PERSPECTIVES ON THE IMPACT OF ADVANCED FOOTWEAR ON RUNNING PERFORMANCE AND INJURY: A REVIEW

Song Min LEE[1,2], Yong Ung KWON[1,2*]

[1]Department of Sports Science, Chung-Ang University, Seoul, Republic of Korea, mugika2@gmail.com

[2]Biomotion Clinical Rehabilitation Laboratory, School of Sports Science, Chung-Ang University, Anseong, Republic of Korea

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ABSTRACT. This review explores the evolution of running from a basic survival skill to a complex sport, highlighting the significant role of advanced footwear in performance enhancement. Running economy, a key determinant of long-distance running success, is influenced by various external factors, including training methods and equipment, as well as individual attributes, such as biomechanics and cardiorespiratory capacity. Recent advancements in high-performance running shoes have shown promise in improving speed and efficiency, as evidenced by record-breaking performance. However, the potential impact of such shoes on natural running mechanics raises concerns regarding health and injury risks. This study examines the characteristics and effects of critical elements in advanced footwear, such as midsole foam and rigid plates to assess their advantages and disadvantages. The findings show that, although these shoes can temporarily enhance performance, proper training and conditioning are crucial for mitigating injury risks, particularly for untrained runners. The footwear industry must balance performance enhancement, injury prevention, and fairness in competition to ensure that technological advancements positively influence runners' health and performance.
KEY WORDS: running economy, shoes, midsole, biomechanics, carbon fiber plate

PERSPECTIVE LEGATE DE IMPACTUL ÎNCĂLȚĂMINTEI AVANSATE ASUPRA PERFORMANȚEI LA ALERGARE ȘI ASUPRA RISCULUI DE ACCIDENTARE: O TRECERE ÎN REVISTĂ

REZUMAT. Această trecere în revistă explorează evoluția alergării de la o abilitate de supraviețuire de bază la un sport complex, subliniind rolul semnificativ al încălțămintei avansate în îmbunătățirea performanței. Economia alergării, un factor cheie al succesului alergării pe distanțe lungi, este influențată de diverși factori externi, inclusiv de metodele și echipamentul de antrenament, precum și de atributele individuale, cum ar fi biomecanica și capacitatea cardiorespiratorie. Progresele recente în realizarea unor pantofi de alergare de înaltă performanță s-au dovedit a fi promițătoare în îmbunătățirea vitezei și eficienței, așa cum demonstrează performanțele record. Cu toate acestea, potențialul impact al unor astfel de pantofi asupra mecanicii naturale de alergare ridică îngrijorări cu privire la riscurile de sănătate și de accidentare. Acest studiu examinează caracteristicile și efectele elementelor critice din încălțămintea avansată, cum ar fi talpa intermediară din spumă și plăcile rigide, pentru a le evalua avantajele și dezavantajele. Descoperirile arată că, deși acești pantofi pot îmbunătăți temporar performanța, antrenamentul și condiționarea adecvate sunt cruciale pentru atenuarea riscurilor de accidentare, în special pentru alergătorii neantrenați. Industria de încălțăminte trebuie să echilibreze factori precum îmbunătățirea performanței, prevenirea accidentărilor și corectitudinea în competiție pentru a se asigura că progresele tehnologice influențează într-un mod pozitiv sănătatea și performanța alergătorilor.
CUVINTE CHEIE: economia alergării, pantofi, talpă intermediară, biomecanică, placă din fibră de carbon

PERSPECTIVES SUR L'IMPACT DES CHAUSSURES AVANCÉES SUR LES PERFORMANCES DE COURSE ET LE RISQUE DE BLESSURES : UNE REVUE

RÉSUMÉ. Cette revue explore l'évolution de la course à pied, d'une compétence de survie de base à un sport complexe, soulignant le rôle important des chaussures avancées dans l'amélioration des performances. L'économie de course, un facteur clé dans la réussite des courses de longue distance, est influencée par divers facteurs externes, notamment les méthodes et l'équipement d'entraînement, ainsi que par des attributs individuels tels que la biomécanique et la forme cardiorespiratoire. Les progrès récents dans le domaine des chaussures de course haute performance se sont révélés prometteurs en termes d'amélioration de la vitesse et de l'efficacité, comme le démontrent les performances record. Cependant, l'impact potentiel de telles chaussures sur la mécanique naturelle de course soulève des inquiétudes quant aux risques pour la santé et les blessures. Cette étude examine les caractéristiques et les effets des éléments critiques des chaussures avancées, tels que les semelles intermédiaires en mousse et les plaques rigides, afin d'évaluer leurs avantages et leurs inconvénients. Les résultats montrent que même si ces chaussures peuvent améliorer temporairement les performances, un entraînement et un conditionnement appropriés sont essentiels pour atténuer les risques de blessures, en particulier pour les coureurs non entraînés. L'industrie de la chaussure doit équilibrer des facteurs tels que l'amélioration des performances, la prévention des blessures et l'équité dans la compétition pour garantir que les avancées technologiques ont un impact positif sur la santé et les performances des coureurs.
MOTS CLÉS : économie de course, chaussures, semelle intermédiaire, biomécanique, plaque en fibre de carbone

* *Correspondence to: Yong Ung KWON, Ph.D., Biomotion Clinical Rehabilitation Laboratory, School of Sports Science, Chung-Ang University, Anseong, Republic of Korea, mugika2@gmail.com*

INTRODUCTION

Throughout human history, running has evolved from a necessity for survival to a pursuit that focuses on fitness and personal achievements. As running gains popularity, so does research aimed at improving speed and performance. Running economy (RE), a critical determinant of long-distance running performance, is influenced by various external factors, such as environmental conditions, training methods, and equipment, as well as individual physical attributes, including cardiorespiratory capacity, metabolism, biomechanics, and neuromuscular function [1, 2]. Historically, athletes have primarily emphasized internal factors, such as training techniques, to improve RE and speed. However, in recent times, a notable shift has occurred towards leveraging modern technology, especially “advanced footwear,” to optimize running performance, which has gained popularity among runners. Specifically, “high-performance running shoes” have emerged as a significant factor in enhancing long-distance running performance [2, 3].

While ancient runners ran barefoot, contemporary runners utilize shoes crafted from diverse materials, including soft compounds, high foam, and rigid plates [4-6]. Despite the recent emergence of advanced footwear, opinions and studies on its impact vary widely, with no clear consensus. Notably, high-performance running shoes have demonstrated the ability to enhance performance, as evidenced by athletes achieving world records while wearing them. Conversely, excessive technological advancements in running shoes may disrupt natural biomechanics and increase the risk of injury [7, 8]. Concerns have also arisen regarding the possibility of high-performance running shoes compromising the fairness of the sport, a fundamental principle in athletics [9].

Research on the effects of key elements in running shoes, such as midsole foam, cushioning, and rigid plates (e.g., carbon), on running performance has yielded inconsistent findings [4-6]. The rise of high-performance running shoes has reportedly led to faster performance times [9]. However, documentation is limited on whether these advancements contribute positively to overall runner health. Therefore, this study aims to comprehensively review the literature on the characteristics, advantages, and disadvantages of the main elements used in advanced footwear.

Shoe Mass

Shoe mass is a critical factor that influences RE [10]. Previous studies have indicated that increased shoe mass significantly decreases RE and overall performance, whereas lighter shoes are expected to enhance RE and performance by reducing muscle effort [2, 10]. Specifically, a 100 g increase in shoe mass raises oxygen consumption by approximately 1%, thereby diminishing RE [11, 12].

Accordingly, running barefoot has been suggested as more economical owing to the absence of shoe weight. Barefoot running can potentially enhance RE by allowing an acute transition from rearfoot strike to forefoot strike, increasing cadence, and minimizing vertical oscillations of the center of mass [6, 13, 14]. Greater plantar-flexed foot placement and increased stride frequency associated with barefoot running may facilitate a more effective recovery of elastic energy in tendons and muscles [13, 15]. Moreover, increased proprioception of the foot by running barefoot has been hypothesized to contribute to the above effects by allowing for the coordination and pre-activation of key running muscles [2, 9].

However, running barefoot does not necessarily optimize RE because the increased ankle joint contact forces and plantar flexor forces during transitions from rearfoot strike to forefoot strike can increase the risk of injury caused by abrupt changes in landing patterns. Furthermore, running with shoes tends to increase leg and ankle stiffness compared to barefoot running [16, 17]. Runners encounter various types of terrain that interact with the leg's spring-mass system, and invariant leg stiffness may decrease efficiency on uneven surfaces, highlighting the importance of stiffness. Notably, significant differences in RE between barefoot and shod running have been observed only when shoe weight exceeded 440 g [9, 10]. Thus, because appropriately weighted running shoes can actually promote more favorable RE compared to running barefoot, carefully integrating additional shoe elements is as crucial as minimizing shoe mass to avoid negative effects on RE [11].

Midsole Features (Stack Height and Cushioning)

Significant advancements have been made in cushioned running shoe design since the Onitsuka Tiger was introduced as the first cushioned running shoe in 1964, establishing cushioning as a fundamental element of modern footwear (Figure 1) [18]. Although cushioning can reduce elastic energy storage and recovery, thereby contributing to the generally lower net efficiency observed in shod running, increased cushioning does not always lead to decreased metabolic cost. In some cases, this may be considerably beneficial for running performance [19-21].

▲ Onitsuka Tiger running shoe in 1964 ▲ Nike zoomX (Braking sub 2 in 2019)

Figure 1. First cushioned running shoe vs modern running shoe (Source: Onitsuka Co., Ltd & NIKE, Inc)

Advantages (Stack Height/Cushioning)

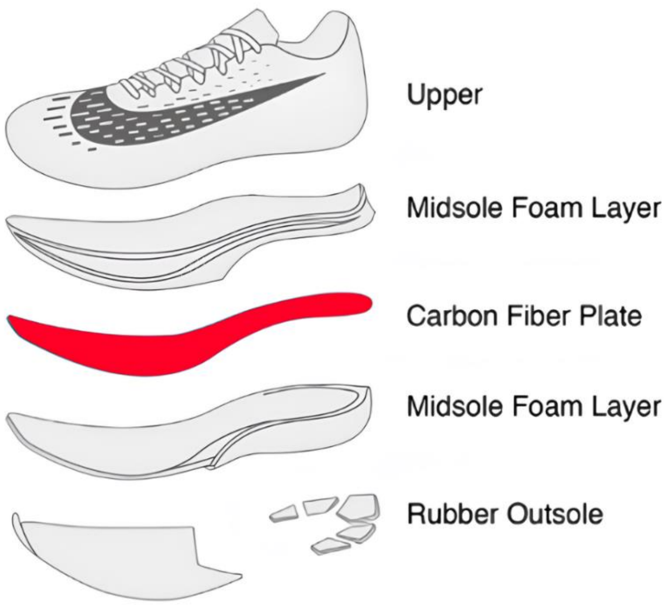

Figure 2. Shoe component (Source: NIKE, Inc)

Running shoes primarily consist of two components (Figure 2): the upper, which covers the foot, and the sole, which interacts with the ground [18]. The sole can be subdivided into the insole, midsole, and outsole, with research increasingly focusing on the midsole's role in cushioning [22]. The midsole is characterized by thickness and elasticity, including the materials used, each of which influences running performance (Figure 3) [18, 22].

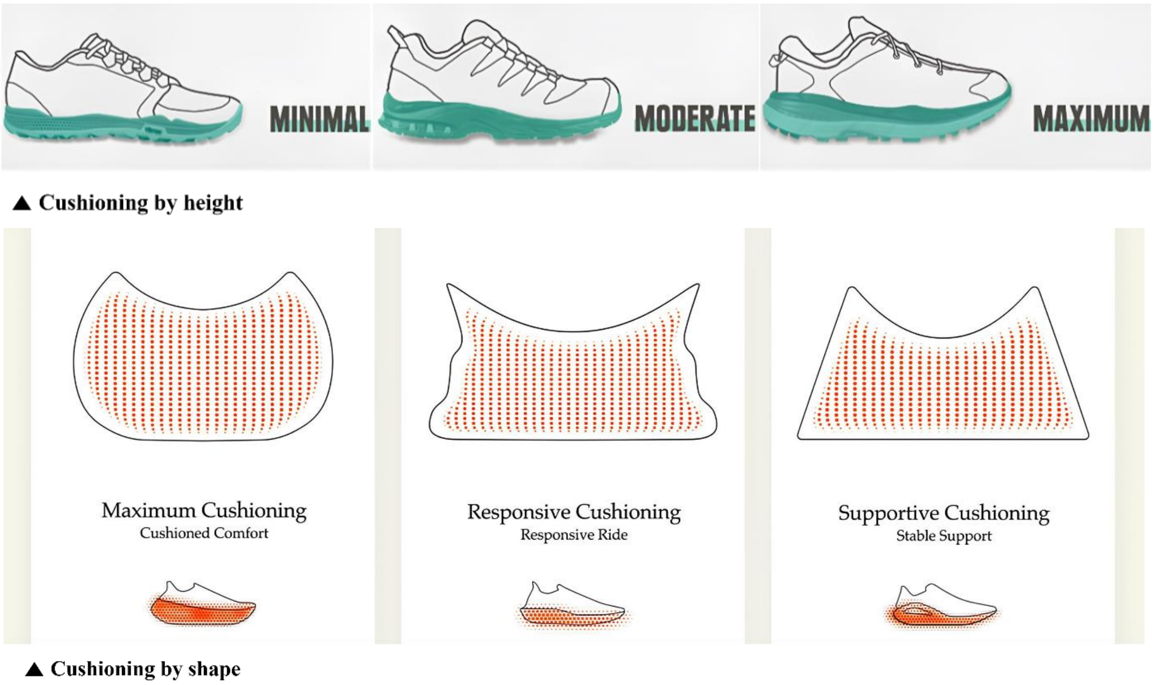

Figure 3. Types of cushioning (Source: Recreational Equipment, Inc & NIKE, Inc)

Thickness (stack height) (Figure 4): The thickness of the midsole, often referred to as stack height, influences ground contact time during a stride. A thicker midsole can extend ground contact time, affecting the ground reaction force-time curve and assisting in energy return timing [12]. Increased stack height can enhance athletes' effective limb length, potentially leading to longer strides during running [23]. Shoes with a greater stack height, particularly those incorporating carbon fiber or rigid plates, also exhibit increased curvature that can benefit RE [24].

Figure 4. Midsole stack height (Source: NIKE, Inc)

Elasticity (material) (Figure 5): Midsole elasticity pertains to the amount of energy the midsole returns with each step. The material used in its construction influences the cushioning and energy return properties of the midsole. Traditional materials include ethylene vinyl acetate and thermoplastic polyurethane, while recent advancements, such as polyether block amide, have introduced lighter, more resilient materials that enhance cushioning and energy return [23, 25, 26]. Research indicates that softer and more resilient midsoles can reduce oxygen consumption by up to 1% [27]. Conversely, poorly cushioned shoes may increase aerobic demand by approximately 2.8% compared to well-cushioned ones [28]. Furthermore, individuals wearing soft shoes have shown lower peak impact forces, longer times to peak force, and lower average loading rates of high-frequency signals than those wearing harder shoes, which might reduce the risk of injury [29].

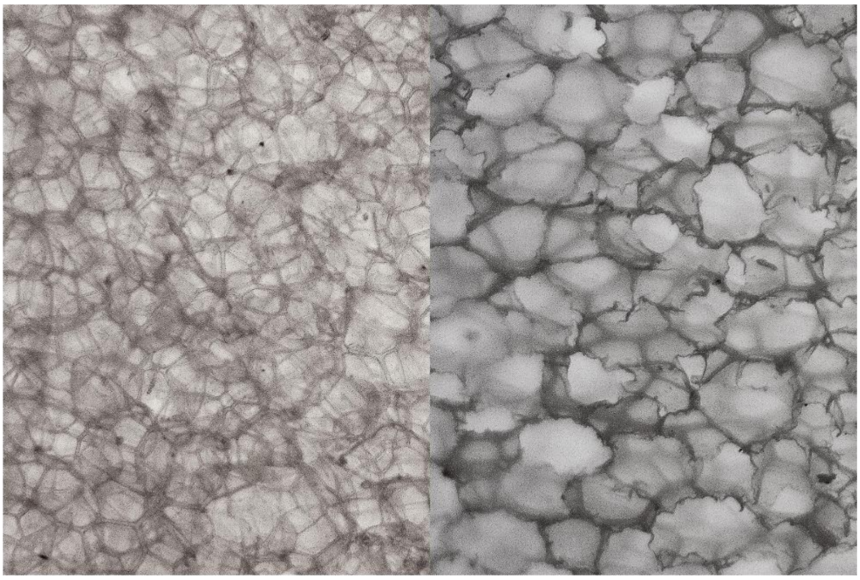

Figure 5. Midsole foam material characteristics (Source: RunRepeat.com)

Disadvantages (Stack Height/Cushioning)

Although midsole cushioning is crucial for absorbing impact, relieving joint pressure, and enhancing comfort, particularly on hard surfaces, some concerns have been expressed regarding the negative effects of excessive cushioning.

Increased body load: Although a thicker stack height can improve energy return, it may also increase the risk of injury by promoting a "heel strike" pattern that adds stress to the knee, potentially leading to knee pain or other injuries. Furthermore, increased joint load can contribute to overuse injuries, such as plantar fasciitis and stress fractures [29].

Impact on natural mechanics: The arch of the foot naturally absorbs shock during running, and foot muscles provide essential stability to maintain foot alignment during running. The prolonged use of highly cushioned footwear may lead to over-reliance on cushioning, causing muscle atrophy, weakness, and reduced activation, thus disrupting the function and natural mechanics of the foot and arch [19-21, 30, 31]. This may result in altered running patterns and an increased risk of injury, thereby increasing instability [32].

Decreased sensory feedback: Excessive cushioning can prevent the foot from receiving accurate sensory feedback from the ground and reduce the sensitivity of the plantar surface during running. This impairs proprioception, the body's ability to sense its own position and movement, which is essential for balance and coordination. This diminished sensory feedback can hinder the body's ability to adapt and respond to uneven terrain, potentially increasing the risk of falls and instability, and leading to injury [33].

Energy inefficiency: According to collision physics, excessive cushioning may increase the impact force on joints and tissues, leading to energy inefficiency. Shoes with excessive cushioning can distribute the body's propulsion forces throughout the shoe, leading to wasted power being transmitted between the foot and ground [10, 34]. Some studies have indicated that excessive cushioning can increase leg stiffness, which decreases perceived shock, but does not effectively reduce joint impact [10, 34]. Recent research suggests that optimal shoe cushioning characteristics (e.g., thickness) may vary depending on the runner's characteristics (e.g., body weight and composition). Specifically, several research findings show that greater cushioning can potentially provide more pronounced benefits for lighter runners [8, 35]. Thus, although cushioning enhances comfort and reduces perceived shock, excessive cushioning may compromise natural foot mechanics, reduce sensory feedback, and increase the risk of injury [10, 34].

Longitudinal Bending Stiffness (Carbon-Fiber Plate) (Figure 6)

Advantages (Performance)

High-performance running shoe development has been significantly advanced by the incorporation of embedded carbon fiber plates. These innovations have markedly affected athletics, leading to the breaking of multiple world records and prompting rule changes by the International Association of Athletics Federations [24].

The foot arch naturally functions as a spring, absorbing impact, while a stiff mid-foot plays a resilient energy-saving role, generating forward propulsion. Reduced arch stiffness diminishes energy return and, subsequently, running efficiency [36, 37]. Several studies have demonstrated that carbon fiber plates minimize energy loss by maintaining the foot's longitudinal bending stiffness, thereby limiting the angle and angular velocity of the metatarsophalangeal joint. Moreover, carbon plates have been linked to increased stride length and ground contact time, enhancing overall running efficiency and performance [38, 39].

Longitudinal bending stiffness, defined as the "resistance to bending around the mediolateral axis of the shoe," is an important factor in running footwear. Enhancing this stiffness reduces energy expenditure and improves RE by approximately 1–4%, as shown in experimental research [38, 40]. Carbon fiber plate effectiveness varies with factors such as location and shape, although most studies indicate that a bottom-loaded, full-length curved plate is the most effective. These plates have demonstrated their ability to significantly enhance marathon performance by increasing RE, thus enabling runners to cover greater distances within the same timeframe [41].

Figure 6. Types of carbon fiber plate (Source: FootStore.au & Engineering.com)

Disadvantages (Injury)

Although some studies suggest that enhancing the longitudinal stiffness of shoes with carbon plates may improve RE, others present conflicting results, indicating that increased longitudinal bending stiffness alters running biomechanics without consistently affecting RE [41-43]. Thus, the physiological relationship between biomechanical changes induced by carbon plates and RE improvements remains unclear.

How effectively carbon plates can influence RE varies based on factors such as the plate's location, length, stiffness, shape, and a runner's individual characteristics, including speed [9, 44]. Specifically, which runners would benefit most from these plates has not been thoroughly investigated, and concerns have been raised that inappropriate use of carbon plates may increase injury risk [45]. For example, carbon plates tend to promote a longer stride, which is one factor that increases running speed [46]. Consequently, this may increase the risk of injury for novice runners who do not have the physical conditioning and strength to adequately control these factors. Despite their perceived advantages and disadvantages, no clear consensus has been reached on the use of embedded carbon fiber plates in footwear [47].

Many athletes adopt carbon fiber plate shoes without fully considering the potential risks, and instead focus primarily on their benefits. Therefore, comprehensive investigations into the impact of these shoes on foot health and injury prevention are crucial. Furthermore, research on carbon plates is needed that involves runners at various levels and under diverse environments and conditions, rather than studies conducted on a limited population or using a single intervention [48].

Sports Fairness

Critics of high-performance running shoes argue that they compromise the integrity of sports. When Eliud Kipchoge broke the "Marathon Sub 2" (Figure 1) barrier in October 2019, which had often been regarded as "the last barrier of modern athletics," it ushered in a new era in advanced athletic footwear and sparked ongoing debates about "technical doping" [49]. "Technical doping" refers to "the use of technological aids to gain a competitive advantage." In this context, high-performance running shoes, such as those with carbon fiber plates, have been primarily considered as "technological aids." These shoes are believed to enhance athletic performance beyond natural human capabilities and limitations [50]. However, technological advancements, including those in footwear, can positively enhance performance levels and unlock athletes' potential. Therefore, shoe development raises concerns about fairness in competition and remains a crucial issue that must be continuously addressed.

CONCLUSION

Running, often regarded as "one of the purest and simplest sports on the Earth," has become increasingly complex [51]. The ongoing research and development of advanced footwear are widely considered key factors in enhancing speed and performance. High-performance running shoes can provide significant temporary performance improvements. However, concerns persist regarding the potential health and injury risks they may pose by possibly having negative effects on an individual's natural running posture or pattern. Although the development of high-performance running shoes is essential, proper training for running is arguably of greater importance. Untrained runners who use these advanced shoes may inadvertently increase their risk of injury. Comprehensive training and conditioning are crucial to fully harness the benefits of high-performance running shoes and achieve optimal synergy between the runner's footwear and body.

The goal of shoe development is to optimize each component for human use, ensuring harmony and balance. To create high-quality products, the footwear industry must carefully consider factors such as "performance," "injury prevention," and "sports fairness." Therefore, critically evaluating the role of high-performance running shoes is crucial. Furthermore, ensuring that these shoes enhance performance while minimizing the risk of injury to runners is essential.

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REFERENCES

1. Hoogkamer, W., Kipp, S., Spiering, B.A., Kram, R., Altered Running Economy Directly Translates to Altered Distance-running Performance, *Med Sci Sports Exerc*, **2016**, 48, 2175-80, https://doi.org/10.1249/MSS.0000000000001012.
2. Rodrigo-Carranza, V., Gonzalez-Mohino, F., Santos-

Concejero, J., Gonzalez-Rave, J.M., Influence of Shoe Mass on Performance and Running Economy in Trained Runners, *Front Physiol*, **2020**, 11, 573660, https://doi.org/10.3389/fphys.2020.573660.
3. Saunders, P.U., Pyne, D.B., Telford, R.D., Hawley, J.A., Factors Affecting Running Economy in Trained Distance Runners, *Sports Med*, **2004**, 34, 465-85, https://doi.org/10.2165/00007256-200434070-00005.
4. Chiu, H.T., Shiang, T.Y., Effects of Insoles and Additional Shock Absorption Foam on the Cushioning Properties of Sport Shoes, *J Appl Biomech*, **2007**, 23, 119-27, https://doi.org/10.1123/jab.23.2.119.
5. Marchena-Rodriguez, A., Ortega-Avila, A.B., Cervera-Garvi, P., Cabello-Manrique, D., Gijon-Nogueron, G., Review of Terms and Definitions Used in Descriptions of Running Shoes, *Int J Environ Res Public Health*, **2020**, 17, https://doi.org/10.3390/ijerph17103562.
6. Perkins, K.P., Hanney, W.J., Rothschild, C.E., The Risks and Benefits of Running Barefoot or in Minimalist Shoes: A Systematic Review, *Sports Health*, **2014**, 6, 475-80, https://doi.org/10.1177/1941738114546846.
7. Nigg, B.M., Baltich, J., Hoerzer, S., Enders, H., Running Shoes and Running Injuries: Mythbusting and a Proposal for Two New Paradigms: 'Preferred Movement Path' and 'Comfort Filter', *Br J Sports Med*, **2015**, 49, 1290-4, https://doi.org/10.1136/bjsports-2015-095054.
8. Theisen, D., Malisoux, L., Genin, J., Delattre, N., Seil, R., Urhausen, A., Influence of Midsole Hardness of Standard Cushioned Shoes on Running-related Injury Risk, *Br J Sports Med*, **2014**, 48, 371-6, https://doi.org/10.1136/bjsports-2013-092613.
9. Hébert-Losier, K., Pamment, M., Advancements in Running Shoe Technology and Their Effects on Running Economy and Performance - A Current Concepts Overview, *Sports Biomech*, **2023**, 22, 335-50, https://doi.org/10.1080/14763141.2022.2110512.
10. Fuller, J.T., Bellenger, C.R., Thewlis, D., Tsiros, M.D., Buckley, J.D., The Effect of Footwear on Running Performance and Running Economy in Distance Runners, *Sports Med*, **2015**, 45, 411-22, https://doi.org/10.1007/s40279-014-0283-6.
11. Franz, J.R., Wierzbinski, C.M., Kram, R., Metabolic Cost of Running Barefoot versus Shod: Is Lighter Better?, *Med Sci Sports Exerc*, **2012**, 44, 1519-25, https://doi.org/10.1249/MSS.0b013e3182514a88.
12. Nigg, B.M., Cigoja, S., Nigg, S.R., Effects of Running Shoe Construction on Performance in Long Distance Running, *Footwear Sci*, **2020**, 12, 133-8, https://doi.org/10.1080/19424280.2020.1778799.
13. Hall, J.P., Barton, C., Jones, P.R., Morrissey, D., The Biomechanical Differences between Barefoot and Shod Distance Running: A Systematic Review and Preliminary Meta-Analysis, *Sports Med*, **2013**, 43, 1335-53, https://doi.org/10.1007/s40279-013-0084-3.
14. Jahn, V.D., Correia, C.K., Dell'Antonio, E., Mochizuki, L., Ruschel, C., Biomechanics of Shod and Barefoot Running: A Literature Review, *Rev Bras Med Esporte*, **2020**, 26, 551-7, https://doi.org/10.1590/1517-869220202606219320.
15. Thompson, M.A., Gutmann, A., Seegmiller, J., McGowan, C.P., The Effect of Stride Length on the Dynamics of Barefoot and Shod Running, *J Biomech*, **2014**, 47, 2745-50, https://doi.org/10.1016/j.jbiomech.2014.04.043.
16. Murphy, K., Curry, E., Matzkin, E., Barefoot Running: Does It Prevent Injuries?, *Sports Med*, **2013**, 43, 1131-8, https://doi.org/10.1007/s40279-013-0093-2.
17. Williams, D.S., 3rd, Green, D.H., Wurzinger, B., Changes in Lower Extremity Movement and Power Absorption during Forefoot Striking and Barefoot Running, *Int J Sports Phys Ther*, **2012**, 7, 525-32.
18. Agresta, C., Giacomazzi, C., Harrast, M., Zendler, J., Running Injury Paradigms and Their Influence on Footwear Design Features and Runner Assessment Methods: A Focused Review to Advance Evidence-Based Practice for Running Medicine Clinicians, *Front Sports Act Living*, **2022**, 4, 815675, https://doi.org/10.3389/fspor.2022.815675.
19. Shorten, M.R., The Energetics of Running and Running Shoes, *J Biomech*, **1993**, 26, 41-51, https://doi.org/10.1016/0021-9290(93)90078-S.
20. Fuller, J.T., Bellenger, C.R., Thewlis, D., Tsiros, M.D., Buckley, J.D., The Effect of Footwear on Running Performance and Running Economy in Distance Runners, *Sports Med*, **2015**, 45, 411-22, https://doi.org/10.1007/s40279-014-0283-6.
21. Cochrum, R.G., Connors, R.T., Coons, J.M., Fuller, D.K., Morgan, D.W., Caputo, J.L., Comparison of Running Economy Values While Wearing No Shoes, Minimal Shoes, and Normal Running Shoes, *J Strength Cond Res*, **2017**, 31, 595-601, https://doi.org/10.1519/JSC.0000000000000892.
22. Hoitz, F., Mohr, M., Asmussen, M., Lam, W.-K., Nigg, S., Nigg, B., The Effects of Systematically Altered Footwear Features on Biomechanics, Injury, Performance, and Preference in Runners of Different Skill Level: A Systematic Review, *Footwear Sci*, **2020**, 12, 193-215, https://doi.org/10.1080/19424280.2020.1773936.
23. Burns, G.T., Tam, N., Is It the Shoes? A Simple Proposal for Regulating Footwear in Road Running, *Br J Sports Med*, **2020**, 54, 439-40, https://doi.org/10.1136/bjsports-2018-100480.
24. Farina, E.M., Haigh, D., Luo, G., Creating Footwear for Performance Running, *Science*, **2019**, 10, 179-87.
25. Rodrigo-Carranza, V., Hoogkamer, W., González-Ravé, J.M., Horta-Muñoz, S., Serna-Moreno, M.D., Romero-Gutierrez, A., González-Mohíno, F., Influence of Different Midsole Foam in Advanced

Footwear Technology Use on Running Economy and Biomechanics in Trained Runners, *Scand J Med Sci Spor*, **2024**, 34, https://doi.org/10.1111/sms.14526.
26. Ou, H.H., Johnson, S., Boosting Energy Return Using 3D Printed Midsoles Designed With Compliant Constant Force Mechanisms, *J Mech Design*, **2024**, 146, https://doi.org/10.1115/1.4064164.
27. Frederick, E., Physiological and Ergonomics Factors in Running Shoe Design, *Appl Ergon*, **1984**, 15, 281-7, https://doi.org/10.1016/0003-6870(84)90199-6.
28. Worobets, J., Wannop, J.W., Tomaras, E., Stefanyshyn, D., Softer and more Resilient Running Shoe Cushioning Properties Enhance Running Economy, *Footwear Sci*, **2014**, 6, 147-53, https://doi.org/10.1080/19424280.2014.918184.
29. Malisoux, L., Gette, P., Backes, A., Delattre, N., Cabri, J., Theisen, D., Relevance of Frequency-Domain Analyses to Relate Shoe Cushioning, Ground Impact Forces and Running Injury Risk: A Secondary Analysis of a Randomized Trial with 800+ Recreational Runners, *Front Sports Act Living*, **2021**, 3, 744658, https://doi.org/10.3389/fspor.2021.744658.
30. Butler, R.J., Davis, I.S., Hamill, J., Interaction of Arch Type and Footwear on Running Mechanics, *Am J Sport Med*, **2006**, 34, 1998-2005, https://doi.org/10.1177/0363546506290401.
31. Miller, E.E., Whitcome, K.K., Lieberman, D.E., Norton, H.L., Dyer, R.E., The Effect of Minimal Shoes on Arch Structure and Intrinsic Foot Muscle Strength, *J Sport Health Sci*, **2014**, 3, 74-85, https://doi.org/10.1016/j.jshs.2014.03.011.
32. Perl, D.P., Daoud, A.I., Lieberman, D.E., Effects of Footwear and Strike Type on Running Economy, *Med Sci Sports Exerc*, **2012**, 44, 1335-43, https://doi.org/10.1249/MSS.0b013e318247989e.
33. Hatton, A.L., Rome, K., Dixon, J., Martin, D.J., McKeon, P.O., Footwear Interventions: A Review of Their Sensorimotor and Mechanical Effects on Balance Performance and Gait in Older Adults, *J Am Podiatr Med Assoc*, **2013**, 103, 516-33, https://doi.org/10.7547/1030516.
34. Borgia, B., Becker, J., Lower Extremity Stiffness when Running in Minimalist, Traditional, and Ultra-cushioning Shoes, *Footwear Sci*, **2019**, 11, 45-54, https://doi.org/10.1080/19424280.2018.1555860.
35. Malisoux, L., Delattre, N., Urhausen, A., Theisen, D., Shoe Cushioning Influences the Running Injury Risk According to Body Mass: A Randomized Controlled Trial Involving 848 Recreational Runners, *Am J Sport Med*, **2020**, 48, 473-80, https://doi.org/10.1177/0363546519892578.
36. Venkadesan, M., Yawar, A., Eng, C.M., Dias, M.A., Singh, D.K., Tommasini, S.M., Haims, A.H., Bandi, M.M., Mandre, S., Stiffness of the Human Foot and Evolution of the Transverse Arch, *Nature*, **2020**, 579, 97-100, https://doi.org/10.1038/s41586-020-2053-y.
37. Ker, R., Bennett, M., Bibby, S., Kester, R., Alexander, R.M., The Spring in the Arch of the Human Foot, *Nature*, **1987**, 325, 147-9, https://doi.org/10.1038/325147a0.
38. Ortega, J.A., Healey, L.A., Swinnen, W., Hoogkamer, W., Energetics and Biomechanics of Running Footwear with Increased Longitudinal Bending Stiffness: A Narrative Review, *Sports Med*, **2021**, 51, 873-94, https://doi.org/10.1007/s40279-020-01406-5.
39. Willwacher, S., König, M., Potthast, W., Brüggemann, G.P., Does Specific Footwear Facilitate Energy Storage and Return at the Metatarsophalangeal Joint in Running?, *J Appl Biomech*, **2013**, 29, 583-92, https://doi.org/10.1123/jab.29.5.583.
40. Day, E.M., Hahn, M.E., Does Running Speed Affect the Response of Joint Level Mechanics in Non-rearfoot Strike Runners to Footwear of Varying Longitudinal Bending Stiffness?, *Gait Posture*, **2021**, 84, 187-91, https://doi.org/10.1016/j.gaitpost.2020.11.029.
41. Rodrigo-Carranza, V., Gonzalez-Mohino, F., Santos-Concejero, J., Gonzalez-Rave, J.M., The Effects of Footwear Midsole Longitudinal Bending Stiffness on Running Economy and Ground Contact Biomechanics: A Systematic Review and Meta-analysis, *Eur J Sport Sci*, **2022**, 22, 1508-21, https://doi.org/10.1080/17461391.2021.1955014.
42. Healey, L.A., Hoogkamer, W., Longitudinal Bending Stiffness Does Not Affect Running Economy in Nike Vaporfly Shoes, *J Sport Health Sci*, **2022**, 11, 285-92, https://doi.org/10.1016/j.jshs.2021.07.002.
43. Beck, O.N., Golyski, P.R., Sawicki, G.S., Adding Carbon Fiber to Shoe Soles May Not Improve Running Economy: A Muscle-Level Explanation, *Sci Rep*, **2020**, 10, 17154, https://doi.org/10.1038/s41598-020-74097-7.
44. Joubert, D.P., Jones, G.P., A Comparison of Running Economy across Seven Carbon-Plated Racing Shoes, *Med Sci Sport Exer*, **2022**, 54, 610-1, https://doi.org/10.1249/01.mss.0000882736.47396.e1.
45. Tenforde, A., Hoenig, T., Saxena, A., Hollander, K., Bone Stress Injuries in Runners Using Carbon Fiber Plate Footwear, *Sports Med*, **2023**, 53, 1499-505, https://doi.org/10.1007/s40279-023-01818-z.
46. Reynolds, S.R., Hastert, L.M., Nodland, N.M., Matthews, I.R., Wilkins, B.W., Gidley, A.D., The Effect of Carbon Fiber Plated Shoes on Submaximal Running Mechanics in Non-elite Runners, *Footwear Sci*, **2023**, 15, 171-7, https://doi.org/10.1080/19424280.2023.2218316.
47. Day, E., Hahn, M., Optimal Footwear Longitudinal Bending Stiffness to Improve Running Economy is Speed Dependent, *Footwear Sci*, **2020**, 12, 1, 3–13, https://doi.org/10.1080/19424280.2019.1696897.
48. Nagahara, R., Kanehisa, H., Fukunaga, T., Influence of Shoe Sole Bending Stiffness on Sprinting

Performance, *J Sports Med Phys Fitness*, **2017**, 58, 1735-40, https://doi.org/10.23736/S0022-4707.17.07834-3.
49. Ruiz-Alias, S.A., Jaén-Carrillo, D., Roche-Seruendo, L.E., Pérez-Castilla, A., Soto-Hermoso, V.M., García-Pinillos, F., A Review of the Potential Effects of the World Athletics Stack Height Regulation on the Footwear Function and Running Performance, *Appl Sci*, **2023**, 13, 11721, https://doi.org/10.3390/app132111721.
50. Willwacher, S., Weir, G., The Future of Footwear Biomechanics Research, *Footwear Sci*, **2023**, 15, 145-54, https://doi.org/10.1080/19424280.2023.2199011.
51. Hewitt, P., *In the Running: Stories of Extraordinary Runners from Around the World*, Hachette UK, **2016**.