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Brief Report

Influence of Carbon-fiber Shoes on Outdoor Running Biomechanics as Assessed with Wearable Sensors

Megan Spencer*[1], Nathan Goldcamp*[1], Jean L. McCrory‡[2]

[1]Department of Chemical and Biomedical Engineering, [2]Department of Health Professions, West Virginia University, Morgantown, WV, USA

*Denotes student investigator, ‡Denotes established investigator

Abstract

International Journal of Exercise Science 18(7): 1121-1132, 2025. https://doi.org/10.70252/JMBI4851 Carbon-fiber shoes feature a stiff yet lightweight curved carbon-fiber plate embedded in the sole and a resilient midsole foam. These shoes create spring-like rebounding effect that has proven to decrease energy consumption and enhance athletic performance. To date, most biomechanics research on carbon-fiber shoes has been laboratory-based. The purpose of our study was to compare running biomechanics in competitive runners wearing carbon-fiber shoes or traditional shoes using wearable sensors on an outdoor composite track. Ten elite runners (9F, 1M) who consistently ran over 30 miles per week and owned a pair of carbon-fiber shoes participated. The experiment consisted of three 40-meter run trials in carbon-fiber shoes and three trials in traditional running shoes. The self-selected speed was held constant between the two conditions. Two Inertial Measurement Units (IMUs) were strapped on subject's right foot and tibia to measure biomechanical parameters including tibial acceleration, eversion velocity, stance time, stride frequency, sagittal plane angular velocity of the foot at toe-off, and sagittal plane angular acceleration of the foot during propulsion. A paired sample *t* test was used to compare between shoe conditions. Sagittal plane angular acceleration of the foot during propulsion was significantly greater in the carbon-fiber shoes, 8774.4±4348.2 deg/sec^2, compared to 7492.9±3495.0 deg/sec^2 for traditional shoes (P=0.01, Cohen's *d*=0.513). Additionally, sagittal plane angular velocity of the foot at toe-off approached significance (carbon-fiber: 953.1±227.9deg/sec, traditional: 881.0±216.1deg/sec, P=0.082, Cohen's *d*=0.326). No other differences were noted. Carbon-fiber shoes create a more efficient toe-off by providing greater propulsive acceleration during push-off.

Keywords: Propulsion, push-off, IMUs, wearable sensors

Introduction

In recent years, an increasing number of competitive runners have utilized highly technological shoes, often termed "super shoes"[1] during racing to improve performance.[2] New world records in events ranging from 5 km races to the marathon have been achieved by athletes wearing these shoes,[3] which provide a mechanical advantage that significantly improves running economy,[1,2,4] Various studies have reported more than a 4% gain in running economy when athletes of a range of expertise levels use these shoes.[1-7] Although shoe design and materials differ between manufacturers, the shoes feature a curved carbon-fiber plate that increases longitudinal bending stiffness of the shoe as well as a compliant and resilient foam midsole.[8] The mechanisms for the efficacy of the shoes are still not well understood. The combination of the carbon-fiber plate and midsole foam may act as a spring to provide a rebound effect and propel the runner forward.[2,6]

Several research groups have studied the biomechanics associated with increased performance in runners wearing the carbon-fiber shoes. Hoogkamer et al[6] and Martinez and colleagues[1] reported a smaller peak ankle extensor moment, as well as smaller negative and positive work at the ankle in athletes wearing the carbon-fiber shoes. No alterations to hip and knee mechanics were noted.[6] Additionally, metatarsophalangeal dorsiflexion and negative work was decreased in the carbon-fiber shoes.[1,6] Healy and Hoogkamer[8] compared running biomechanics in intact carbon-fiber shoes and similar shoes with mediolateral cuts through the carbon plate to reduce its effectiveness. They also reported decreased metatarsophalangeal dorsiflexion, MTP dorsiflexion angular velocity, and negative power in the intact carbon-fiber shoes.[8] This reduced metabolic demand at the ankle and metatarsophalangeal joints likely contributes to the improved running economy of runners using the carbon-fiber shoes.[1] EMG data are inconclusive, as some researchers report increased medial gastrocnemius activation,[9] while others report decreased activation[10] in runners wearing carbon-fiber insoles. No differences in comfort between carbon-fiber and regular insoles have been reported.[9]

However, these studies were conducted in indoor laboratory settings and may not truly represent outdoor running on a typical running surface.[11-15] Inertial Measurement Units (IMUs) are small wearable sensors that allow convenient determination of some common biomechanical variables outside of the laboratory.[16] These devices incorporate a three-dimensional accelerometer to assess linear acceleration as well as a 3D gyroscope to measure angular velocity.[16] Recent studies using IMUs have reported greater axial tibial acceleration at impact in outdoor field-testing compared to indoor testing in runners wearing traditional shoes.[13,14] Moon[14] reported greater stride frequency of runners on a treadmill compared to on grass, and higher eversion velocity on a harder surface, such as a track or asphalt, compared to on a softer surface such as grass or treadmill. No research that used IMUs to examine the biomechanical adaptations associated with the use of carbon-fiber shoes in an outdoor environment was found in the refereed literature.

The purpose of our study was to use IMU technology to compare various biomechanical properties of running gait outdoor on a composite track between carbon-fiber shoes and traditional shoes. These properties included peak tibial acceleration, stance time, stride frequency, mean eversion, maximum eversion, maximum sagittal plane angular velocity of the foot at toe off and sagittal plane angular acceleration of the foot during propulsion. We hypothesized that sagittal plane angular acceleration of the foot during propulsion and maximum angular velocity at toe off would increase with the addition of the carbon-fiber plate and that all other variables would remain unchanged by the influence of the carbon-fiber shoes.

Methods

Participants

Ten competitive runners (age: 22.5±5.3 yrs, height: 164.9±5.7cm, mass: 55.6±4.5kg, 9F/1M) who reported running at least 30 miles per week (average: 40.8±10.1 miles/week) and who owned a pair of carbon-fiber shoes were asked to participate. All subjects were habituated to the shoes because they reported running in their traditional and their carbon-fiber shoes for at least 1 month prior to the study. No subjects reported any lower extremity injuries in the past 6 months and no previous cardiopulmonary condition. Eight subjects were NCAA varsity athletes on our university's D1 cross country team. One subject was on our 'club' (non-NCAA) cross country team, and one was a local marathon runner. Subjects were recruited by advertisement letter or verbal recommendation. Participation was voluntary and participants received no additional compensation for their time.

We first conducted an apriori power analysis from the step frequency reported by Hoogamer, Kipp, and Kram.[6] In that study, step frequency was 2.91 steps/sec when subjects wore carbon-fiber shoes and 2.96 when traditional shoes were worn. Standard deviation was 0.09 in the traditional shoe condition. The power analysis revealed that 20 subjects would be needed to achieve statistical significance of that variable. Furthermore, we wanted to estimate our sample size based on the propulsion variables in the current study. Data from the first three participants were used for a priori power analysis. Because a primary purpose of using the carbon-fiber shoes is to increase propulsion during toe off, we used the sagittal plane angular acceleration of the shoe from midstance to toe-off as the variable of interest in our power analysis. The average was 10617.9 deg/s^2 for first three subjects when using the carbon-fiber shoes and 7456.5 deg/s^2 when in traditional shoes, with a standard deviation of 3118.4 deg/s^2. This power analysis estimated that 13 participants would be needed to find significance in this variable. However, we were only able to identify and recruit 10 subjects who met our inclusion criteria in the timeframe allowed for this student project.

Protocol

Data were collected at the West Virginia University track and field complex to accurately represent athletes using carbon-fiber shoes during track races. Participants were explained the procedure and informed about any minimal risk of participation. Subjects were encouraged to ask questions or concerns at any time during the briefing or the experiment itself. Participants then provided University-approved informed consent, as well as their age, height, weight, and miles run per week.

Next, two Vicon (Centennial, CO) Blue Trident IMU sensors were placed on the subject's right leg (Figure 1). Each IMU included an accelerometer (± 200g, 1600 Hz) and gyroscope (± 2000 deg/s, 1125 Hz). One IMU was securely fastened on the back of the heel counter on the subject's right shoe such that the X-axis of the IMU was aligned with the vertical axis of the shoe, the Y-axis was aligned with the mediolateral axis of the shoe and the Z-axis was aligned with the anteroposterior axis of the shoe. With this alignment, angular velocities were measured as follows: X=transverse plane, Y=sagittal plane, and Z=frontal plane. A second IMU was placed on the distal tibia such that the X-axis of the IMU was aligned with the anteroposterior axis of the tibia, the Y-axis with vertical axis of the tibia and the Z-axis with the mediolateral axis of the tibia. Therefore, the acceleration data from the Y-axis of the IMU recorded tibial axial (longitudinal) acceleration at impact. Although the tibial-mounted IMU also assessed angular velocity, we did not process these data for this experiment.

Subjects were asked to warm-up until they felt that they were ready to participate. A timing system (Dashr 2.0, Lincoln, NE) was used to ensure consistent running speeds between trials. Specifically, two timing gates were placed on the track at the 10m and 40m marks. The distance was chosen to ensure that at least 10 strides would be captured on the IMU. Subjects were asked to run at a comfortable speed during the duration of the experiment (3 on the scale of 1 to 10). An initial baseline time was collected with a ±5% tolerance range. Subjects were instructed to maintain constant speed throughout the duration of the experiment and trials outside the range were repeated. The average speed run by our participants during the testing was 4.6 m/s.

Figure 1. Frontal and sagittal view of the tibial and shoe-mounted IMUs during testing. Note: IMUs are shown secured with athletic tape to prevent extraneous movement.

Next, participants were instructed to complete a total of six 40-meter runs, with three trials in the carbon-fiber shoes and three in their everyday running shoes. We did not control for the everyday shoe type, although all runners were comfortable in their shoes wearing them on their daily runs. We did not assess the amount of rearfoot control provided by the subjects' everyday running shoes. All trials were conducted on the composite track at our university. Each trial time was measured and recorded to ensure it was within the acceptable time range. Subjects were permitted to take breaks between trials to prevent fatigue; however, no subjects reported fatigue during the experiment. The order of the shoe condition was randomized, with six participants starting with carbon-fiber shoes first and four beginning with traditional shoes.

All data were extracted from the IMU sensor and processed with MATLAB R2023b (Mathworks, Inc., Natick, MA). Data were filtered with a dual-pass 4th order Butterworth filter with a cutoff frequency of 70 Hz.[13] A custom MATLAB script was used to determine our outcome variables.[14] First, heel strike and toe off were found using the sagittal plane velocity of the foot-mounted IMU.[14,17-19] Stance time was determined by calculating the time difference between toe-off and heel strike in each gait cycle.[14,17,19] Stride time was determined as the time between successive heel strike events. The reciprocal of the average stride time in a trial was used to calculate stride frequency.[14] Maximum and average eversion velocities were obtained through the Z-axis gyroscope of the foot-mounted IMU.[14] Peak tibial acceleration was found as the local maximum for each axial acceleration from the shank-mounted IMU.[13]

To assess the amount of propulsion provided by the shoes, we assessed two additional variables from the Y-axis of our foot-mounted IMU data: sagittal plane angular velocity of the foot at toe-off and sagittal plane angular acceleration of the foot during propulsion. These are determined as shown in Figure 2. Midstance angular velocity was determined through finding the minimum angular velocity, which occurred halfway between heel-strike and toe-off. The other component, maximum sagittal plane angular velocity at toe-off, was found by determining the maximum value during the toe-off phase. Angular acceleration during propulsion was calculated by dividing the difference in angular velocity by the time difference between the two components. Each trial used ten steps to find average propulsion at mid-stance and average maximum angular acceleration at toe-off.

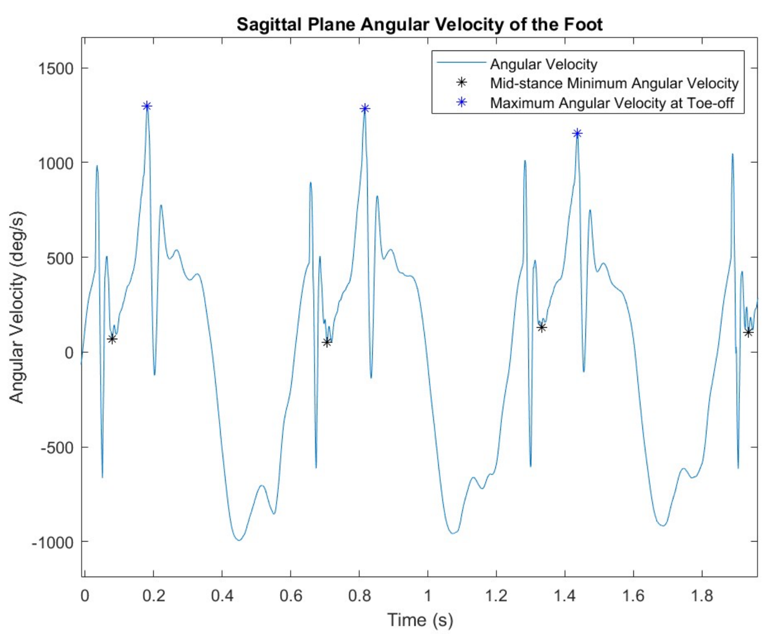

Figure 2. Sagittal plane angular velocity obtained from the shoe mounted IMU. Angular acceleration during propulsion was determined as the difference between the maximum angular velocity at toe-off and the minimum angular velocity at midstance divided by the time between the two events.

Statistical Analysis

Statistical analyses were performed using IBM SPSS statistical software (v29.0, Armonk, NY). A paired sample *t*-test was performed on each dependent variable to compare between carbon-fiber and traditional shoes. A Cohen's *d* effect size was calculated to determine the effect magnitude between shoe conditions (small effect $d \leq 0.2$, moderate $0.2 < d < 0.8$, and large: $d \geq 0.8$). Dependent variables were stance time, stride frequency, maximum eversion velocity, average eversion velocity, tibial acceleration, maximum sagittal plane angular velocity of the shoe at toe-off and sagittal plane angular acceleration during propulsion. The alpha level of significance was set at 0.05.

Results

During our experiment, we compared biomechanical running parameters obtained from IMUs of participants running on the composite track at our university track and field facility. The experiment was conducted under two shoe conditions: carbon-fiber and traditional running shoes. Data are shown in Table 1. Use of the carbon-fiber shoes resulted greater propulsion, as assessed by a 17% greater ($p=0.010$, Cohen's $d = 0.513$) sagittal plane angular acceleration of the foot during propulsion compared to when the athletes wore their traditional shoes. Additionally, the maximum sagittal plane angular velocity of the foot at toe-off was 8% greater when athletes used the carbon-fiber shoes compared to their traditional everyday shoes, however this did not reach statistical significance in our small subject pool ($p=0.082$, Cohen's $d = 0.326$). No statistical differences were observed in maximum eversion, mean eversion, stance time, stride frequency, and tibial acceleration, and all of their effect sizes were small.

Table 1. Biomechanical running measures in elite runners wearing carbon-fiber shoes and traditional shoes (mean ± standard deviation).

Variable Name	Carbon-fiber Shoes	Traditional Shoes	P-Value	Cohen's *d* Effect Size
Stance time (sec)	0.19 ± 0.02	0.20 ± 0.05	0.106	0.310
Stride frequency (Hz)	1.56 ± 0.11	1.54 ± 0.11	0.464	0.138
Axial tibial acceleration (g)	13.8 ± 7.0	13.8 ± 7.1	0.985	0.004
Maximum eversion velocity (deg/sec)	879.1 ± 283.6	847.1 ± 213.5	0.619	0.093
Average eversion velocity (deg/sec)	11.6 ± 66.2	25.1 ± 64.0	0.367	0.170
Max sagittal plane angular velocity at toe off (deg/sec)	953.1 ± 227.9	881.0 ± 216.1	0.082	0.326
Sagittal plane angular acceleration during propulsion (deg/sec^2)	8774.4 ± 4348.2	7492.9 ± 3495.0	0.010	0.513

** Data were statistically significant between shoe conditions.

Discussion

The purpose of our study was to use wearable technology to compare biomechanical aspects of outdoor running gait between shoes embedded with carbon-fiber plates and traditional running shoes. Our dependent variables were tibial acceleration, stance time, stride frequency, mean eversion velocity, maximum eversion velocity, maximum sagittal plane angular velocity of the foot at toe off and sagittal plane angular acceleration of the foot during propulsion. We hypothesized that sagittal plane angular acceleration of the foot during propulsion and maximum angular velocity at toe off would increase with the addition of the carbon-fiber plate and that all other variables would remain unchanged by the influence of the carbon-fiber shoes.

Our results support our hypotheses. Sagittal plane angular acceleration of the foot during propulsion was significantly greater in the carbon-fiber shoes (8774.4 ± 4348.2 deg/sec^2) than in traditional shoes (7492.9 ± 3495.0 deg/sec^2). Effect size was moderate. This supports a consistent line of evidence suggesting that carbon-fiber shoes improve propulsion.[1,3,6,8,20] Also, we revealed that sagittal plane angular velocity of the foot at toe-off was 8% greater in the carbon-fiber shoes, although this was not statistically significant and effect size was small. These differences were noted even though we held running speed constant between the two conditions. Biomechanical differences between the two shoes conditions in this study were limited to those in the propulsive phase of gait.

This study contributes to prior laboratory-based research on the efficacy of carbon-fiber shoe technology. Martinez et al[1] report increased peak propulsive ground reaction force in runners wearing these shoes. This occurred in conjunction with decreased metatarsophalangeal work, decreased ankle negative and positive work, and greater running economy, while running at the same speed as in traditional shoes[1]. Similarly, Hoogkamer et al[6] reported a smaller peak ankle extensor moment, and negative and positive work at the ankle in the carbon-fiber shoes, also while controlling for speed on a motorized treadmill. Our study was conducted outdoor in an overground condition, which may have some differences compared to running on a treadmill.[21]

The properties of stiff carbon-fiber insole in combination with the resilient midsole foam facilitates the movement of the ankle and toe up and forward over the toes, aiding in the progression of the body.[2] Furthermore, another advantage of these shoes is their ability to create an efficient toe-off, providing extra boost generating greater power and acceleration.[20]

While it is believed that carbon-fiber technology enhances propulsion of athletes, limited data of outdoor running are available on that topic. This study presents numerical data from outdoor running to support the evidence that carbon-fiber creates increased propulsion and may help to explain how runners are able to experience 4% energy reduction while wearing the shoes, potentially due to the additional propulsion provided by the shoes.[4] Our study reinforces the theory that carbon-fiber helps runners gain a better 'push-off'. The sagittal plane acceleration of the foot during propulsion and velocity at toe-off focused on the subject's final moments on the ground. The larger value indicated in the carbon-fiber shoes reflects a stronger push off, enabled by better storage and release of energy from the technological design and materials comprising the shoes.[20]

Stance time and stride frequency were not different between our shoe conditions. Other studies have examined the effect of carbon-fiber technology on spatiotemporal variables. In two separate studies, Hoogkamer and colleagues[6,8] also reported no difference in stance time in athletes wearing carbon-fiber shoes; however, Martinez and colleagues found a decrease in contact time and an increased in step length.[1] Hoogkamer, Kipp, and Kram[6] reported a decreased step frequency. It should be noted that running speed was held constant in these studies, just as in our study, so that any differences could be attributed to the shoe-type and not speed. It is likely that stance time and stride frequency would be altered if the athletes had been permitted to run at a (likely increased) speed that felt natural to them in the carbon-fiber shoes.

We did not observe statistical difference in axial tibial acceleration between carbon-fiber and traditional running shoes. Our results indicated that axial tibial loading was virtually identical between the two conditions (carbon-fiber shoes: 13.8 ± 7.0g, traditional: 13.8 ± 7.1g). Although the use of carbon-fiber technology is shown to modify foot and ankle biomechanics,[1,6] its influence did not extend up to the tibia to produce a greater tibial axial loading during ground contact in our study.

Because carbon-fiber shoes improve running economy and reduce race times, they are revolutionizing the running industry.[2,3,7] However, coaches remain apprehensive about allowing their athletes to wear the shoes due to concern about stress related running injuries.[5,22] There is a belief that carbon-fiber could potentially induce stress on the skeletal system due to altered metatarsophalangeal and ankle joint mechanics.[22] Our data do not support an increased risk of a tibial stress injury from carbon-fiber technology. It should be noted that speed was held constant in this study, which may not reflect real-life, as speed would likely be faster when athletes use carbon-fiber technology. This increased speed could alter the biomechanics significantly, perhaps resulting in a greater tibial axial load and increased risk of injury. Future research is necessary to examine injury risk associated with the use of carbon-fiber shoes. Use of new data analysis techniques, such as deep neural network and layer-wise relevance propagation[23] and/or metaheuristic optimization-based selection[24] may provide insight into the reasons behind the efficacy of the carbon-fiber shoes in improving race performance and changing injury risk.

We assessed maximum and average eversion velocity to gain insight into the effect of carbon-fiber shoes on frontal plane foot kinematics compared to traditional shoes. We did not find statistical differences between shoe conditions. No other studies have published data on these measures in highly technological shoes for comparison with our study. We did not control for the motion control capabilities of either pair of the subjects' shoes. Some researchers assert that overpronation is associated with certain running injures such as anterior knee pain[25-27] and Achilles tendinitis,[28,29] although the evidence is inconclusive.[30,31] Pronation is a motion that occurs between the foot and shank. Our IMU data exclusively examine the eversion velocity of the foot with respect to the world and do not include motion of the foot with respect to the shank. Therefore, given that we do not have data on the amount of rearfoot control provided by either shoe, and that our data reflect eversion velocity and not pronation range of motion/velocity, we do not feel that we can adequately address the effect of carbon-fiber shoes on rearfoot motion.

One limitation of our experiment was the small sample size. Due to the relatively small population in our community who met our criteria of running at least 30 miles per week and owning a pair of carbon-fiber shoes, finding subjects proved challenging. Despite not meeting our recruitment goal of 13 participants, we found increased propulsion in the carbon fiber shoes. The majority of our participants were athletes on our university track and field team. Because the team includes only female athletes, recruiting male participants posed an additional challenge. Therefore, another limitation of our study was the inclusion of only one male participant. As carbon-fiber shoes become more widely available to runners, we hope to recruit a larger subject population that includes both males and females and that more broadly represents running enthusiasts of various skill levels.

Another limitation of the study is the fact that we controlled running speed between conditions. Other key studies exploring the efficacy of the carbon-fiber shoe technology have also held speed constant between conditions.[1,6,8] Carbon-fiber shoes have shown to enhance running economy by over 4%, resulting in a 2% decrease in run time.[2,3] Since carbon-fiber shoes are made to improve running speed, the decision to keep this variable constant likely influenced the natural stride of runners wearing them. It would be beneficial to analyze the influence of speed on the same variables while wearing carbon-fiber shoes. Subjects could undergo the same experiment but be instructed to run a speed that feels most natural to them in that shoe condition.

Another potential area for future research would be to investigate the influence of different surfaces. Running races occur on various surfaces including roads, grass, and trails. All could influence how the carbon-fiber shoes modify the biomechanical variables. Moon[14] reported that surface (grass, track, asphalt, and treadmill) significantly alters the variables of stride frequency, eversion velocity, and axial tibial acceleration during running, even when speed is held constant. Specifically, stride frequency was highest on the treadmill and slowest on grass. Peak tibial longitudinal acceleration was greater on the three outdoor surfaces compared to the treadmill. Maximum rearfoot eversion velocity was significantly slower when running on grass compared to when running on the composite track and asphalt. Thus, research using IMUs to examine how surface affects running biomechanics associated with carbon-fiber shoe technology is warranted. Additionally, there are specialized carbon-fiber shoes made specifically for trail races that would prove to be interesting to compare with track carbon-fiber shoes.

Since the debut of carbon-fiber shoes, new world records for both men's and women's distances from 5K to marathon have been achieved. There is no doubt that carbon-fiber shoes are playing a major role in helping athletes achieve those remarkable times[3]. The significance of this study lies in providing field-based data that demonstrate increased sagittal plane angular acceleration of the foot during propulsion, even when running speed was held constant. This further confirms the propulsive advantage of using the carbon-fiber shoes in an outdoor environment.

Note: This research adheres to the ethical standards for scientific discovery in exercise science outlined in Navalta et al.[32]

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Corresponding author: Jean L. McCrory, PhD; jlmccrory@hsc.wvu.edu