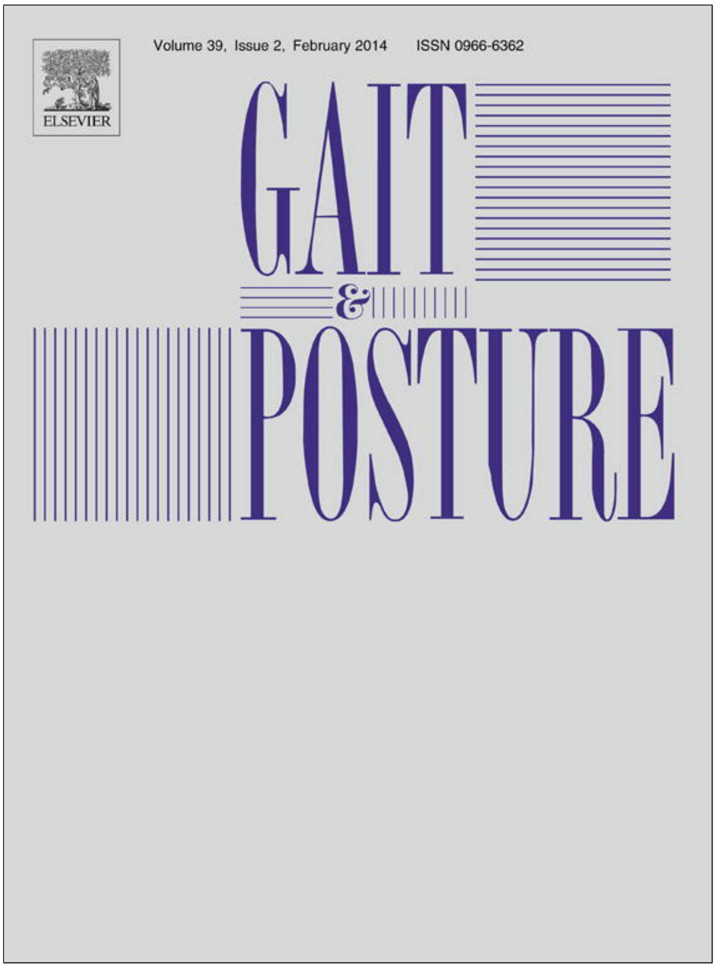
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Plantar loading during jumping while wearing a rigid carbon graphite footplate

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ABSTRACT

Fifth metatarsal stress fractures are common in sports and often result in delayed and non-union. The purpose of this study was to examine the effect of a rigid carbon graphite footplate (CGF) on plantar loading during take-off and landing from a jump. Nineteen recreational male athletes with no history of lower extremity injury in the past 6 months and no foot or ankle surgery in the past 3 years participated in this study. Subjects completed 7 jumping tasks while wearing a standard running shoe and then the shoe plus the CGF while plantar loading data was recorded. A series of paired *t*-tests were used to examine differences between the two footwear conditions independently for both takeoff and landing ($\alpha = 0.05$). The contact area in the medial midfoot ($p < .001$) and forefoot ($p = .010$) statistically decreased when wearing the CGFP. The force–time integral was significantly greater when wearing the CGFP in the middle ($p < .001$) and lateral forefoot ($p = .019$). Maximum force was significantly greater beneath the middle ($p < .001$) and lateral forefoot ($p < .001$) when wearing the CGFP, while it was decreased beneath the medial midfoot ($p < .001$). During landing, the contact area beneath the medial ($p = .017$) and lateral midfoot ($p = .004$) were significantly decreased when wearing the CGFP. The force–time integral was significantly decrease beneath the medial midfoot ($p < .001$) when wearing the CGFP. The maximum force was significantly greater beneath the medial ($p = .047$) and middle forefoot ($p = .001$) when the subject was wearing the CGFP. The maximum force beneath the medial midfoot ($p < .001$) was significantly reduced when wearing the carbon graphite footplate. The results of the study indicate that the CGF is ineffective at reducing plantar loading during jumping and landing.

1. Introduction

Previous studies have identified many risk factors for foot and ankle injury when playing sports. These factors include the sport being played, the position on the field, as well as age, gender, competition level, bone density, and type of shoe [1–4]. Stress fractures account for approximately one-tenth of all overuse injuries and are one of the most common bony injuries in sports [5]. The most common locations for stress fractures are in the tibia, followed by the metatarsals [6,7]. Metatarsal stress fractures comprise a quarter of all stress fractures of the foot [4]. The incidence of 5th metatarsal stress fractures have never been well defined in the literature, however, this type of fracture is difficult to heal and results in substantial loss of time from sport. However, little is known about the factors that relate to the mechanism of metatarsal loading during jumping.

Previous studies have shown that sex has a role in fifth metatarsal stress fractures incidence, indicating that men are much more likely than women to sustain these injuries [3,4]. Gender differences in plantar loading has been reported in previous studies and may indicate that men are at increased risk for injury due to the increase in plantar loading during athletic tasks [8,9]. Additionally, male athletes exhibit increased plantar loading on the lateral portion of their forefoot and midfoot during cutting athletic tasks [10]. This additional loading may be associated with the elevated risk of this injury in males.

One way that the load on the 5th metatarsal is off loaded in patients with a stress fracture is with a combination of modified footwear, custom orthoses, and foot braces [11–13]. Different types of custom orthoses are available, including semiflexible or rigid carbon varieties [14]. Custom orthotics are often used in treatment to lower the risk of stress fractures through a reduction in the plantar load beneath the base of the 5th metatarsal [15].

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Using custom orthoses in combination with a carbon shank has been shown effective in allowing elite collegiate athletes to return to play with this modified footwear while their metatarsal stress fractures healed [16]. However, to date it is not known how these orthoses change loading under the 5th metatarsal during typical athletic activities and if the reduction in loading is what is allowing these athletes to return to activity more quickly.

The goal of this study was to quantify the effect of a rigid carbon graphite footplate on plantar loading during the takeoff and landing of a jump. Our hypothesis was that plantar loading beneath the lateral aspect of the foot would be decreased after placing the carbon graphite footplate into athletic shoes. If the carbon graphite footplate is capable of decreasing loads beneath the lateral column of the foot, it could be used to unload the foot following fifth metatarsal stress fractures during recovery and to reduce the high rate of recurrent injury when the athlete returned to full sport participation.

2. Methods

A total of 19 male subjects were tested. Subjects in this study were college-aged, recreational athletes who participated in physical activity three times per week for approximately 1 h each session. Subjects were excluded if they had any history of lower extremity injury in the past 6 months, foot or ankle surgery in the past 3 years, or previous metatarsal stress fractures. Each subject read and signed informed consent that had been approved by the medical center's institutional review board.

Plantar pressure data was collected using a Pedar-X in-shoe pressure measurement system (Novel, St. Paul, MN, USA). The plantar pressure insoles were placed bilaterally inside the subject's shoes on top of the sock liner of the shoe and covered the entire plantar surface of the foot. The plantar pressure data were sampled using these plantar pressure insoles at 100 Hz via Bluetooth technology. All plantar pressure insoles were calibrated prior to data collection according to manufacturer's guidelines. Subjects were fitted with the appropriate size shoe, plantar pressure insole, and rigid carbon graphite footplate. The rigid carbon graphite footplate was placed beneath the sock liner of the shoe during testing, while the plantar pressure insole was placed on top of the sock liner. All testing was completed in a neutral cushioning running shoe (Nike Air Pegasus, Nike, Inc.; Beaverton, Oregon).

After the footwear that included the plantar pressure insoles was donned, each subject was asked to complete a series of jumping tasks. Subjects were asked to complete a simulated layup task 7 times. Subjects were asked to complete a 4 step approach take off on one foot and then land on the same foot, which is consistent with a basketball layup. This simulated layup task was completed in both test conditions (with and without the rigid carbon graphite footplate). The testing order was randomized for test condition (with and without the rigid carbon graphite footplate) to avoid fatigue and learning effects. Subjects were given a 30 s rest between trials and a 5-min rest between testing conditions.

For analysis, the foot was divided into eight anatomical regions (heel (or rearfoot), medial midfoot, lateral midfoot, medial forefoot, middle forefoot, lateral forefoot, hallux, and the lesser toes) using a percentage mask in the Novel Multiproject-ip software (Novel) [17–21]. The plantar pressure variables that were obtained during all trials were the force–time integral, maximum force, peak pressure, contact time and contact area. These variables were calculated for the jumping and landing aspects of the trials. The seven trials for each testing condition were averaged for statistical analysis. The maximum force was

Table 1
Differences in plantar loading when wearing the carbon graphite footplate (CGFP) during (A) Jumping and (B) Landing. (* indicates a statistically significant difference between the footwear conditions.).

	Foot region	No CGFP	CGFP	p-Value
(A)				
Contact area (NICA)	MMF	.128 ± .03	.082 ± .04	<.001*
	LMF	.154 ± .01	.148 ± .02	.124
	MFF	.073 ± .01	.070 ± .01	.010*
	MidFF	.086 ± .003	.086 ± .001	.379
	LFF	.083 ± .002	.083 ± .002	.955
Force–time integral (Ns)	MMF	16.26 ± 5.48	9.65 ± 5.43	<.001*
	LMF	55.71 ± 24.54	52.33 ± 28.11	.154
	MFF	33.10 ± 16.53	31.79 ± 17.46	.568
	MidFF	46.50 ± 19.71	54.24 ± 18.85	<.001*
	LFF	43.58 ± 13.76	46.88 ± 13.74	.019*
Maximum Force (BW)	MMF	.21 ± .073	.12 ± .074	<.001*
	LMF	.54 ± .21	.56 ± .26	.374
	MFF	.32 ± .10	.32 ± .12	.643
	MidFF	.46 ± 10	.55 ± .14	<.001*
	LFF	.43 ± .11	.48 ± .12	<.001*
(B)				
Contact area (NICA)	MMF	.145 ± .02	.130 ± .04	.017*
	LMF	.156 ± .003	.130 ± .04	.004*
	MFF	.076 ± .003	.075 ± .004	.239
	MidFF	.086 ± .002	.086 ± .002	.985
	LFF	.084 ± .001	.083 ± .003	.136
Force–time integral (Ns)	MMF	20.46 ± 8.54	14.69 ± 8.31	<.001*
	LMF	40.69 ± 24.03	35.82 ± 16.10	.256
	MFF	59.58 ± 27.35	63.46 ± 25.35	.205
	MidFF	62.46 ± 25.19	78.11 ± 28.45	<.001*
	LFF	43.23 ± 18.44	44.29 ± 17.06	.619
Maximum force (BW)	MMF	.48 ± .18	.35 ± .17	<.001*
	LMF	.62 ± .22	.60 ± .22	.359
	MFF	.46 ± .16	.50 ± .16	.047*
	MidFF	.50 ± 15	.60 ± .17	.001*
	LFF	.39 ± .12	.39 ± .12	.947

normalized to each subject's body weight and the contact area of the entire foot and each foot region was normalized to the entire insole contact area (NICA) [19].

Statistical analysis was completed using a series of paired *t*-tests in order to examine the differences between the two test conditions (with and without rigid carbon graphite footplate) first during the take-off phase of the jump and then the analysis was completed again to examine the landing phase ($\alpha < 0.05$) for each of the study variables of interest. While measurements were obtained for the entire foot and all eight anatomical regions of the foot, the only regions of interest for this study were the medial, middle and lateral forefoot and the medial and lateral midfoot and therefore statistical analysis was completed only on these 5 foot regions.

3. Results

The subjects had an average height of 1.78 ± 0.07 m, mass of 75.47 ± 8.57 kg, BMI of 23.8 ± 2.2, and were 21.4 ± 2.38 years of age. When examining the differences in plantar loading parameters during jumping a statistically significant difference existed in the contact area in the medial midfoot ($p < .001$) and medial forefoot ($p = .010$) (Table 1, Fig. 1). The contact area was decreased in both of these regions when the subjects were wearing the carbon graphite footplate. In addition, the force–time integral was significantly greater when wearing the carbon graphite foot plate beneath the middle forefoot (p,.001) and the lateral forefoot ($p = .019$) (Table 1, Fig. 1). However, the force–time integral was significantly decreased when wearing the carbon graphite footplate beneath the medial midfoot ($p < .001$). Finally, when examining the maximum force in the foot regions of interest the maximum force was significantly greater beneath the middle forefoot ($p < .001$) and the lateral forefoot ($p < .001$) when wearing the carbon graphite footplate, while it was decreased beneath the medial midfoot ($p < .001$) (Table 1, Fig. 1).

The second task of interest was landing from a jump. The landing results were different than those that were observed during jumping. During landing, the contact area beneath the medial midfoot ($p = .017$) and lateral midfoot ($p = .004$) were significantly decreased when wearing the carbon graphite insert. (Table 1b, Fig. 2) In addition, when examining the changes in the force–time integral the subjects demonstrated a significant decrease beneath the medial midfoot ($p < .001$) when wearing the carbon graphite footplate. In contrast the force–time integral was significantly increased beneath the middle forefoot ($p < .001$) when wearing the carbon graphite footplate (Table 1b, Fig. 2). Finally during landing the maximum force was significantly greater beneath the medial forefoot ($p = .047$) and the middle forefoot ($p = .001$) when the subject was wearing the carbon graphite footplate. However, the maximum force beneath the medial midfoot ($p < .001$) was significantly reduced when wearing the carbon graphite footplate (Table 1b, Fig. 2). No other study variables were statistically significant differences existed between the two testing conditions.

4. Discussion

The purpose of this study was to determine the magnitude of change in plantar loading during takeoff and landing of a jump with the use of a rigid carbon fiber footplate. The results of this study indicate that plantar pressure is not reduced beneath the lateral portion of the foot with the rigid carbon graphite footplate, but rather is remains unchanged during landing and increases during jumping in a normal healthy control group. During the jump, the maximum force was increased beneath the lateral forefoot when the carbon footplate was used.

Previous literature on the effect of jumping on plantar pressure distributions is limited. One study by Queen et al., looked at the effect of jumping with different foot types. For subjects with flat feet, landing from a jump resulted in higher contact area and maximum forces in the medial midfoot when compared to subjects with normal foot types [22]. However, the current study only minor differences in plantar loading beneath the lateral column

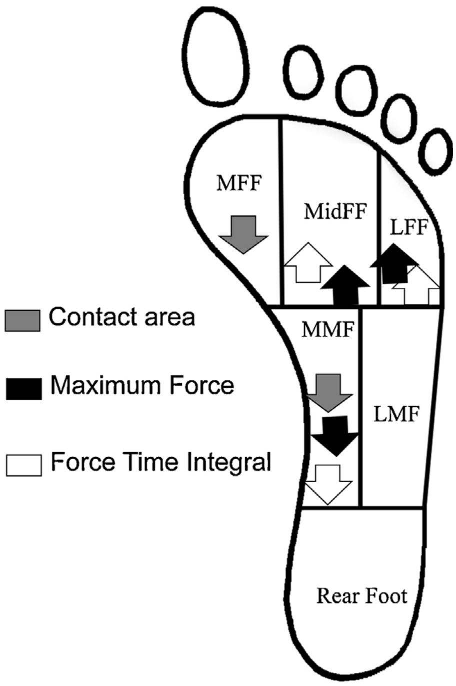

Fig. 1. Changes in regional plantar data during jumping due to test condition (rigid carbon graphite footplate, no rigid carbon graphite footplate). Arrow indicates the change in the specific variable when the carbon graphite footplate was worn in the shoe.

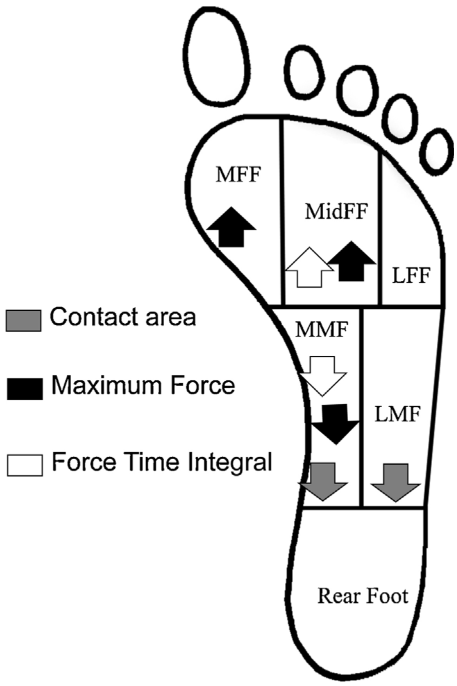

Fig. 2. Changes in regional plantar data during landing from a jump due to test condition (rigid carbon graphite footplate, no rigid carbon graphite footplate). Arrow indicates the change in the specific variable when the carbon graphite footplate was worn in the shoe.

which could result in base of the 5th metatarsal stress fracture. The lack of difference in lateral column loading reported in the current study could have been the result of differences in foot type, which were not assessed in this study. However, this study had a completely within subject design and therefore foot type should not have influenced the relative differences between trials in which the subjects wore the carbon graphite foot plate and those trials when they did not unless the lack of differences was the result of increased foot mobility that has been shown in subjects with a flat foot.

Another study by Orendurff et al., examined the effect of running, cutting, jumping and landing on plantar pressures throughout the foot [23]. This study found no statistically significant difference in plantar pressure during the takeoff or landing phases of jumping as compared to normal running. More specifically, the study also did not find any statistically significant differences in plantar pressure under the 5th metatarsal head performing jumping athletic maneuvers. While the Orendurff study did not show any change in the lateral aspect of the foot during normal movement tasks the study did not examine the effect of altering the foot–shoe interface with something like a rigid carbon graphite footplate, which as shown in the current study can alter plantar loading beneath the lateral portion of the foot during jumping.

During both phases of the jump, takeoff and landing, different regions of the foot experienced increased pressures and decreased contact area. When examining the effect of plantar loading on the incidence of 5th metatarsal stress fractures, the area of interest is the lateral column, which includes the lateral forefoot and lateral midfoot. For the rigid carbon graphite footplate to be an effective treatment following 5th metatarsal stress fractures, we hypothesize that the loading along the lateral column, underneath the 5th metatarsal, should be reduced. However, the results of this study demonstrate increased plantar loading after placing the rigid carbon graphite footplate into the subjects' shoes, during jumping which opposes our hypothesis. These findings are consistent with other studies in the literature examining the effect of athletic tasks, such as cutting, on plantar loading [17,19]. During the jumping task, subjects wearing the rigid carbon graphite footplate experienced decreased contact area in the medial midfoot and increased maximum force in the middle and lateral forefoot.

The increased force and decreased contact area at these two regions of the foot when using the rigid carbon graphite footplate indicates that instead of being a viable post-injury rehabilitation tool and reducing the chances of developing a repeated stress fracture in the 5th metatarsal, the carbon graphite footplate may actually increase the loading at the injury site on the foot and could delay return to play, extend healing time, and increase chances of recurrence. However, the interaction of loading the fracture in way and healing is not well understood. The loading of the fracture site through the use of the carbon graphite footplate could possibly improve healing through the initiation of bone remodeling under this type of loading condition. Therefore, increasing loads over the lateral column may actually help to heal 5th metatarsal stress fractures, however, this would need to be examined in future studies examining loading differences with the use of a rigid carbon graphite footplate in subjects with a 5th metatarsal stress fracture while monitoring the healing process.

There are many factors which can increase plantar loading and which are risk factors for 5th metatarsal fractures [2], therefore, other forces that may also be at work must also be considered. One example is shear force, which may exist between the foot, shoe, and rigid carbon footplate, however, shear forces cannot be measured using current plantar loading systems. Shear stress could be a key factor in tissue and bone injury that may affect healing from a fifth metatarsal stress fracture as well as the development of additional stress fractures and injuries in the foot by working singularly or even in combination with the effects of plantar loading [24]. Therefore, the effect of shear forces and the inability to quantify them along with plantar loading is a limitation of this study. Better understanding of the combination of these forces during different athletic maneuvers could better define the risk of potential injury. While many factors were controlled for in this study, such as gender, shoe, and athletic task, other factors might interact during jumping to influence the pressure distribution patterns, including, but not limited to, speed of movement and type of movement [19,25,26]. Another potential limitation of this study was that the self-selected jumping height. Further, the jumps were all performed when the subjects were not fatigued, a factor in acute [27] and overuse injury [28]. Relative changes in plantar loading due to fatigue are unknown. The interactions of these different limitations in normal subjects, injured athletes, as well as during and after returning to sports participation are unknown.

The study results do not support our hypothesis that using a rigid carbon graphite footplate will reduce plantar loading during jumping as compared to performing these tasks in shoes without the rigid carbon graphite footplate. To the contrary, our results show that use of a rigid carbon graphite footplate in healthy active subjects actually increases the load under the lateral column of the foot. Based on the results of this study the use of a rigid carbon graphite footplate in the treatment of patients recovering from a fifth metatarsal stress fractures should be done cautiously with medical monitoring in order to ensure that the fracture is healing as expected. The results of this study point to the potential need to do additional studies in subjects with a previous history of metatarsal stress fractures to determine if these injured patients respond to the rigid carbon graphite footplate in the same way as the non-injured control subjects. In addition, the results of this work indicate there is a need for exploring other treatment modalities in patients following 5th metatarsal stress fractures to improve healing and decrease the risk of recurrent injury.

5. Perspective

Stress fractures of the 5th metatarsal continue to affect athletes across various sports and impair ability to play. Standard of care for these injuries have included the use of rigid carbon graphite footplates, along with custom orthotics and foot braces [16]. The results of this study show that plantar loading is increased under the lateral column during jumping when wearing a rigid carbon graphite footplate. These findings may point to the need to explore other treatment modalities for 5th metatarsal stress fractures that could improve fracture healing, reduce the occurrence of re-injury, and accelerate return to play for athletes.

Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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