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The Effects of a Carbon Fiber Shoe Insole on Athletic Performance in Collegiate Athletes

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Abstract: Sports equipment such as athletic footwear is designed to prevent injury and/or improve performance. There is limited research about the effects of foot orthoses or shoe insoles on performance improvement via enhanced energetics. One possible solution to improve the energy storage and return of athletic footwear is to utilize a carbon fiber shoe insole (CFI) optimally tuned for the human body-footwear system. The purpose of this study was to examine the effects of a CFI on athletic performance. Thirty-four (15 males, 19 females) collegiate athletes performed a vertical jump, a pro agility test, and a 10-yard sprint while wearing normal athletic footwear and footwear incorporating a CFI. Vertical jump height was measured using a commercial Vertec device; pro agility test and 10-yard sprint times were measured using a laser timing system. The use of a CFI resulted in significant improvements in the vertical jump (+2.5%, $p = 0.012$) and the 10-yard sprint (+1.5%, $p = 0.020$), but not in the pro agility test. These results demonstrated a CFI can enhance speed/acceleration and power in collegiate athletes. Individual anatomical and biomechanical differences may influence the appropriate CFI stiffness required for each athlete to achieve maximal performance in sports involving running, jumping, and change-of-direction.

Key words: Footwear bending stiffness, 10-yard sprint, pro agility test, vertical jump.

1. Introduction

There are various factors which lead to optimal athletic performance, such as an athlete's natural talent, appropriate strength and conditioning programming, and the ideal athletic equipment. Athletic equipment is designed to prevent injury and/or improve performance. To understand how athletic equipment can be used to enhance an athlete's performance, the mechanical work and energy produced can be evaluated by defining the individual as the system of interest and applying the law of conservation of energy. To maximize performance, athletes must optimize their work-energy balance. Based on the first law of thermodynamics and the work-energy principle, an athlete has three major strategies available to improve the work-energy balance during training and competition: (1) maximize energy storage and return, (2) minimize the loss of energy, and (3) optimize muscle function [1-3].

Athletes often attempt to select equipment, such as footwear in running events, which is designed to maximize energy storage and return. Manufacturers of athletic footwear such as Adidas® and Nike® often highlight the enhanced energy storage and return provided by their footwear as compared to competing brands. Sport scientists and athletic equipment manufacturers have investigated ways of improving the storage and re-use of elastic strain energy in sport shoes since footwear constitutes part of the equipment used in almost every sport. However, athletic footwear is typically characterized by poor energy storage and return (~1-2%) as a result of current technological limitations in the design of and material properties used in shoe midsole construction [1, 3]. Therefore, most of the energy (~98-99%) stored in a shoe midsole when the foot contacts the ground is dissipated (lost) through heat, friction, and vibrations and, thus, decreases an athlete's efficiency.

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The effectiveness of foot orthoses/shoe insoles for the treatment and prevention of lower limb injuries has been studied extensively e.g., Refs. [4-6]. However, there is limited research to date that has addressed the role of foot orthoses/shoe insoles on performance improvement as a result of enhanced energetics via either maximizing energy storage and return or minimizing the loss of energy. In addition, there is growing interest in examining the role of shoe bending stiffness on improving athletic performance (for a review, see Refs. [7]).

The use of carbon fiber plates inserted into shoe midsoles and insoles for enhancing performance by optimizing shoe bending stiffness has been examined in a variety of activities emphasizing speed and power. Previous research has demonstrated that increasing the stiffness of shoes (via the use of carbon fiber plates inserted into the shoe midsole) resulted in a 1.7 cm increase in vertical jump height for a group of 25 participants [8]. However, systematically increasing footwear stiffness was not found to have an effect on jump height in 20 recreational basketball players [9]. Sprint running performance in 34 high-level sprinters was improved by the use of carbon fiber plates inserted under the shoe sock liner in track spikes to increase forefoot bending stiffness [10]. In comparison to a standard sprint spike, wearing a shoe with a carbon fiber plate improved sprint performance by 1.2% over the 20 m to 40 m interval during maximal effort 40 m sprints. Conversely, increased footwear bending stiffness resulted in a 6.3% reduction in acceleration during the first step of a 5 m sprint in 15 male athletes [11] and no change in 40 m sprint performance in 12 trained sprinters [12]. Cycling-specific carbon fiber insoles have also been used to improve sprint performance in cycling. While one study indicated a 6.9% increase in power output during 8-second isokinetic sprint tests in 25 amateur cyclists [13], another study found that Wingate test power output did not improve in a group of 18 male cyclists and triathletes [14]. Therefore, there is conflicting evidence regarding the efficacy of using carbon fiber plates or shoe insoles for improving athletic performance. Moreover, while carbon fiber plates used in conjunction with standard athletic footwear may improve sprint running and vertical jump performance, this technology has not been available to the general public until recently with the release of the Nike® Zoom Vaporfly 4% running shoe.

A carbon fiber shoe insole (CFI) that is designed to overcome the current limitations in athletic footwear design and construction and allows for increased energy storage and return has been developed (XG4 Performance Insole; ROAR Performance; Milford, CT, USA). Anecdotal evidence suggests that athletes can run faster and jump higher when using the XG4 shoe insole. However, there are no published data available to support these claims. Therefore, the purpose of this study was to examine the effects of a commercially-available CFI on athletic performance. The specific parameters related to athletic performance that were assessed in this study were speed (acceleration), agility (change of direction), and power. The authors hypothesized that the use of the CFI would result in improved linear speed and acceleration (assessed by a 10-yard sprint), agility (assessed by a pro agility test/20-yard shuttle run), and lower-body muscular power (assessed by a vertical jump). These three performance tests were selected since this combination of tests is the best predictor for success in power sports [15].

2. Materials and Methods

2.1 Participants

Thirty-four National Collegiate Athletic Association (NCAA) Division II collegiate athletes participated in this study; for a description of the participants, see Table 1. The male participants were members of baseball (n = 6) and American football (n = 9) teams; the female participants were members of field hockey (n = 3), lacrosse (n = 11), soccer (n = 3), and softball (n = 2)

Table 1 Participant characteristics.

	Male	Female
N	15	19
Age (years)	20.0 ± 1.5	19.6 ± 1.1
Height (m)	1.76 ± 0.69	1.63 ± 0.60
Mass (kg)	88.4 ± 11.0	63.8 ± 6.8
Shoe size (US/Euro)	11.5 ± 1.3/44.5 ± 1.3	8.0 ± 1.0/38.5 ± 1.0

Fig. 1 The carbon fiber shoe insole (XG4 Performance Insole) used in the present study: (Top) Top and bottom view, and (Bottom) medial side profile view.

teams. Potential participants were invited to an orientation/familiarization session during which all study procedures and test protocols were explained. If an individual agreed to participate in the study, he/she provided informed consent according to the policies and procedures of the Institutional Review Board at Southern Connecticut State University.

After providing informed consent, all participants completed a physical activity readiness questionnaire (PAR-Q) [16] and a medical history questionnaire to determine if they were at an elevated risk for suffering an adverse event during the study. Participants who reported to have a pre-existing history of (or possessed current risk factors for) heart/pulmonary disease or musculoskeletal injuries were excluded from participating in the study. Height, mass, and arterial blood pressure of all participants were measured following the completion of the PAR-Q and medical history questionnaire. Following these measurements, participants were fitted in the footwear and carbon fiber shoe inserts to be used during the sprint, agility, and vertical jump testing.

2.2 Procedures

All participants used the same footwear (Minimus 20v4; New Balance Athletics, Inc.; Boston, MA, USA) during the vertical jump, pro agility, and 10-yard sprint tests. The CFI (XG4 Performance Insoles; ROAR Performance; Milford, CT, USA) used in this study was inserted into the footwear in place of the normal sock liner. The CFI was constructed from a proprietary blend of woven and unidirectional prepreg carbon fiber layers covered with a 3.0 mm thick layer of Spenco® foam; the mass ranged between 50-60 g (size 10.5 US/44 European), depending on the stiffness (or flex) of the CFI (Fig. 1). The shape of the CFI used in the present study was designed to match the contour of the longitudinal arch of the foot and behave as a leaf spring when the foot was loaded and unloaded during running and jumping activities (Fig. 1) in contrast to the flat carbon fiber plate design used in previous studies [8, 10]. Two different shoe insole conditions were evaluated during the vertical jump, pro agility, and 10-yard sprint tests: (1) a control condition with footwear using a sham CFI, and (2) a condition with footwear using either a medium flex CFI (female participants) or a stiff flex CFI (male participants). The bending stiffness of the CFIs was determined by a three-point bending test; the measured stiffness levels of the medium and stiff flex CFIs were 60 $N \cdot mm^{-1}$ and 120 $N \cdot mm^{-1}$, respectively.

Within one week after providing informed consent and completing the physical activity readiness questionnaire, participants reported to the Human Performance Laboratory/Moore Field House on the campus of Southern Connecticut State University for testing in groups of 2-4 individuals. Participants were asked to refrain from strenuous exercise for 48 hours before the test session. All study volunteers were participating in their respective athletic team's off-season strength and conditioning program and were very familiar with the administration of the 10-yard sprint, pro agility, and vertical jump tests at the time of testing.

Before the series of athletic performance tests, all participants performed a standardized 15-20 min dynamic warm-up designed by the National Strength and Conditioning Association (NSCA) [17] using the test footwear. The warm-up consisted of the following exercises: (1) walking knee to chest (1 × 10 yards); (2) forward lunge with elbow to instep (1 × 5 each side); (3) side lunge (1 × 5 each side); (4) toy soldier (1 × 10 yards); (5) high knees (2 × 10 yards); (6) heel ups (2 × 10 yards); and (7) carioca (2 × 10 yards). The test protocol began immediately after completion of the dynamic warm-up.

The series of three performance tests was performed in two rounds during this single test session: participants alternated between the control and CFI footwear conditions for each round of testing. Each round was separated by a period of 15-20 min to minimize the effects of fatigue. If a participant used the control footwear in the first round, then he/she used the footwear with CFI in the second round and vice versa. The footwear condition was randomized to minimize any learning and/or fatigue effects. Immediately prior to each round of testing, sprints (3 × 30 yards with intensity increasing from 50-100%) were performed using the assigned footwear condition (either the control footwear condition using a sham CFI or the CFI footwear condition) to allow the participants to become accommodated to the footwear. The manufacturer of the CFI indicated that a 2-3 min accommodation period was sufficient to allow an athlete to adjust to the use of the CFI.

The dynamic warm-up and all performance testing took place on an indoor synthetic track. Each round of tests was performed in the following order: (1) vertical jump, (2) pro agility test, and (3) 10-yard sprint. This test order was based on NSCA guidelines [18, 19]. In addition, the administration of each performance test followed NSCA recommendations [18, 19]. To assess jump height performance, participants performed three maximal effort countermovement vertical jumps; jump height was measured to the nearest 1.27 cm (0.5 in.) using a commercial device for vertical jump testing (Vertec; Sports Imports, Inc.; Columbus, OH, USA). Participants were provided with 30-60 s of active recovery between trials to avoid fatigue. The highest vertical jump of the three trials was used for data analysis. To assess agility performance, participants performed two maximal effort pro agility test trials which consisted of a 5-yard sprint, a 180° turn, a 10-yard sprint, a 180° turn, and a 5-yard sprint; agility time was measured to the nearest 0.01 s using a laser timing system (Power Agility Timer; Zybek Sports; Broomfield, CO, USA). Participants were provided with 2-3 min of active recovery between trials to avoid fatigue. The fastest agility time of the two trials was used for data analysis. To assess sprint performance, participants performed two maximal effort 10-yard sprints using a three-point stance; sprint time was measured to the nearest 0.01 s using a laser timing system (Power Dash 1×; Zybek Sports; Broomfield, CO, USA). Participants were provided with 2-3 min of active recovery between trials to avoid fatigue. The fastest sprint time of the two trials was used for data analysis. Participants provided overall footwear comfort ratings using a 15-cm visual analogue scale at the conclusion of each round of testing; the left and right ends of the scale were labeled “not comfortable at all” (0 comfort points) and “most comfortable condition imaginable” (15 comfort points), respectively [20].

2.3 Statistical Analysis

The mean ± *SD* was used to report the descriptive statistics of all dependent variables. To determine whether carbon fiber shoe insoles improved athletic performance, a 2 × 2 repeated-measures factorial multivariate analysis of variance (MANOVA) was used to compare the two different footwear conditions (control and CFI) and gender (male and female) for the vertical jump, pro agility, and 10-yard sprint tests. In addition, a comparison of overall comfort between the test footwear, the control footwear (with sham CFI), and CFI footwear conditions was performed using a one-way repeated-measures analysis of variance (ANOVA). All statistical analyses were performed using SPSS statistics software (Version 24.0; IBM Corp.; Armonk, NY, USA). The level of significance was set at $p < 0.10$ because “the consequences of incorrectly accepting a false result (slightly increased expenses for athletes and shoe manufacturers) are minor in comparison to the benefits of a positive effect (improved performance)” [10]. The meaningfulness (effect size) of a difference between two means was calculated using Cohen’s *d*; effect sizes were considered trivial, small, moderate, large, very large, and nearly perfect when Cohen’s *d* was 0.0, 0.2, 0.6, 1.2, 2.0, and 4.0, respectively [21].

3. Results and Analysis

The multivariate statistical test revealed that there were significant between-subjects effects of gender [$F(3, 30) = 46.002$, $p = 0.0001$] and within-subjects effects of footwear condition [$F(3, 30) = 3.727$, $p = 0.022$] across the three performance tests. In addition, there was no within-subjects interaction effect between footwear and gender [$F(3, 30) = 1.117$, $p = 0.358$] across the three performance tests. The results for all three performance tests will be discussed in greater detail below.

3.1 Vertical Jump Performance

The univariate statistical test of vertical jump performance indicated that there was a significant 2.5% increase in vertical jump height when using a CFI [$F(1, 32) = 7.091$, $p = 0.012$] (Fig. 2). A pairwise comparison of the two footwear conditions revealed an effect size of $d = 0.10$. There was no interaction between footwear and gender [$F(1, 32) = 0.713$, $p = 0.405$]; male and female participants experienced similar performance improvements in vertical jump height when using a CFI (Table 2). Most individuals had their best performance when using the CFI: 10 out of 15 males (66.7%) and 15 out of 19 females (78.9%) had their highest jump in the CFI footwear condition.

3.2 Agility Performance

The univariate statistical test of agility performance indicated that there was no improvement in agility time when using a CFI [$F(1, 32) = 2.096$, $p = 0.157$] (Fig. 3). A pairwise comparison of the two footwear conditions revealed an effect size of $d = 0.08$. There was no interaction between footwear and gender [$F(1, 32) = 1.017$, $p = 0.321$]; male and female participants did not experience significant improvements in agility time when using a CFI (Table 2).

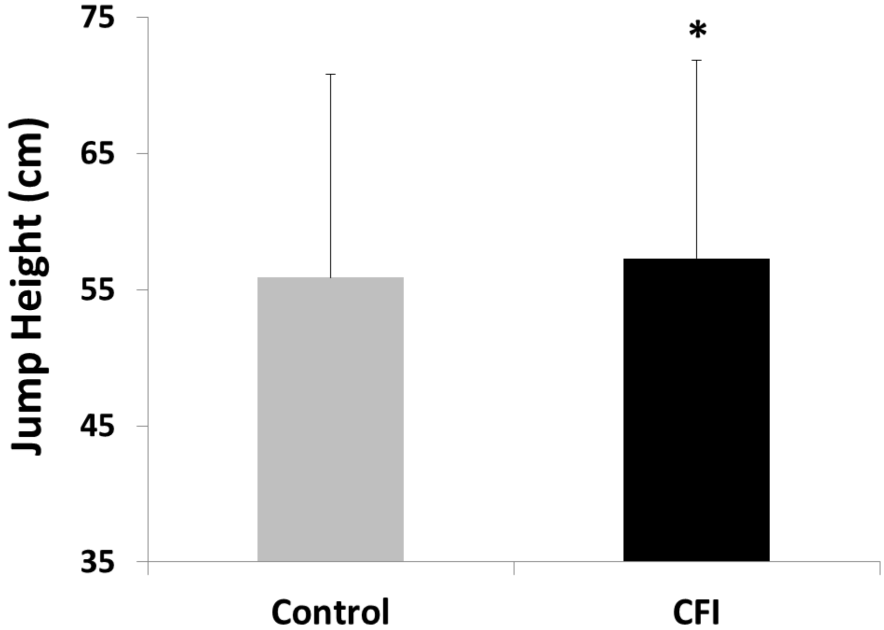

Fig. 2 Mean (± *SD*) vertical jump height for the control and carbon fiber shoe insole (CFI) footwear conditions.
* Significantly different from the control condition ($p = 0.012$).

Table 2 Athletic performance test data for the control and carbon fiber shoe insert (CFI) footwear conditions.

	Male		Female	
	Control	CFI	Control	CFI
Vertical jump (cm)	69.7 ± 11.5	70.6 ± 11.4	45.0 ± 4.6	46.8 ± 4.8
Pro agility test (s)	4.44 ± 0.13	4.40 ± 0.11	4.98 ± 0.19	4.97 ± 0.17
10-yard sprint (s)	1.84 ± 0.16	1.82 ± 0.14	2.08 ± 0.09	2.04 ± 0.14

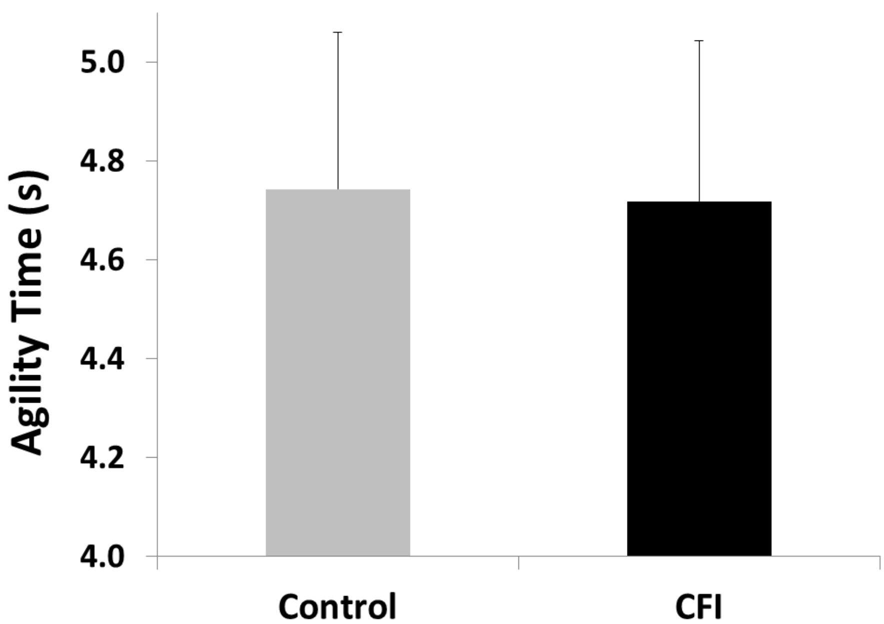

Fig. 3 Mean (± *SD*) pro agility test time for the control and carbon fiber shoe insole (CFI) footwear conditions.

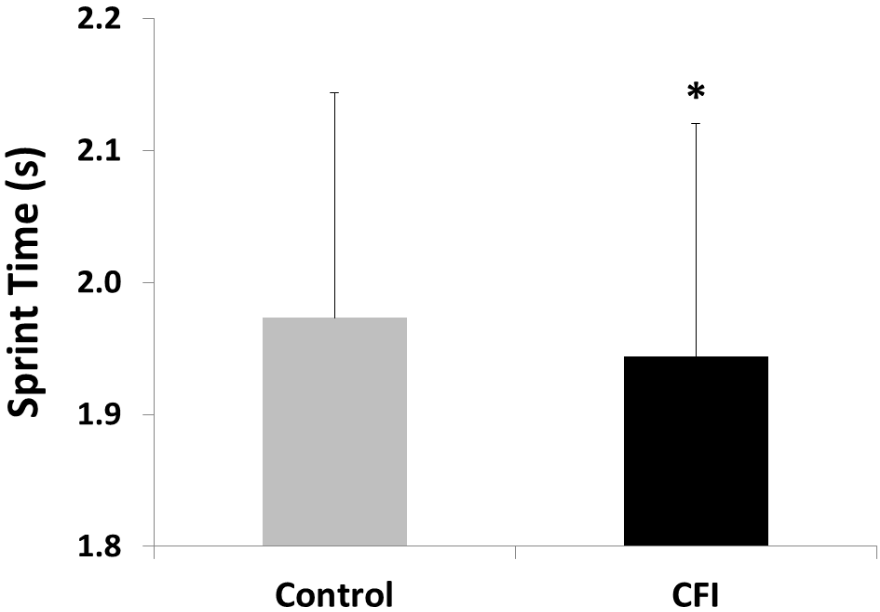

Fig. 4 Mean (± *SD*) 10-yard sprint time for the control and carbon fiber shoe insole (CFI) footwear conditions.
*Significantly different from the control condition ($p = 0.020$).

3.3 Sprint Performance

The univariate statistical test of sprint performance indicated that there was a significant 1.5% improvement in 10-yard sprint time when using a CFI [$F(1, 32) = 5.973$, $p = 0.020$] (Fig. 4). A pairwise comparison of the two footwear conditions revealed an effect size of $d = 0.17$. There was no interaction between footwear and gender [$F(1, 32) = 0.795$, $p = 0.379$]; male and female participants experienced similar performance improvements in 10-yard sprint time when using a CFI (Table 2). Most individuals had their best performance when using the CFI: 11 out of 15 males (73.3%) and 14 out of 19 females (73.7%) had their fastest sprint in the CFI footwear condition.

3.4 Footwear Comfort

The univariate statistical test of footwear comfort indicated that there was no difference in overall footwear comfort ratings between the test footwear, the control footwear (with sham CFI), and CFI footwear conditions [$F(1, 33) = 1.558$, $p = 0.104$]. The overall footwear comfort ratings obtained using a 15-cm visual analog scale were 10.2 ± 3.1, 10.6 ± 2.9, and 8.8 ± 3.9 for the test footwear, control footwear, and CFI footwear conditions, respectively.

4. Discussion

The purpose of this study was to examine the effects of a commercially-available CFI on athletic performance. The authors hypothesized that the use of a CFI would result in increased linear speed/acceleration (assessed by a 10-yard sprint), agility (assessed by a pro agility test), and lower-body muscular power (assessed by a vertical jump). We found that the use of a CFI in athletic footwear improved performance during the sprint and vertical jump through increases in speed/acceleration and lower-body muscular power, respectively. However, there were no improvements in change of direction performance when using a CFI.

The results of this study demonstrated that the use of a CFI increased vertical jump height by 1.4 cm (2.5%); the associated effect size ($d = 0.10$) is considered trivial to small [21]. While the Vertec is a widely accepted and validated device for measuring vertical jump height in strength and conditioning testing and research [19], the ability to only measure jump height in 1.27 cm (0.5 in.) increments is a limitation of this study [22]. However, we specifically chose to use the Vertec to measure vertical jump height instead of a device with greater validity such as a force platform so that we could directly compare the results of this study with previous research that examined the effects of footwear bending stiffness on vertical jump height performance [8, 9, 23]. The results of this study are similar to those found by previous research which demonstrated that increasing the stiffness of shoes (via the use of a carbon fiber plate inserted into the shoe midsole, with a bending stiffness approximately five times greater than the control condition) resulted in a 1.7 cm increase in vertical jump height for a group of 25 male participants [8]. While footwear stiffened with a carbon fiber plate did not increase the amount of energy stored and reused at the hip, knee, ankle, and metatarsophalangeal (MTP) joints, there were large decreases in MTP joint dorsiflexion resulting in an average reduction in the amount of energy absorbed (lost) at the MTP joint by 5-8 J [8]. This minimization of energy loss was theorized to be the basis for the corresponding improvement in jump height. The findings of both [8] and the present study were based on the results of testing only one footwear bending or CFI stiffness level against a control condition (standard footwear). While 25 participants (73.5%) jumped the highest while using a CFI, 9 participants jumped the highest wearing standard footwear; therefore, the one CFI stiffness level used in the present study may not have been optimal for all individuals. Preliminary research examining the effects of a range of CFI stiffness levels on vertical jump performance has demonstrated that the CFI stiffness level required by each athlete for maximal performance was subject-specific due to individual anatomical and biomechanical differences [24].

In addition to increased vertical jump height, the results of the current study demonstrated that the use of a CFI improved 10-yard sprint time by 0.03 s (1.5%); the associated effect size (d = 0.17) is considered small [21]. These results are similar to those found by previous research which demonstrated that increasing the bending stiffness of sprint shoes (via carbon fiber plates inserted under the shoe sock liner) resulted in a 1.2% improvement in 20-40 m split time during a maximal effort 40 m sprint for a group of 34 high-level male and female sprinters [10]. Similar to the results found when the relationship between footwear bending stiffness and improved vertical jump performance was observed [8], footwear stiffened with a carbon fiber plate did not increase the amount of energy stored and reused at the hip, knee, ankle, and MTP joints [8]. Instead, improvements in running were found to correspond with a reduction in the amount of energy absorbed (lost) at the MTP joint by 8-10 J on average as a result of increased shoe bending stiffness [8]. This minimization of energy loss was theorized to be the basis for the corresponding improvement in sprint performance. Although previous research examining the relationship between footwear bending stiffness and sprint performance has compared three or four levels of shoe stiffness [10-12, 24], the results of the current study were based on a comparison of only one CFI stiffness level with the control footwear condition. While 25 participants (73.5%) had their fastest 10-yard sprint time while using a CFI, 9 participants had their fastest sprint time wearing standard footwear; therefore, the one CFI stiffness level used in this study may not have been optimal for all individuals. Each individual has a preferred footwear bending stiffness for best sprint performance; this subject-specific response has been documented in several studies [10, 12, 24]. Significant reductions in sprint acceleration performance due to suboptimal footwear bending stiffness may occur in athletes who lack appropriate lower-extremity strength and are unable to take advantage of the gearing function created by footwear with increased levels of longitudinal bending stiffness [11].

While the use of a CFI resulted in significant improvements in vertical jump and sprint performance, the 0.02 s (0.5%) improvement in agility performance measured using a pro agility test was not significant; the associated effect size ($d = 0.08$) is considered trivial [21]. The lack of significant improvement in agility performance has also been demonstrated in previous research [23] in which 10 collegiate football players performed a pro agility test using a low stiffness control shoe, a stiff shoe (90% stiffer than the control), and a very stiff shoe (232% stiffer than the control). Although we did not measure MTP joint motion during this study, reductions in MTP joint range of motion are associated with increases in footwear bending stiffness [8, 12]. Therefore, one can speculate that a CFI-related reduction in MTP joint motion may have resulted in altered movement biomechanics during the two 180° turns that are part of the pro agility test and offset any improvements in linear speed that may have occurred.

While the performance improvement characteristics of the CFI used in this study are of primary importance, overall footwear comfort when using a CFI is a matter of practical significance: if a CFI is not comfortable to wear, athletes will not likely use one during training and competition. Several investigations have speculated that footwear comfort is related to muscle activation and, thus, to fatigue and performance [1, 6, 25]. In general, individuals seem to prefer soft over hard materials [20]. The stiffness of the CFI used in this study caused the test footwear to have a “hard” feel. Therefore, it is not surprising that most participants provided the lowest comfort rating for the CFI footwear condition. However, some participants did rate the CFI footwear condition as most comfortable indicating that different individuals have different preferences with respect to shoe insole material and shape. Since the overall comfort ratings were not significantly different between footwear conditions, athletes should be comfortable wearing the CFI used in the present study in training and competition.

A limitation of our study is that we only compared one CFI stiffness level with the baseline control footwear condition. Previous research [10, 12, 22, 26] has shown that different athletes require different shoe insole/midsole stiffness to achieve their maximal performance. Therefore, the athlete must select the correct bending stiffness of the footwear or insole used during training or competition to benefit from improvements in performance. Athletes may not experience performance improvement when using footwear incorporating a carbon fiber insole or midsole of random stiffness. Since simple anthropometric variables such as body height/mass and shoe size are not able to predict optimal bending stiffness [10], strength and conditioning coaches and athletes must choose the correct stiffness through trial-and-error. Individual differences in plantarflexor strength and the length-tension and force-velocity relationships of the calf musculature may influence the appropriate footwear bending stiffness required for each athlete to achieve his/her maximal performance in sports involving running and jumping [10-12]. Moreover, the beneficial effects of increased shoe bending stiffness as a result of midsole construction or shoe insoles can be compromised if the normal range of motion of the MTP joint is altered [26].

Another limitation of our analysis of the effects of a CFI on athletic performance was that we did not collect kinematic (motion capture) or kinetic (force plate) data. Therefore, we could not calculate the joint angles and the positive and negative work performed (energy produced and absorbed) at each of the hip, knee, ankle, and MTP joints during the vertical jump, pro agility test, or sprint. Thus, we cannot address the mechanism(s) by which the CFI used in the present study resulted in improved vertical jump and sprint performance. The two mechanisms that potentially have the greatest influence on the work-energy balance resulting in these performance improvements are: (1) increasing energy storage and return, and (2) decreasing energy loss [2, 3].

The manufacturer of the CFI used in this study promotes the energy storage and return capabilities of its product. However, this mechanism is unlikely to provide a major contribution to performance improvement. For energy storage and return of athletic equipment to play a significant role, three conditions must be met: (1) the return of stored energy must occur at the right time in an athlete's performance, (2) the energy must be returned at the right location, and (3) the energy must be returned with the right frequency [1, 27]. While the second and third conditions may be met with the CFI used in this study, it is not likely that the first condition can be met. As reported in previous research [8], there was no increased energy and only a very small amount of energy generated at the MTP joint during jumping and running, respectively, as footwear bending stiffness increased. Since the shoe does not straighten until after take-off during jumping and toe-off during running, the return of energy is too late to have an influence on performance. Because previous research has shown that increasing the bending stiffness of footwear through the use of carbon fiber plates did not increase the amount of energy stored and reused at the hip, knee, ankle, and MTP joints but did result in decreased energy lost at the MTP [8], performance improvements with the CFI used in this study are most likely based on the minimization of energy loss concept. However, a detailed understanding of the mechanisms underlying changes in performance due to alterations in footwear bending stiffness is lacking [11].

While most of the research examining the role of footwear bending stiffness on athletic performance has not translated into any commercially-available products, current research has examined the use of carbon fiber in shoe insoles (such as the XG4 Performance Insole tested in this study) and shoe midsoles (such as the recently released Nike Zoom Vaporfly 4% running shoe) in products that are available to the general public [24, 28]. The advantage of a carbon insole when compared to a carbon plate inserted into a shoe midsole is that the CFI can be used in more than one pair of footwear and athletes can select the stiffness level most appropriate for themselves based on the activity in which they are participating and their individual movement biomechanics.

5. Conclusions

Athletes attempt to improve their performance through technique improvement, training improvement, and equipment design. One aspect of athletic equipment shared by individuals across many sports is the use of footwear in training and competition. If the footwear athletes use can improve speed/acceleration, agility, and power via enhanced energetics, then there is the potential to improve performance in many sporting disciplines. The results of this study demonstrate that the use of a CFI in conjunction with standard athletic footwear can improve athletic performance. Our findings are in parallel with previous research that examined the effects of increased shoe bending stiffness (via the use of carbon fiber plates inserted into the shoe midsoles or under the shoe sock liners) on running and jumping performance [8, 10]. While the absolute changes in performance when using a CFI appear to be trivial to small (demonstrated by effect sizes ranging between 0.08-0.17), the practical significance may be substantial for sports in which hundredths of a second mean the difference between success and failure. For example, a performance improvement in sprinting of about 0.36-0.63% should make a difference in a sprinter's chance of winning a race [29]. Since we currently lack a detailed understanding of the potential mechanism(s) for performance improvement when using a CFI, athletes and coaches must experiment with varying stiffness levels to determine the optimal stiffness for sports involving sprinting, jumping, and change of direction.

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