk, Ø., & Solli, G. S. (2022). Performance related physiological and haematological changes during pregnancy and postpartum in a well-trained cyclist performing endurance training. *Frontiers in Physiology, 13*, 762950. https://doi.org/10.3389/fphys.2022.762950

Bhopal, R. S., & Tonks, A. (1994). The role of letters in reviewing research. *BMJ, 308*(6944), 1582–1583. https://doi.org/10.1136/bmj.308.6944.1582

Blagrove, R. C., Howatson, G., & Hayes, P. R. (2018). Effects of strength training on the physiological determinants of middle- and long-distance running performance: A systematic review. *Sports Medicine, 48*(5), 1117–1149. https://doi.org/10.1007/s40279-017-0835-7

Cardoso, F., Costa, M. J., Colaço, P., Vilas-Boas, J. P., Pinho, J. C., Pyne, D. B., & Fernandes, R. J. (2025). Ventilatory and perceived ergogenic effects of mandibular forward repositioning during running at maximal oxygen uptake intensity. *Journal of Strength and Conditioning Research, 39*(1), e13–e19. https://doi.org/10.1519/jsc.0000000000004953

Da Silva, E. S., Hoogkamer, W., Kipp, S., & Kram, R. (2025). Could a female athlete run a 4-minute mile with improved aerodynamic drafting? *Royal Society Open Science, 12*(2), 241564. https://doi.org/10.1098/rsos.241564

Edge, J., Bishop, D., & Goodman, C. (2006). Effects of chronic $NaHCO_3$ ingestion during interval training on changes to muscle buffer capacity, metabolism, and short-term endurance performance. *Journal of Applied Physiology, 101*(3), 918–925. https://doi.org/10.1152/japplphysiol.01534.2005

Esteve-Lanao, J., Rhea, M. R., Fleck, S. J., & Lucia, A. (2008). Running-specific, periodized strength training attenuates loss of stride length during intense endurance running. *Journal of Strength and Conditioning Research, 22*(4), 1176–1183. https://doi.org/10.1519/jsc.0b013e31816a861f

Fernandes, R., Oliveira, E., & Colaço, P. (2013). Bioenergetical assessment and training control as useful tools to improve performance in cyclic sports. In B. D. Carmichael & A. B. Mitchell (Eds.), *Sports medicine and training tools* (pp. 61–88). Nova Science Publishers.

Hill, D. W., & Smith, J. C. (1993). A comparison of methods of estimating anaerobic work capacity. *Ergonomics, 36*(12), 1495–1500. https://doi.org/10.1080/00140139308968017

Krüger, A. (2006). Training theory and why Roger Bannister was the first four minute miler. *Sport in History, 26*(2), 305–324. https://doi.org/10.1080/17460260600786955

Le Hyaric, A., Aftalion, A., & Hanley, B. (2024). Modelling the optimization of world-class 400 m and 1,500 m running performances using high-resolution data. *Frontiers in Sports and Active Living, 6*, 1293145. https://doi.org/10.3389/fspor.2024.1293145

Li, F., Wang, R., Newton, R. U., Sutton, D., Shi, Y., & Ding, H. (2019). Effects of complex training versus heavy resistance training on neuromuscular adaptation, running economy and 5-km performance in well-trained distance runners. *PeerJ, 7*, e6787. https://doi.org/10.7717/peerj.6787

Llanos-Lagos, C., Ramirez-Campillo, R., Moran, J., & Villarreal, E. S. (2024). Effect of strength training programs in middle- and long-distance runners' economy at different running speeds: A systematic review with meta-analysis. *Sports Medicine, 54*(4), 895–932. https://doi.org/10.1007/s40279-023-01978-y

Lopes, A., Magalhães, J., Fernandes, R. J., & Ascensão, A. (2023). Adding protein to a carbohydrate pre-exercise beverage does not influence running performance and metabolism. *Journal of Sports Medicine and Physical Fitness, 63*(1), 53–59. https://doi.org/10.23736/s0022-4707.22.13714-x

McMahon, G., & Cook, J. (2024). Female tendons are from Venus and male tendons are from Mars, but does it matter for tendon health? *Sports Medicine, 54*(10), 2467–2474. https://doi.org/10.1007/s40279-024-02056-7

Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine, 46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

Nuzzo, J. L. (2023). Letter writing assignment for exercise physiology students. *Advances in Physiology Education, 47*(2), 346–351. https://doi.org/10.1152/advan.00258.2022

Osborne, R. J., Kirby, B. S., Black, M. I., Vanhatalo, A., & Jones, A. M. (2025a). Last word on viewpoint: Seven (.65) seconds away: The possibility and physiology of a women's sub-4 min mile. *Journal of Applied Physiology, 139*(1), 263–264. https://doi.org/10.1152/japplphysiol.00521.2025

Osborne, R. J., Kirby, B. S., Black, M. I., Vanhatalo, A., & Jones, A. M. (2025b). Seven (.65) seconds away: The possibility and physiology of a women's sub-4-minute mile. *Journal of Applied Physiology, 138*(6), 1335–1340. https://doi.org/10.1152/japplphysiol.00074.2025

Pellegrino, J., Ruby, B. C., & Dumke, C. L. (2016). Effect of plyometrics on the energy cost of running and MHC and titin isoforms. *Medicine & Science in Sports & Exercise, 48*(1), 49–56. https://doi.org/10.1249/mss.0000000000000747

Richard, N., Claydon, V., Koehle, M., & Coté, A. (2024). Sprint interval training in the postpartum period maintains the enhanced cardiac output of pregnancy: A case study. *Experimental Physiology, 109*(12), 1629–1636. https://doi.org/10.1113/ep091994

Rodrigo-Carranza, V., Cruz, V. M., & Hoogkamer, W. (2025). Influence of advanced-footwear-technology spikes on middle- and long-distance running performance measures in trained runners. *International Journal of Sports Physiology and Performance, 20*(5), 689–699. https://doi.org/10.1123/ijspp.2024-0377

Rønnestad, B. R., & Mujika, I. (2014). Optimizing strength training for running and cycling endurance performance: A review. *Scandinavian Journal of Medicine & Science in Sports, 24*(4), 603–612. https://doi.org/10.1111/sms.12104

Ruiz-Alias, S. A., Pérez-Castilla, A., Soto-Hermoso, V. M., & García-Pinillos, F. (2024). Influence of the carbon fiber plate curvature of advanced footwear technology on the running energetic cost and 3,000 m performance. *Sports Engineering, 27*(2), 21. https://doi.org/10.1007/s12283-024-00465-5