Advancements in Running Shoe Technology: The Impact of Carbon Fiber Plates

Brief Review

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Abstract

Recent advancements in running shoe technology have led to increased utilization of carbon fiber plates (CFP) in running shoe construction. This brief review aims to evaluate the current literature to examine the relationship between CFP design and running performance, running economy, biomechanics and risk of injury. A literature search was completed, and ten relevant peer-reviewed articles published between 2020 and 2024 were reviewed. CFP conditions were found to alter lower extremity biomechanics, including changes in plantar pressure distribution and muscle-tendon unit function. Several studies reported no significant improvements in metabolic cost or performance despite these biomechanical changes. A clear relationship between the CFP midsoles and improvements in running economy and performance could not be established. Further research is necessary to determine how variations in CFP design interact with other shoe features to influence running economy, biomechanics, performance and injury risk.

Key Words: carbon fiber plates, longitudinal bending stiffness, midsole, running performance, running economy, biomechanics

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Introduction

In recent years the U.S. has seen a significant increase in running participation,[1] and with this, an increased interest in understanding the factors that influence running performance. One such factor is shoe anatomy, and the role footwear plays in the running experience. Advancements in shoe construction and technology have led to the incorporation of carbon fiber plates (CFPs) into the foam midsole of the shoe. Design considerations include the shape and length of the CFPs, the stack height of the shoe, the foam material, and the shoe mass. Each of these has demonstrated influence on biomechanical and physiological factors affecting running performance.[2]

Innovations in shoe design, including the utilization of CFP's, stemmed from the desire to increase longitudinal bending stiffness (LBS) in the hopes of improving running economy and running performance. In 2006 Roy et al. concluded that an increase in LBS led to improved running economy after finding a 1% increase in metabolic energy savings in a shoe modified with a CFP compared to the control shoe.[3] While it was noted that the underlying mechanisms for this savings required further research the modifications to running shoes began shortly thereafter. The evidence suggesting that increasing LBS improved running performance likely led to the first commercially available shoe featuring a CFP midsole, Nike Vaporfly 4% released in 2017.[4] The Vaporfly construction incorporated a full length curved CFP within a thick midsole made of Pebax, a lightweight compliant and resilient foam.[4] Since the initial introduction of CFP's in commercially available running shoes, brands have marketed shoes with curved, flat, full length and segmented CFPs.

With the evolution of running shoe design it remains necessary to investigate the impact of footplate variations on running economy, biomechanics, performance and injury risk.[5-8] The novelty of these designs means there is minimal evidence and a lack of consensus on the significance of the CFP midsole in relation to running economy and performance. These modern running shoes are being marketed with the promise of improving in running performance. The aim of this review is to examine the literature regarding CFP's and their relationship to running performance. This review explores the impact of CFPs on biomechanics, running gait parameters, and running economy.

Scientific Methods

Searches were conducted using the discovery search function of the Slippery Rock University Bailey Library website, providing access to multiple databases. Publications were limited to studies from 2020-2024, written in English, and focused on human subjects. Key words for search included: carbon fiber footplates, running economy, running biomechanics and footwear, shoe anatomy and running performance, carbon fiber footplates and injury risk. Studies were included if they examined the effects of CFP's on running performance, biomechanics, or physiologic outcomes. To ensure study quality, only primary research articles reporting measurable outcome data were included. The selection process involved an initial screening of titles and abstracts, followed by full-text review. All articles were selected and reviewed by the primary investigator.

A total of fourteen studies met the initial selection criteria. Inclusion criteria were identified as: published in a peer reviewed journal and included the independent variable condition of CFP midsole, or use of carbon fiber to modify biomechanics of the foot and ankle. Exclusion criteria included abstracts, conference posters, and unpublished theses. Based on the limited body of literature investigating this topic in the last 5 years, all studies meeting the initial selection criteria were reviewed. Four articles were excluded; one because the carbon fiber plate was an orthotic and not a shoe modification, one because it was an editorial, one was a dissertation study focused on older runners, and one was a current opinion on bone stress injuries related to CFPs.[9-12]

Ten articles were included for analysis. All ten articles investigated the impact of modifications to (LBS) by way of CFPs. Most experimental studies included a small sample size of male runners, and outcomes were taken during treadmill running. All included for review investigated one or more of the following: running economy, gait parameters, and/or biomechanical implications of carbon fiber plate midsoles.

Results

Six of the studies included curved full-length CFP's, one study included a segmented CFP, and two included CFP's of varying thicknesses. The studies consisted of randomized control trials, a systematic review, a case study, and a computational simulation. Three articles found no change in running economy or performance, three found biomechanical effects without linking them to running economy or performance outcomes, one article found improvements in mechanical energy compensation and three found improvements in running economy or metabolic cost.

Carbon Foot Plate Design and Biomechanics

The biomechanical effects of CFPs vary based on their design. Six of the ten studies included shoes with curved footplates like the Nike Vaporfly 4%, or specifically compared the curved footplate to a flat, or segmented plate. In the case of the segmented CFP compared to the full CFP, the segmented CFP induced biomechanical changes, including increased metatarsophalangeal joint (MTPJ) plantarflexion velocity and knee joint work, but did not significantly affect running performance or LBS in the shoe.[13] Fu et al. found that increasing LBS reduced energy loss at the MTPJ, via an increased plantarflexion moment.[13] The segmented CFPs were found to reduce midsole pressure by 29.4% without affecting energy return or stiffness.[13] Thicker, low-loaded, curved CFPs reduced peak forefoot plantar pressure and redistributed loads more evenly.[14] The curved CFP reduced the peak forefoot plantar pressure compared to the flat CFP by a range of 5.51%-12.62%.[14] Miyazaki et al. found that curved CFPs improved mechanical efficiency at the ankle joint by enhancing energy transfer and reducing energy expenditure.[15] In the CFP condition the concentric mechanical energy expenditure at the ankle joint was significantly reduced compared to the non CFP condition, and the Curved CFP's decreased ankle plantarflexion torque and velocity during part of the stance phase of running gait.[15] Healey et al., compared an intact Nike Vaporfly 4% to a Nike Vaporfly 4% with 6 cuts medio-lateral cuts through the CFP and observed a 1.19% shorter contact time, higher MTPJ dorsiflexion angle, angular velocity, and negative power in the cut shoe compared to the intact shoe which were all statistically significant.[16] Song et al. investigated CFP's of 1mm, 2mm, and 3mm thickness placed at different levels within the midsole (low, medium, and high).[17] Peak plantar pressure under the forefoot decreased by up to 31.91% in the 3 mm low loaded condition compared to the no CFP condition, and peak metatarsal stress was increased by up to 12.91% in the high-loaded CFP condition.[17]

Carbon Foot Plates and Running Performance

Of the ten articles reviewed three concluded CFPs had no significant effect on running economy, and one study concluded that CFPs improved running economy.[7,8,13,16] The systematic review performed by Rodrigo et al. reported that increased LBS improved RE by 2.22% compared to control conditions and led to significant increases in stride length (29%) and contact time (17%).[7] Improvements in RE were found to be greater at increased speeds ranging from 1.48% improvement at slow speeds to 3.45% improvement at high speeds.[7] Stiffness was found to have a ceiling of positive impact with a 100-240% increase in stiffness improving RE by 2.91%, but no greater improvement after 240% stiffness increase.[7] Metabolic cost was assessed by Hunter et al. and found that the CFP shoe provided a 1.5% reduction in metabolic cost and this was not significantly different across uphill, level and downhill running grades.[4] Beck et al. compared three full length CFPs with thicknesses of 0.8 mm, 1.6 mm, and 3.2 mm.[8] There was no significant difference in ground reaction forces, joint kinematics and kinetics, or soleus muscle-tendon fascicle dynamics, or gross aerobic power.[8] Despite the biomechanical impact found by Healey et al. there was no significant difference in the running economy of the cut versus intact Nike Vaporfly 4%.[16] Cigoja et al. suggest that increasing LBS alters the compliance of the foot shoe interface and has implications in long distance running.[5] The CFP condition resulted in reduced arch deformation, reduced plantar muscle-tendon unit (pMTU) shortening, reduced shortening velocities of the pMTU and shank muscle-tendon unit (sMTU), reduced positive work and increased negative work of the pMTU, and reduced net work of the sMTU. Kiesewetter et al. looked at physiological and biomechanical differences finding no significant differences in physiological parameters such as oxygen consumption, running economy, or heart rate.[2]

Table 1. Previous research overview.

Author	Title	Year	Type of Footplate	Study Design	Theme	Outcomes
Fu et al.[13]	Effect of the Construction of Carbon Fiber Plate Insert to Midsole on Running Performance[13]	2021	Segmented vs Full	Randomized, repeated measures, within-subjects design. 15 male subjects. Fast and slow running with segmented CFP and full CFP midsole. 15 male rearfoot strike runners	Segmented CFPs did not significantly affect running performance or LBS compared to full CFP.	Forefoot flexion and bending simulation show no effect between segmented CFP and full CFP. Segmented and full CFPs showed greater ground reaction forces, ankle, knee and hip range of motion, MTPJ and shoes slap velocity, and positive and negative work in fast speed ($p<0.05$). Segmented CFP induced more MTPJ dorsi-plantar velocity from 18%-26% ($p<0.05$)
Rodrigo-Carranza et al.[7]	The effects of footwear midsole longitudinal bending stiffness on running economy and	2022	Full vs forefoot, and curved vs flat	Systematic review and meta-analysis of crossover experimental studies that	Increased LBS improved RE. Increased RE was accompanied by increased	Increased LBS demonstrated 2.22% improvement in RE compared to control

	ground contact biomechanics: A systematic review and meta-analysis[7]			examined the effects of LBS in running shoes on running economy and biomechanics.	contact time and stride length. Plate type, length of plate, shoe mass, degree of LBS and running speed influenced RE.	($P<0.001$). Increased LBS led to increased stride length ($p=0.003$) and contact time ($p=0.02$). Curved plates showed 3.45% improvement in RE compared to control ($p<0.001$). Flat plate did not improve RE.
Song et al.[17]	The Influence of running shoe with different carbon-fiber plate designs on internal foot biomechanics A pilot computational analysis[17]	2023	1mm, 2mm and 3mm full	Computational simulation pilot study.	Low-loaded thicker plates reduce pressure and strain without increasing stress.	CFP thickness of 3mm decreased peak plantar pressure at the impact peak instant by up to 31.91% compared to no CFP. High and middle loaded 1 mm CFP increased peak plantar pressure compared to no CFP
Healey et al.[16]	Longitudinal bending stiffness does not affect running economy in Nike Vaporfly Shoes[16]	2021	Intact Nike Vaporfly 4% curved CFP vs cut Nike Vaporfly 4% curved CFP	Randomized, within-subjects crossover.	No significant difference in RE between the intact CFP and cut CFP in the Nike Vaporfly 4%. In the cut version contact time was shorter and MTPJ dorsiflexion and negative power were increased.	No significant difference in RE between intact and cut CFP ($p=0.306$) Significantly shorter contact time in cut CFP ($p<0.001$) Greater MTPJ dorsiflexion ($p=0.013$) and peak MTPJ dorsiflexion ($p=0.002$) in cut CFP Higher MTPJ angular velocity in cut CFP ($p=0.001$) Increased negative MTPJ power ($p<0.001$), and negative MTPJ work ($p=0.008$) in cut CFP.
Miyazaki et al.[15]	Curved carbon plates inside running shoes modified foot and	2024	Curved full CFP	Randomized, repeated-measures	Curved CFP improved mechanical	Concentric MEC at the ankle joint

	shank angular velocity improving mechanical efficiency at the ankle joint[15]				efficiency at the ankle joint	higher in CFP shoe (p=0.004) Concentric MEE at the ankle joint lower in CFP (p=0.042) No difference in step variables (p=0.163)
Hunter et al.[4]	Energetics and Biomechanics of Uphill, Downhill and Level Running in Highly-Cushioned Carbon Fiber Midsole Plated Shoes[4]	2022	Sacuony Endorphin Pro full curved CFP	Randomized, controlled, crossover	Endorphin Pro shoe reduced metabolic cost compared to no CFP. Metabolic benefit was similar across uphill, level, and downhill running conditions.	CFP shoe reduced metabolic cost compared to non CFP shoe (p=0.004). Metabolic benefit of CFP shoe similar across uphill, level and downhill conditions (p=0.788) Stride length, peak vertical force, ground contact time, and flight time did not predict metabolic benefit of CFP shoe across running grades (p=0.12)
Song et al[14]	Curved carbon-plated show may further reduce forefoot loads compared to flat plate during running[14]	2024	Curved vs flat CFP	Observational, single-case study	Curved CFP reduced peak plantar pressure and redistributes load more evenly	Peak forefoot plantar pressure reduced by 5.51%-12.62% in curved compared to flat CFP Negligible impact on 2nd and 3rd metatarsal bone stress Curved CFP enabled more uniform force transmission by reducing contact force on medial columns of foot
Beck et al[8]	Adding carbon fiber to shoe soles may not improve running economy: a muscle-level explanation[8]	2020	0.8, 1.6, and 3.2 mm full CFP	Randomized, within-subjects crossover	Adding a CFP to increase LBS does not significantly affect running biomechanics or economy.	Increased LBS was associated with longer ground contact time (p=0.048) LBS did not affect hip, knee,

						or ankle angles or moments. LBS did not affect muscle-tendon dynamics. LBS did not affect gross aerobic power (p=0.458)
Cigoja et al.[5]	The Effects of Increased Midsole Bending Stiffness of Sport Shoes on Muscle-Tendon Unit Shortening and Shortening Velocity: a Randomised Crossover Trial in Recreational Male Runners[5]	2020	Full length CFP	Randomized, crossover trial-13 male runners	Increasing LBS with addition of CFP reduced arch deformation, plantar muscle-tendon unit shortening, and shortening velocities of the plantar and shank muscle-tendon units.	Reduced arch deformation (p≤0.05) Reduced pMTU shortening (p≤0.01) Reduced shortening velocities of pMTU (p≤0.01) and sMTU (p≤0.001) Reduced positive work (p≤0.001) and increased negative work (p≤0.001) by pMTU Reduced net work by sMTU (p<0.05)
Kiesewetter et al.[2]	Do Carbon-Plated Running Shoes with Different Characteristics Influence Physiological and Biomechanical Variables during a a 10 km Treadmill Run?[2]	2022	Puma Fast-FWD-curved full length CFP, Puma Fast-R, full length split between heel and forefoot, Nike Vaporfly Next%-curved full length CFP	Randomized, repeated-measures crossover	Biomechanical parameters were altered in response to shoe type, but no differences in physiological parameters including RE.	Peak angular velocity was different in shoe 1 compared to shoe 3. (p=0.004) Peak eversion velocity significantly different in all shoes. (p<0.001) Heel strike angle less in shoe 1 compared to shoes 2 and 3. (P<0.001) No differences in peak tibial acceleration

Definitions:
CFP, carbon fiber plate
LBS, longitudinal bending stiffness
MTPJ, metatarsophalangeal joint
GRF, ground reaction force
pMTU, plantar muscle tendon unit
sMTU, shank muscle tendon unit

Discussion

The results presented in this review suggest that CFP midsoles provide potential for improved running performance, but there is no consensus. Although previous research links increased LBS to improved RE, this review finds inconsistent evidence supporting that relationship. Among the 10 articles reviewed, the majority suggest that CFPs do not significantly impact RE.[2,8] Healey et al. suggests that energy savings seen in CFP conditions may be more related to a combination of foam, geometry and factors beyond CFP design.[16] CFPs appear to optimize lower extremity mechanics, improve energy return, and reduce muscular contraction costs.[2,4,5,14-17] The biomechanical effects of CFPs are influenced by the design of the plate, and findings suggest that curved CFPs provide the greatest biomechanical and energy savings benefit. Curved plates were found to significantly improve load distribution and reduce plantar pressure.[13,15] The results of this brief review suggest that there are biomechanical influences of CFPs, and some studies suggest improvement in running economy and performance. However, it remains unclear if these improvements are due to CFP design or to the synergistic interaction of the CFP with the other shoe anatomy. Considerations include midsole foam type, stack height, heel to toe drop, and rocker geometry. Therefore, it cannot be concluded that CFPs alone account for the observed changes in biomechanics and running performance outcomes.

Potential Injury Risks and Clinical Considerations

While research highlights many benefits of increasing LBS through CFPs, their role in injury remains unclear. Few studies have examined how increased LBS affects injury risk, highlighting a key gap in the literature. Cigoja et al. found potential for decreased risk of injury through reduced arch deformation, muscle tendon unit shortening, and shortening velocities in the CFP condition[5]. The design and location of the CFP in the shoe must be considered, as Song et al. demonstrated a 1mm CFP in the high and middle loading positions increased peak plantar pressure.[17] When forces are being redistributed, and biomechanics are altered it is reasonable to be concerned about the implications of these shoe modifications. Tenforde et al. expressed concern for bone stress injuries, specifically of the navicular bone, when these shoes are used excessively or without adequate caution.[12] This emphasizes the importance of individual variability in injury susceptibility. Running overuse injuries are often a result of poor load management, such as increasing training volume without adequate time for tissue adaptation or changing a variable without reducing training intensity. Individual variability including intrinsic motivation, anthropometrics, running history, and running environment all play a role in injury risk and CFPs cannot compensate for these individual differences. Conversely studies investigating the biomechanical advantages of CFPs suggest that curved CFPs reduce peak forefoot plantar pressure and redistribute loads more evenly without increasing metatarsal stress, potentially minimizing the risk of overuse injuries.[17] Adaptations to shoe design are often biomechanical in nature, with runners adjusting their foot strike or joint mechanics to accommodate the shoe. While these biomechanical adaptations are important, subjective comfort and individual perception of stiffness remain essential. Perception of comfort and the individual response to stiffness varies and changes in stiffness or shoe structure do not always correlate with improved subjective comfort.[2] Continued research on long-term use of shoes with CFP midsoles, taking into account individual injury susceptibility and subjective response, will be essential to understanding injury risks associated with CFPs in modern running shoes.

Limitations

There are several limitations to note. Several studies relied on small sample sizes, and male only participants which limits the generalizability of results. Many of the studies used treadmill running conditions, and one was a computational simulation which cannot accurately replicate outdoor running dynamics. The lack of research to determine a universally accepted influence of CFP design on running biomechanics, economy and performance make it difficult to determine specific effects of CFPs. Most of the studies included did not control for shoe factors such as foam, mass, stack height etc. and prolonged use of CFP running shoes was not included. These factors are important for real world application and will foster necessary research to inform running shoe design.

Conclusions

The introduction of CFPs in running shoe design has aimed to improve running performance, particularly by increasing LBS and optimizing lower extremity mechanics. While evidence suggests that CFP shoes improve energy return, reduced forefoot peak pressures, and reduced muscular contraction costs, their overall impact on performance and injury risk remains inconclusive. Research indicates that the benefits of CFP integration into the midsole depends on various factors, including plate design, location, foam composition, and individual biomechanics. Although some studies demonstrate improvements in running economy, most in this review found no significant advantage. Additionally, potential injury risks associated with CFPs are not yet well understood, supporting the need for future research into long-term effects and biomechanical adaptations. This review emphasizes the need for controlled trials to aid in more conclusive results outlining the benefits and risks of CFP midsoles. Continued research will be crucial in guiding shoe manufactures, coaches, athletes, and healthcare professionals toward optimizing performance while minimizing injury risk.

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References

1. Willwacher S, Kurz M, Robbin J, et al. Running-Related Biomechanical Risk Factors for Overuse Injuries in Distance Runners: A Systematic Review Considering Injury Specificity and the Potentials for Future Research. Article. *Sports Medicine*. 2022;52(8):1863-1877. doi:10.1007/s40279-022-01666-3
2. Kiesewetter P, Bräuer S, Haase R, Nitzsche N, Mitschke C, Milani TL. Do Carbon-Plated Running Shoes with Different Characteristics Influence Physiological and Biomechanical Variables during a 10 km Treadmill Run? *Applied sciences*. 2022;12(15):7949. doi:10.3390/app12157949
3. Roy J-PR, Stefanyshyn DJ. Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG. *Med Sci Sports Exerc*. 2006;38(3):562-569. doi:10.1249/01.mss.0000193562.22001.e8
4. Hunter I, Bradshaw C, McLeod A, Ward J, Standifird T. Energetics and Biomechanics of Uphill, Downhill and Level Running in Highly-Cushioned Carbon Fiber Midsole Plated Shoes. *J Sports Sci Med*. 2022;21(1):127-130. doi:10.52082/jssm.2022.127
5. Cigoja S, Asmussen MJ, Firminger CR, Fletcher JR, Edwards WB, Nigg BM. The Effects of Increased Midsole Bending Stiffness of Sport Shoes on Muscle-Tendon Unit Shortening and Shortening Velocity: a Randomised Crossover Trial in Recreational Male Runners. *Sports Med - Open*. 2020;6(1)doi:10.1186/s40798-020-0241-9
6. Ma R, Lam W-K, Ding R, Yang F, Qu F. Effects of Shoe Midfoot Bending Stiffness on Multi-Segment Foot Kinematics and Ground Reaction Force during Heel-Toe Running. *Bioengineering*. 2022;9(10). doi:10.3390/bioengineering9100520
7. Rodrigo-Carranza V, González-Mohíno F, Santos-Concejero J, González-Ravé JM. The effects of footwear midsole longitudinal bending stiffness on running economy and ground contact biomechanics: A systematic review and meta-analysis. *European journal of sport science*. 2022;22(10):1508-1521. doi:10.1080/17461391.2021.1955014
8. Beck ON, Golyski PR, Sawicki GS. Adding carbon fiber to shoe soles may not improve running economy: a muscle-level explanation. *Sci Rep*. 2020;10(1):17154-17154. doi:10.1038/s41598-020-74097-7
9. Henderson A, Hulcher T, Koller C, Bruening D, Arch E. Deformable foot orthoses redistribute power from the ankle to the distal foot during walking. *J Biomech*. 2021;128:110728-110728. doi:10.1016/j.jbiomech.2021.110728
10. Nigg BM, Cigoja S, Nigg SR. Teeter-totter effect: a new mechanism to understand shoe-related improvements in long-distance running. *Br J Sports Med*. May 2021;55(9):462-463. doi:10.1136/bjsports-2020-102550
11. Beltran RT, Powell DW, Greenwood D, Paquette MR. The Influence of Footwear Longitudinal Bending Stiffness on Running Economy and Biomechanics in Older Runners. *Research quarterly for exercise and sport*. 2023;94(4):1062-1072. doi:10.1080/02701367.2022.2114589
12. Tenforde A, Hoenig T, Saxena A, Hollander K. Bone Stress Injuries in Runners Using Carbon Fiber Plate Footwear. *Sports Med*. Aug 2023;53(8):1499-1505. doi:10.1007/s40279-023-01818-z
13. Fu F, Levadnyi I, Wang J, et al. Effect of the Construction of Carbon Fiber Plate Insert to Midsole on Running Performance. *Materials*. 2021;14(18):5156. doi:10.3390/ma14185156
14. Song Y, Cen X, Sun D, et al. Curved carbon-plated shoe may further reduce forefoot loads compared to flat plate during running. *Sci Rep*. 2024;14(1):13215-8. doi:10.1038/s41598-024-64177-3
15. Miyazaki T, Aimi T, Yamada Y, Nakamura Y. Curved carbon plates inside running shoes modified foot and shank angular velocity improving mechanical efficiency at the ankle joint. *J Biomech*. Jul 2024;172:112224. doi:10.1016/j.jbiomech.2024.112224
16. Healey LA, Hoogkamer W. Longitudinal bending stiffness does not affect running economy in Nike Vaporfly Shoes. *J Sport Health Sci*. 2022;11(3):285-292. doi:10.1016/j.jshs.2021.07.002
17. Song Y, Cen X, Chen H, et al. The influence of running shoe with different carbon-fiber plate designs on internal foot mechanics: A pilot computational analysis. *J Biomech*. 2023;153:111597-111597. doi:10.1016/j.jbiomech.2023.111597