Article

Short-Term Effects of Carbon Fiber Insole on Sports Performance, Lower Extremity Muscle Activity, and Subjective Comfort

Myeonghoon Ko[1], Tiejun Ma[1], and Shuping Xiong[1,*]

[1] Department of Industrial and Systems Engineering, Korea Advanced Institute of Science and Technology (KAIST); namichun97@kaist.ac.kr; matj@kaist.ac.kr; shupingx@kaist.ac.kr
* Correspondence: shupingx@kaist.ac.kr; Tel.: +82-42-350-3132

Abstract: Carbon fiber insole (CFI), which is lightweight and stiff to reduce energy loss and help wearers perform better in sports, has recently been introduced. However, there are scarce reports on the effects of CFI on sports performance, muscle fatigue and wearing comfort. This study investigated the short-term effects of CFI on sports performance, lower extremity muscle activity, and subjective comfort. Thirty young healthy males performed various sports tasks and treadmill runs with wearable sensors under two experimental insole conditions (benchmark insole as a baseline, CFI). The results showed that compared to the benchmark insole, CFI significantly improved sports performance in terms of power generation and agility. However, it activated more of the Tibialis Anterior and Gastrocnemius Medialis muscles and was perceived stiffer, and less comfortable. These findings suggested that CFI can improve sports performance, but it could cause more lower extremity muscle fatigue and subjective discomfort.

Keywords: Footwear; Carbon Fiber Insole; Sports Performance; Comfort; Muscle Fatigue.

1. Introduction

Wearing the proper athletic footwear is essential for an athlete to improve comfort, prevent injury, and most importantly, enhance athletic performance. As a result, the impact of footwear on athletic performance has been extensively studied, especially from an energy perspective. During athletic movements, there are two phases: one where energy is absorbed and the other where energy is generated. Thus, the main strategy to improve sports performance is to increase energy return and reduce energy loss [1-2]. Although many attempts have been made to effectively return energy, few have been successful because strong conditions must be satisfied at the same time: the energy must return at the correct location, at the right moment, and with the precise frequency [3-5]. As a result, there has been extensive research on minimizing the loss of energy during dynamic activities. If the energy is absorbed and dissipated or not stored for later use, it will be inefficient for performing sports activities. Therefore, a reduction in energy absorption may lead to an increase in athletic performance. Especially, the metatarsophalangeal (MTP) joint was predominantly dorsiflexed during the stance phase, resulting in negative work and no energy generation before take-off [6-7]. Consequently, a way of limiting the range of motion to reduce energy loss in the MTP joint was proposed, and it was confirmed that this could be achieved by stiffening the footwear, such as embedding a carbon plate in the shoes.

Several studies have explored the role of carbon plates embedded in shoes on sports performance and injury. They reported that stiffer shoes improve running economy, speed, agility, and jump performance [8-11]. As the different combinations of shoe designs and carbon plates may affect the results due to confounding, it is difficult to examine the direct effect of carbon fiber plates. Only a few studies have examined the effects of insoles with carbon fiber plates. Gregory et al. studied the effects of carbon fiber insoles (CFI) on

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athletic performance, and they reported that CFI could help athletes perform better by minimizing energy loss [12]. Also, it could increase the ratio of the lever arms of the output ground reaction force and lever arm of the ankle plantar flexor, termed the gear ratio, by adding extra gear to the foot [13]. A higher gear ratio could induce a slower shortening velocity of the plantar flexor muscles, which could improve force production on account of the force-velocity relationship [14-15]. Thus, CFI could benefit acceleration and power generation, which are critical for athletic performance. It also has the advantage of being relatively inexpensive and adaptable, as it can be inserted into a variety of shoes and easily replaced.

Footwear could play an important role in inducing localized pain, muscular fatigue, and wearing discomfort, all of which can limit sports performance. Effects on muscular fatigue and wearing discomfort were reported according to the different features and characteristics of the insole, such as material, thickness, and wedge for arch support [16-18]. Especially, insoles composed of soft material were more effective in creating a more uniform, less localized plantar pressure, and lower fatigue index [19-20]. However, more rigid and stiffer insoles demand more muscle work to absorb the impact or provide greater propulsive force to push it, which could result in muscular fatigue and wearing discomfort [21-25]. Additionally, the advanced footwear with a full-length stiff plate embedded showed a greater increase in positive work, which implies increased positive work from active foot muscle contractions [26]. The point of the force application was also affected by the increased footwear stiffness. Stiffer footwear showed the increased moment arm of the ground reaction force, which could increase the ankle joint moment and the force demand [27]. Since the triceps surae muscle group containing the soleus, lateral gastrocnemius, and medial gastrocnemius is primarily responsible for absorbing and generating the power of the ankle joint, the use of rigid footwear could induce more activation of these muscles. Although it is necessary to investigate the muscular activation when wearing CFI, there are few comprehensive reports on the influence of CFI on muscular fatigue, subjective comfort, and sports performance.

Therefore, the purpose of this study is twofold: 1) to investigate whether CFI can improve sports performance; 2) to check if CFI affects muscular activation and wearing comfort during treadmill running. It is hypothesized that the use of CFI will improve sports performance, increase muscular activation, and decrease wearing comfort.

2. Materials and Methods

2.1. Participants

Thirty healthy young males with shoe sizes between 260 and 270 mm participated in the experiment. Table 1 summarizes the demographic information of the participants. None of the participants had any type of back or lower limb pain, and they were able to complete all of the required tasks. Written informed consent was obtained from participants, and the experimental protocol was approved by the Institutional Review Board (IRB NO.: KH2021-140).

Table 1. Demographic information of participants.

Characteristics	**Mean ± SD (n=30)**
Age (years)	25.4 ± 3.2
Height (cm)	173.2 ± 5.5
Weight (kg)	69.8 ± 11.3
Shoe size (mm)	266.5 ± 4.6

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2.2. Experimental design

A within-subject design was used to investigate the influence of CFI on sports performance, muscle activation, and subjective comfort. Two experimental insoles were tested in random order: benchmark commercial insole (COM) and CFI (Figure 1). COM was made of polyurethane foam with an approximate thickness of 0.7 cm towards the front of the insole and 1cm in the heel. CFI was made of EVA, which included a carbon plate with a thickness of 0.1cm, and had an approximate thickness of 0.4 cm in the front and 0.4 cm in the heel of the insole. The experiment was conducted with participants' own sports shoes to better generalize the findings.

Figure 1. Experimental insoles. Left: benchmark commercial insole (COM); Right: carbon fiber insole (CFI)

2.3. Experimental task

In this study, three aspects of sports performance were examined: power generation test was composed of standing long jump (L-jump) and vertical jump (V-jump); agility was assessed using 5-10-5 meters agility drill (Agility); and speed was assessed using 50 meters sprint (Sprint). During L-jump, the distance was measured using a steel measuring tape ruler (Model JX-68 5 meters, JIUXING). The motion capture system was used to measure the jump height during V-jump, and data was recorded with an acquisition frequency of 120 HZ (Model V120, OptiTrack). During the agility drill, a stopwatch and a video recording were used to measure the time (Model XL-013, AnyTime). For the sprint test, completion time was measured with a stopwatch to assess the speed.

The effect of CFI on muscle usage and localized muscle fatigue was investigated by measuring muscular activation while running on a treadmill (Model S21T, STEX fitness Europe). The activation of lower extremity muscles was recorded with a sampling frequency of 1000Hz using surface electromyography sensors (EMG, Bagnoli, Delsys).

2.4. Experimental Procedure

The experiment consisted of two phases, which were conducted outdoors and indoors, respectively. In the outdoor phase, all participants were asked to perform a stretching and dynamic warm-up for at least 10 minutes. After warming up, participants performed the outdoor experimental task in L-jump, Agility, and Sprint sequence. The L-jump consisted of a counter-movement jump with an arm swinging to jump as far horizontally as possible. Participants stood upright with a marked line on the ground, then performed the maximum effort L-jump. For a successful trial, participants were required to land on their feet and were not allowed to move. The performance was assessed as the horizontal distance from the starting line to their shoe heel location (Figure 2A). After finishing the L-jump task, participants performed an Agility composed of three sprints and two cutting movements to change their directions. There were two cones with a bar

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on the place that occurred cutting movement, and participants were required to touch the bar when they changed their direction (Figure 2B). Performance was defined as the time to complete the drill. Lastly, participants performed Sprint to measure their speed. They sprinted from the starting line on the track and stopped after passing the end line marked as the two cones with the bar 50 meters from the starting line. The performance outcome was defined as the speed to complete the Sprint.

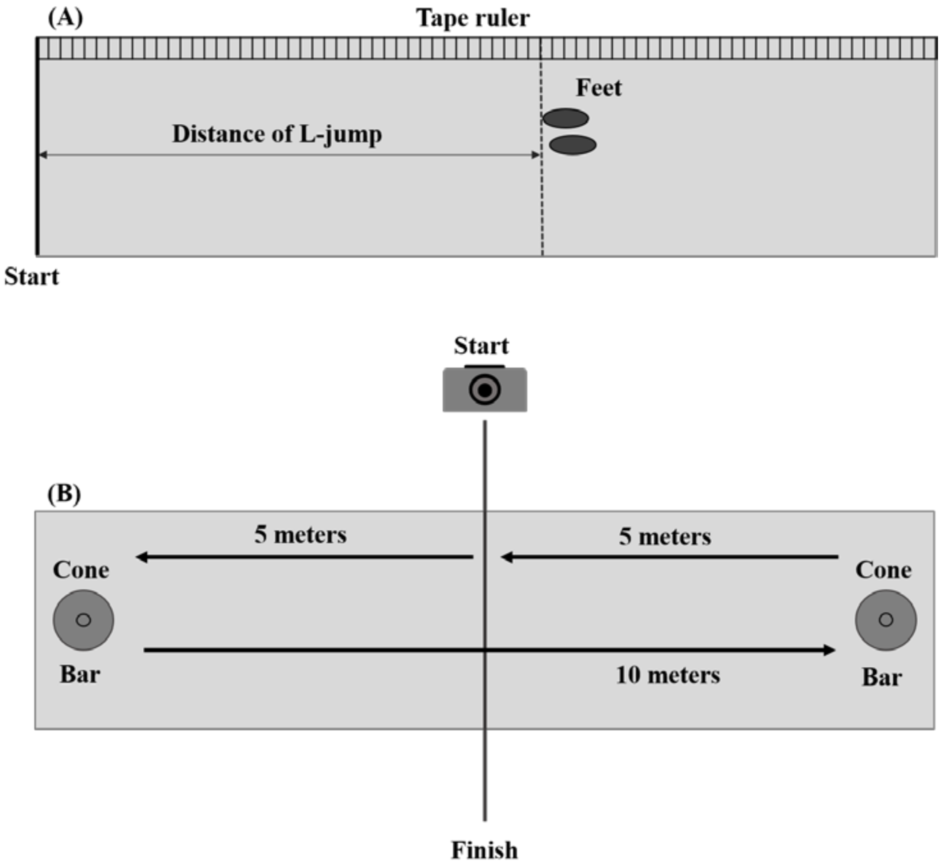

Figure 2. Schematic diagram of sports performance tests (A: L-jump test, B: Agility test)

After finishing all outdoor experimental tasks, the last sports performance test, V-jump, was performed indoors due to the need for an optical motion capture system to accurately measure vertical jump heights. A reflective marker was attached to the shin where no disturbance occurred during V-jump. The V-jump consisted of a counter-movement jump with an arm swinging to jump as far vertically as possible. Participants stood upright with a marked point on the floor, then performed the maximum effort V-jump. For a successful trial, participants were required to stretch their lower legs after toe-off from the ground. Performance was assessed as the height from the reference to the maximum location of the marker, and the reference was defined as the average location of the marker for standing posture for two seconds before the jump. The participants completed three successful trials for each task in each insole condition.

Before the treadmill running task, participants were given at least 10 minutes to relieve muscular fatigue. Then, the participants' skin was prepared by removing excessive hair and cleaning with alcohol. Next, four EMG sensors were attached to the skin using adhesive tape and firmly fixed with the strap to minimize potential noise from any detachment or tremble. As shown in Figure 3, four EMG sensors were attached to Rectus Femoris (RF), Tibialis Anterior (TA), Biceps Femoris (BF), and Gastrocnemius Medialis

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(GM) muscles, which mainly activated muscles during sprinting [28]. Each muscle's maximum voluntary contraction (MVC) was measured twice, with two minutes of rest between each trial.

Figure 3. Locations of EMG sensors on the lower extremity (A: Rectus Femoris, B: Tibialis Anterior, C: Biceps Femoris, and D: Gastrocnemius Medialis)

Participants were instructed to walk at 3km/h for at least 30 seconds to familiarize themselves with the task of running on the treadmill. Afterward, they jogged at 6km/h for at least 30 seconds and ran at a speed of 10km/h for 5 minutes. Participants then ran or walked at their preferred speeds for at least one minute to cool down. After completing a trial run with each insole, participants gave their subjective evaluation of perceived insole stiffness, energy support, overall comfort, and fatigue through a 9-point rating scale. Participants were given at least ten minutes to rest between trials to avoid the fatigue effect.

2.5. Data analysis

Dependent variables were performance measures for each sports task (power generation: distance of L-jump and height of V-jump; agility: completion time of agility test; speed: sprint speed), muscular activation of four muscles, and subjective ratings after treadmill running. The average value of three successful trials during sports was used to determine the effect of CFI. The EMG data during the whole task were rectified, normalized, and smoothed using the root mean square (RMS) filter to perform a linear envelope.

All data were checked with the Shapiro-Wilk test and box-plot to identify the deviations from normality and detect outliers [29]. A paired-samples t-test (normally distributed data) or a one-sample Wilcoxon signed-rank test (normality violated) was conducted to statistically evaluate the effects from two different insoles, with the level of significance set to $\alpha=0.05$ [30]. In addition, for parametric data, the effect size was calculated using Cohen's d which is defined as the difference between two means divided by a standard deviation for the data: Small (d=0.20), Medium (d=0.50), Large: (d≥0.80). For nonparametric data, r was calculated by dividing the absolute standardized test statistic by the square root of the number of pairs: Small (r=0.10), Medium (r=0.30), Large (r≥0.50) [31-32]. Excel (Microsoft, USA) and EMGworks (Delsys, USA) were used to process all data, and SPSS software version 20.0 (SPSS Inc., Chicago Illinois) was employed to conduct all statistical tests.

3. Results

3.1. Sports performance

Comparison results between sports performance from two different insoles (COM, CFI) are presented in Table 2 and Figure 4. CFI wearers showed better performance in jumping. The V-jump height of CFI wearers was averaged at 45.66 cm, marginally higher (p=0.054) than that of COM wearers (44.97 cm). In addition, CFI wearers had significantly greater (p=0.032) L-jump distance than COM wearers (211.27 vs. 208.19 cm). For agility, CFI wearers displayed marginally more agile performance than COM wearers (task completion time: 5.71 seconds vs. 5.76 seconds, p=0.098). In Sprint, however, there was no significant difference (p=0.223).

Table 2. Summary results comparing the sports performance from two different insoles: benchmark commercial insole (COM) versus carbon fiber insole (CFI).

Task		Performance measurement (Mean±SD)		Paired t-test			Effect Size
		COM	CFI	t	df	P-value	
Power Test	V-jump (Height, cm)	44.97±7.43	45.66±7.27	-2.009	28	0.054ǂ	0.37
	L-jump (Distance, cm)	208.19±19.17	211.27±20.75	-2.255	29	0.032*	0.41
Agility Test	5-10-5 meters agility drill (Time, second)	5.76±0.36	5.71±0.36	1.712	29	0.098ǂ	0.29
Speed Test	50-meter sprints (Speed, m/s)	6.21±0.45	6.27±0.49	-1.244	29	0.223	0.23

Remarks: * indicates a statistically significant difference ($p < 0.05$), and ǂ indicates a marginally significant difference ($0.05 < p < 0.10$).

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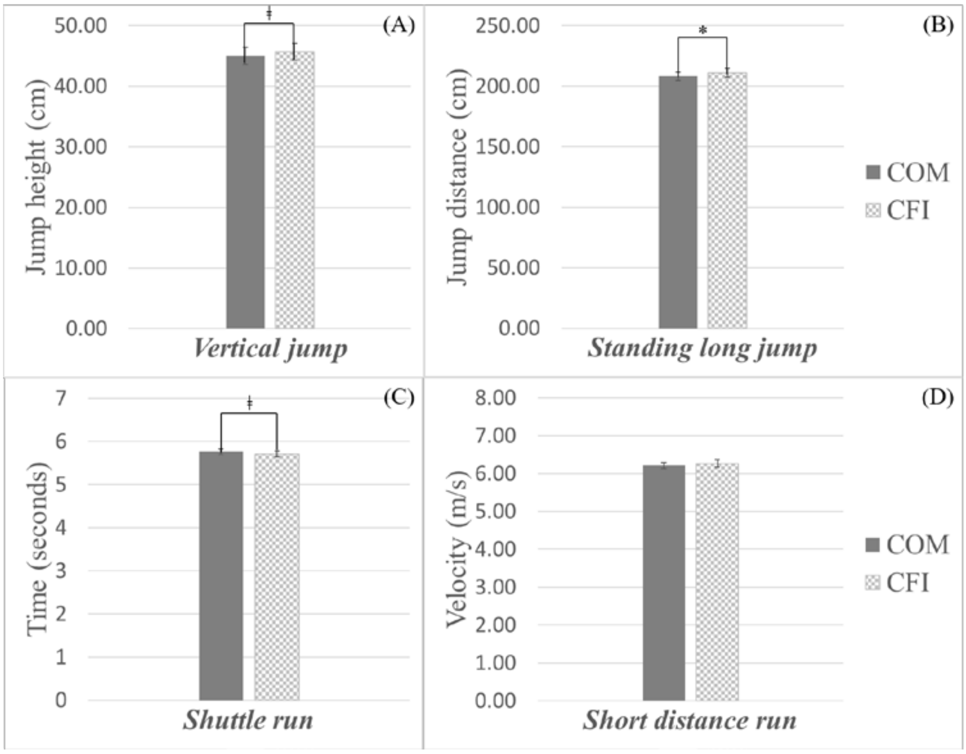

Figure 4. Sports performance measures from the benchmark commercial insole (COM) and carbon fiber insole (CFI). (A: V-jump, B: L-jump, C: Agility, and D: Sprint) Note. * indicates a statistically significant difference, and ǂ indicates a marginally significant difference.

3.2. Muscular activation

Table 3 shows the comparison results on muscular activation from two different insoles. There were significant differences in muscular activation during treadmill running for the different insole conditions (Figure 5). The paired t-test revealed significant differences between COM and CFI on activation of TA and GM. However, there was no significant difference between the two different insoles in muscular activation of RF (p=0.164) and BF (p=0.879). When the participants wore CFI, their TA muscle activation was significantly higher (+0.68%; p=0.015) than while wearing COM. In addition, muscular activation of GM while wearing CFI was marginally higher (+0.83%; p= 0.067) than when wore COM.

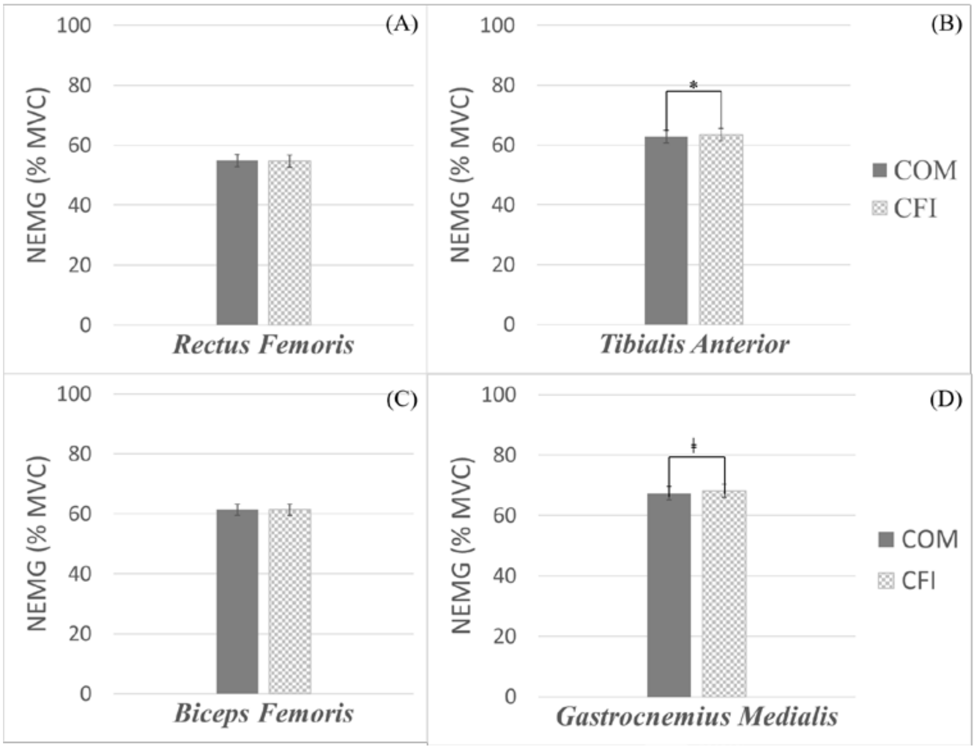

Figure 5. Normalized muscular activation (%) during treadmill running task from the benchmark commercial insole (COM) and carbon fiber insole (CFI). (A: Rectus Femoris, B: Tibialis Anterior, C: Biceps Femoris, and D: Gastrocnemius Medialis)

Note. * indicates a statistically significant difference, and ǂ indicates a marginally significant difference.

Table 3. Summary results comparing muscular activation from two different insoles: benchmark commercial insole (COM) versus carbon fiber insole (CFI).

	Muscles	**NEMG: % MVC (Mean±SD)**		**Paired t-test**			**Effect Size**
		COM	**CFI**	**t**	**df**	**P-value**	
Localized muscular fatigue	**RF**	54.85±11.24	54.68±11.11	1.428	28	0.164	0.27
	TA	62.76±11.04	63.44±10.90	-2.617	26	0.015*	0.50
	BF	61.42±10.24	61.40±10.23	0.153	28	0.879	0.03
	GM	67.33±11.87	68.17±11.61	-1.902	29	0.067ǂ	0.35

Remarks: * indicates a statistically significant difference, and ǂ indicates a marginally significant difference.

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3.3. Subjective evaluation

Table 4 summarizes the comparison results on subjective ratings from two different insoles. The participants perceived significant differences in stiffness, energy support, and overall comfort between COM and CFI while running on a treadmill (Figure 6). However, they did not perceive any significant difference in fatigue between the two different insoles ($p=0.389$). When the participants wore CFI, they felt that it was significantly stiffer ($p<0.001$), provided larger energy support ($p=0.047$), but resulted in less comfort ($p=0.002$) than when they wore COM.

Table 4. Summary results comparing subjective ratings from two different insoles: benchmark commercial insole (COM) versus carbon fiber insole (CFI).

	Items	**Median±SD**		**Wilcoxon signed-rank test**			**Effect Size**
		COM	**CFI**	**Z**	**N**	**P-value**	
Subjective rating (1-9 scale)	**Stiffness**	2.60±1.04	6.17±1.34	-4.727	30	<0.001*	0.86
	Energy support	4.67±1.97	5.67±1.71	-1.982	30	0.047*	0.36
	Overall comfort	6.77±1.68	5.43±1.72	3.048	30	0.002*	0.56
	Fatigue	3.83±1.60	4.13±1.55	-0.861	30	0.389	0.16

Remarks: * indicates a statistically significant difference, and ǂ indicates a marginally significant difference.

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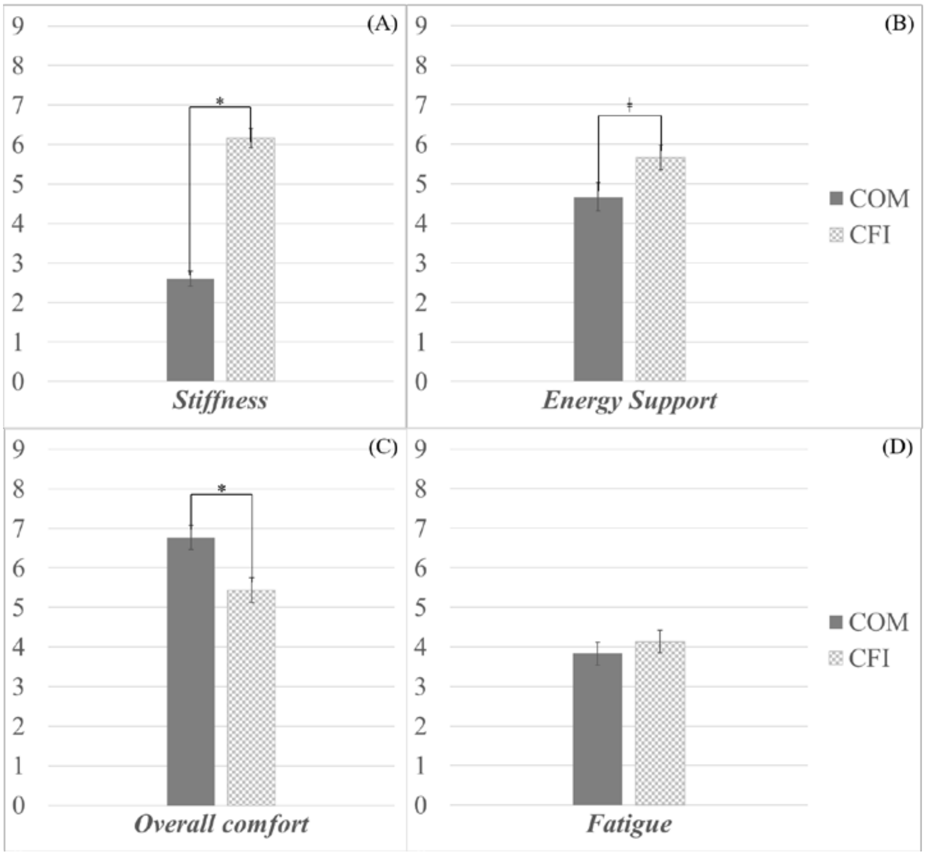

Figure 6. Subjective ratings after treadmill running from the benchmark commercial insole (COM) and carbon fiber insole (CFI). (A: Stiffness, B: Energy support, C: Overall comfort, and D: Fatigue)

Note. * indicates a statistically significant difference, and ǂ indicates a marginally significant difference.

4. Discussion

As expected, CFI significantly improved sports performance compared to COM. In terms of power generation, the average distance of the L-jump and height of the V-jump was improved by about 1.5 %. A possible reason for this improvement may be related to energy loss in the MTP joint. While jumping, it has been shown that the MTP joint does not extend until take-off [33]. Since the joint is flexed during stance, there is no energy generated, resulting in lost energy. In terms of sports performance, this energy dissipation appeared to be inefficient. Reduced energy loss in the MTP joint was observed when the participants wore a stiffer shoe, and jump performance was improved while wearing this shoe [6]. Thus, wearing CFI, which is stiffer than COM, could improve the jump performance by reducing energy loss in the MTP joint. In addition, CFI could help generate power by adding extra gear to the forefoot [13]. An extra gear could increase the moment arm of ground reaction force, resulting in a higher gear ratio. It could induce a slower shortening velocity of the plantar flexor muscles and longer contact time with the forefoot and ground, which could be favorable for force production [14].

There was a marginal improvement (~1%) in agility while wearing CFI. This finding is in line with a previous study that reported that shoes with stiffer plates enhanced agility performance [34]. Even though the underlying reasons for this result remain unclear, one possible hypothesis is that when the participants wore CFI, they kept more of their running speed when changing directions. Improvement of agile performance from CFI might be because the carbon fiber plate stiffened the insole to provide energy support, dynamic

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balance, and ankle joint stability by supporting the ankle. On the other hand, the softer sole provides an unstable support base and decreased somatosensory feedback from the foot's cutaneous receptors, leading to reduced balance performance than the stiffer sole [35-36]. Thus, it might be one possible reason CFI wearers showed better agile performance than COM wearers. Further research is needed to test this hypothesis with kinematic measurements collected by a motion capture system while performing multi-directional movements.

For sprint running, the effect of footwear stiffness on sprint performance is still being examined among researchers, but the evidence is conflicting. While wearing stiffer shoes, a decrease in sprint time was reported in the previous study [10]. Conversely, stiffer shoes were also reported to have no significant effect on sprint performance [37-38]. This study also did not appear to have any improvements in sprint performance with CFI. It may have originated from factors affecting running performance, such as contact time, ground reaction force, etc. According to a previous study [39], there was an increase in contact time and reduced average ground force application when wearing stiffer shoes, which could have led to decreased sprint performance. The improvement in sprint may not have been achieved because the increased contact time due to the use of CFI might offset the improvement in sprint performance obtained by using CFI. Also, a higher gear ratio could affect the sprint performance. Although several studies have investigated the effect of gear ratio on running performance, it is not well understood. A higher ratio could increase running performance by exerting greater tendon force, leading to greater storage and release of elastic strain energy [40-41]. However, this explanation disregards the possibility that the extra force demands more effort than greater storage and release of energy. During the sprint, larger muscular force was required for propulsion while wearing CFI, and if these are accumulated step by step, there is a possibility that they might have a deleterious effect on the sprint performance. This assumption could be supported by Kovács et al.. They reported that a higher gear ratio demanded more muscular effort and concluded that a lower gear ratio could be beneficial for running [42].

Sports performance tests in this study showed that increased stiffness of the insole improves power generation and agility, but not speed. There was a significant increase in distance and height of the jump when using CFI. In addition, there was a marginally decrease in time to complete the Agility wearing CFI. The absolute measures of each sports performance for each insole, as well as the effect size for each comparison, are shown in Table 2. Even though the improvements are minor and the effect size is relatively small, performance improvement in sports performance of about 0.36 to 0.63 % could change an athlete's chances of winning a game [43]. For an athlete, even a small amount of improvement is worthwhile. The jump and agility performance while wearing CFI was improved by about 1.5% and 1 %, respectively. Thus, these changes can be meaningful and practical.

Although sports performance can be improved while wearing CFI, when running on a treadmill, muscular activation was significantly higher. When the participants wore CFI, the activation of TA was significantly higher by 0.7%, with a moderate effect size (Table 3). This is because the primary function of the TA muscle is to absorb the impact [28, 44]; on the other hand, CFI is designed for reducing energy loss to improve sports performance, resulting in impact absorption reduction. Thus, the participants were required to exert the TA muscle more to cushion the impact. Additionally, GM muscle activation was marginally higher by 0.8%, with a small to moderate effect size (Table 3). There are two potential reasons for the increased activation of GM muscle. First, stiffer footwear may change the point of the force application. Previous studies found that a stiffer shoe's anterior point of force application was moved anteriorly during the last 25% of the stance phase [45]. It resulted in increasing the participant's moment arm, which could increase the moment of the ankle joint and the force demand. Because GM muscle is a kind of the triceps surae that plays a primary role in absorbing and producing the power of the ankle joint [27], stiffer footwear could lead to greater GM muscle activation. Second, it might come from a higher stiffness of CFI. The insole should be bent during the propulsion phase, but CFI is more difficult to be flexed than COM. As a result, the participant had to put more effort into bending CFI, increasing GM muscular activation. Increased muscular activation can lead to localized pain, inflammation, and muscle fatigue, negatively affecting sports performance. It was shown that wearing CFI while running on a treadmill had a negative effect on localized fatigue.

Comfort is an essential factor in designing footwear since uncomfortable footwear can alter the gait and lower extremity muscle activity during running, which could affect sports performance as well as the risk of injury [24, 46]. In addition, the wearing comfort of the shoes was identified as a major parameter in considering foot health, energy demand, and muscle strain [21]. In this study, CFI was perceived as uncomfortable compared with COM since it is significantly stiffer, generating greater muscle activity during the fast run. Also, the effect size of comparing the overall comfort showed a large effect, meaning that there is a practical significance in perceived comfort between CFI and COM (Table 4). According to the findings of this study, using CFI improved sports performance and provided energy support perception, but it also caused wearing discomfort and increased muscle usage, implying that CFI should be used appropriately for the user's purpose.

This study has some limitations. First, although wearing the stiffer CFI improved athletic performance, the optimal stiffness cannot be investigated in this study as only two different insoles were available. Second, the duration of the treadmill running (5 minutes per trial) may be somewhat short compared to some previous studies [9, 47]. Thus, the RMS values of the normalized EMG (<70%) in this study were lower than in the previous study [48]. Further studies with various insoles of different stiffness and longer test durations could be conducted to examine the long-term effects of CFI.

5. Conclusions

This study investigated the short-term effects of CFI on sports performance, lower extremity muscular activation and subjective comfort. The results showed that compared to the benchmark insole, CFI significantly improved sports performance in terms of power generation and agility. However, it activated more of the Tibialis Anterior and Gastrocnemius Medialis muscles and was perceived stiffer and less comfortable. These findings suggested that CFI can improve sports performance, but it may lead to more muscular fatigue and subjective discomfort.

Author Contributions: Conceptualization, S.X and M. K; methodology, M. K and T. M; formal analysis, M. K and T. M; investigation, M. K and T. M; resources, S.X.; data curation, M. K and T. M; writing—original draft preparation, M. K; writing—S. X; supervision, S.X.; project administration, S.X.; funding acquisition, S. X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by BK21 FOUR Program through the National Research Foundation of Korea (NRF-5199990113928).

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of KAIST (IRB NO.: KH2021-140).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We thank all the subjects who participated in this study.

Conflicts of Interest: The authors declare no conflict of interest.

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