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The Effects of Carbon Insoles on Vertical Leg Stiffness and Reactive Strength as Indicators of Sprint Performance

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ABSTRACT

Background: Sprinting is the peak expression of running performance and different strength and physical characteristics play roles in the expression of sprint speed. Leg stiffness and reactive strength index (RSI), which measures the strength of stretch-shortening cycle, are two major factors on rate of force development and performance. It is well known that carbon fiber insoles optimize energy return while minimizing energy loss. **Objectives:** The purpose of this study was: (1) to investigate the effects of a carbon fiber insole on the expression of vertical leg stiffness (k_{vert}) and RSI during 20-yard sprint and drop jump; and (2) to examine the effects of the carbon insoles on sprint kinetics and kinematics. **Methods:** Using a randomized crossover design, fifteen participants performed a drop jump and a 20-yard sprint in two shoe conditions (carbon, traditional insoles) to measure RSI, K_{vert}, peak vGRF, ground contact time (GCT), speed, knee angle at contact, and knee angle at toe-off. **Results:** Significant differences between conditions for the performance variables occurred only in the drop jump (k_{vert}, $p = 0.023$; peak vGRF, p = 0.001). **Conclusions:** Further research is needed to examine sprint kinetics and kinematics with varying insole stiffness at maximal velocity.

Key words: Drop Jump, Running Shoes, Athletic Performance, 20-Yard Sprint, Vertical Ground Reaction Force, Knee Kinematics

INTRODUCTION

Sprinting is an intricate and complex movement requiring a high level of coordination and sequencing of muscle actions. Speed is a function of stride length and stride frequency and elite sprinters generate a stride length as great as 2.6 meters long and stride frequency up to five steps per second (Clark et al., 2017). The force generated at ground contact is a key factor in determining speed (Brughelli et al., 2011). An increase in running speed is the result of increased forces, particularly vertical ground reaction force. Ideally, vertical force should be increased without increasing ground contact time so it does not affect stride frequency. Making use of the vertical ground reaction force is important during sprinting because after the momentum has been developed during the initial acceleration phase (first 20 m), the body will normally continue moving forward at the same speed as long as the internal and external forces acting on the body are in equilibrium (Haugen et al., 2018). Once the maximum running speed is reached, runners generally maintain their optimal stride length because attempting to increase stride length will only increase horizontal braking force, thus hurting running economy, especially in distance running (Hunter & Smith, 2007).

Increasing leg stiffness improves vertical ground reaction forces (vGRF) which allows runners to more effectively counteract the effects of gravity (Haugen et al., 2018). The stiffness in the human leg has a major influence on various variables including the rate of force development, elastic energy storage and utilization, and sprint kinematics (Brughelli & Cronin, 2008). Leg stiffness is defined as the ratio of ground reaction forces to maximum leg compression at the middle of the stance phase (Brughelli & Cronin, 2008). Vertical stiffness is calculated by mass and the natural frequency of oscillation (Serpell et al., 2012).

Along with leg stiffness, many strength traits are important throughout the execution of a sprint. During the ground contact phase of sprinting, there is a pairing of an eccentric contraction with a concentric contraction which is termed the stretch-shortening cycle (SSC) and it is frequently used in various sports motions (Healy et al., 2019). The strength of SSC has been assessed by the reactive strength index (RSI) which equals flight time divided by ground contact time during a drop jump (Pedley et al., 2017). Elite sprinters are better adapted to make contact with the ground with a stiffer leg spring, increasing vertical ground reaction forces and maximizing the use of the muscle-tendon unit's (MTU) elastic elements, leading to higher running speeds (Douglas et al., 2020).

Running shoes have evolved technologically over the years. While runners in cushioned shoes require less phys-

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ical work, those who go barefoot must use more muscle to cushion their foot's impact when it collides with the ground. One drawback to wearing shoes is that they add to the overall mass which increases the metabolic cost (Tung et al., 2014). According to the cushioning hypothesis of requiring less physical work with shoes, for every 100 grams of mass added to a shoe, VO_2 increases by approximately 1%. Recently, carbon fiber insoles have received attention to improve gait (Taseh et al., 2024), speed, agility, and performance (Ko et al., 2023). When Nike was able to break the 2-hour marathon with the use of their carbon fiber insoles, the research community became more interested in the potential biomechanical benefits of carbon fiber insoles. As a result, many recent studies have investigated running economy and the energetic cost of running (Barnes & Kilding, 2019; Hoogkamer et al., 2018).

However, there have not been many studies on jumping and sprinting with a carbon insole. These few studies have examined the use of carbon insoles to increase midsole bending stiffness specifically targeting the metatarsophalangeal (MTP) joint. A stiffer midsole reduces the energy lost at the MTP joint from landing to take-off phase of running (Nagahara et al., 2018; Willwacher et al., 2013). A stiff-soled shoe restores the lost forces during the support phase, enhancing the plantarflexion at the MTP joint towards the toe-off (Nagahara et al., 2018). Nike has started incorporating carbon into their running shoes which has already been proven effective in the marathon. An excellent return of energy is credited to rising stiffness, which is related to an improvement in athletic explosiveness by 9.3% claimed by a corporation that primarily markets to power and speed sports.

Named 2020s top choice for runners by Runner's World, VKTRY Performance Insoles have a full-length carbon fiber base with five levels of flexibility that can be customized to provide optimum performance and protection. VKTRY Insoles were originally created for the US Olympic Bobsled Team to improve athletic explosiveness. VKTRY's insoles have a flexible forefoot, a stiff midfoot, and flexible rearfoot. A flexible forefoot allows adequate toe flexion and propels the athlete forward; the flexible heel helps absorb some of the shock that occurs at landing, and the stiff midsole is designed to limit the bending and reduce the loss of energy at that MTP joint.

VKTRY carbon insoles, with five stiffness levels to accommodate various sports and their demand, claims 1.6-inch increase in vertical jump height, 0.12 sec off a 40 yd dash, and 9.3% increase in the rate of force development. While their claim did not improve running economy (Gregory et al., 2018), if these claims are true, then VKTRY insoles should show an increase in reactive strength index (RSI) and vertical stiffness. Carbon insoles have not received much attention in the literature regarding reactive strength and vertical stiffness; however, the body of existing information suggests that performance might be enhanced. The purpose of the study was to determine if the advantage of VKTRY insoles can be extended to sprinting through increase in reactive strength and vertical stiffness. We hypothesize that this carbon insole will have an effect on sprinting.

METHODS

Participants and Study Design

Using randomized crossover design, the participants ran a 20-yard sprint and executed a drop jump (DJ) in running shoes with carbon insole and traditional insole. In the sprint, the following dependent variables were measured: K_{vert}, peak vGRF, ground contact time (GCT), speed, knee angle at contact, and knee angle at toe-off. In the drop jump, reactive strength index (RSI), vertical leg stiffness (K_{vert}), and peak vGRF were assessed. They completed both tasks after being randomly assigned to either the carbon insole or the traditional insole. The participant's choice of insole was kept a secret from them. The drop jump was done three times while sprint was done 5 times. The order was counterbalanced with at least 5-minute break between insole conditions. All participants wore the Nike Zoom Structure 22 shoes but with different insoles inserted in the shoes.

Participants

There were 15 total participants in the study. All participants did not have a history of lower extremity injury and had participated in at least four weeks of moderate to vigorous exercise leading up to the study (Table 1). All participants provided written consent, and the study was approved by the Institutional Review Board.

Instruments

Kinematics and kinetics were measured through a motion capture system that utilizes high-speed cameras and force plates. The system consists of 14 Vicon Vantage cameras (300 Hz) for motion capture and 3 AMTI force plates (1,500 Hz). Markers were placed with double-sided tape based on the lower body using the plug-in-gait model (Vicon, Oxford, UK) (Kadaba et al., 1990). The lower body plug-in-gait model consists of 16 total markers on various locations on the pelvis, knee, leg, and ankle.

Procedures

The participants attended two sessions on the same day at least two hours apart, and they were randomly assigned to either carbon insole or traditional insole condition at the beginning of their first session. Participants had reflective markers placed on the lower extremities based on the plug-in-gait model (Kadaba et al., 1990). After marker placement, participants performed a structured 10-minute warmup routine be-

Table 1. Participant baseline characteristics

Participant Characteristics	Men	Women
Sample Size (n)	7	8
Age (years)	24.6±3.6	23.0±3.1
Height (cm)	182.7±8.2	171.9±7.5
Body Mass (kg)	79.1±5.9	65.1±6.5

All data are presented as mean±standard deviation.

fore performing five drop jump and five 20-yard sprint. The warm-up started with a five-minute jog on the treadmill at a self-selected speed. Participants were instructed to keep the RPE between an 8-12 on the Borg scale. Then they followed up with a series of six dynamic stretches that covered a 10 yd span. The dynamic stretches included: high knees, butt kicks, A-skips, B-skips, punter kicks, and flexed-foot hops.

We used the drop jump (DJ) to measure the reactive strength index (RSI). This assessment consists of an athlete stepping off a box, landing with minimum ground contact time and jumping for maximum height. The drop jump RSI is calculated by flight time divided by ground contact time (Douglas et al., 2020). We verbally instructed the participants to step off the 68 cm box by pushing off with one foot rather than jumping off with both feet. The participant would step off the box, land with two feet on the force plate, jump vertically, and land back on the force plate with two feet. Instead of emphasizing vertical leap height, participants were primarily instructed to reduce the amount of time spent on the ground. Participants were also instructed to put their hands on their hips throughout the entire drop jump to prevent the use of the arms.

The vertical leg stiffness (K_{vert}) was measured using the 20-yard sprint test. The participants were in the 3-point start on one end of the lab and they were instructed to reach top speed by the end of the 20 yards. A successful trial was when a foot landed completely in one of 3 force plates setup along the middle of their running path. We did not instruct them to strike a specific force plate so that they would not intentionally change their normal stride length to land on a force plate. Between five successful trials, there was a one-minute rest time to achieve the work-to-rest ratio necessary for complete recovery following a session of hard maximum activity. We calculated vertical stiffness using Cavagna et al's (Cavagna et al., 1988) method where $k_{vert} = m\omega^2$. The natural frequency of oscillation (ω) can be derived from $2\pi/P$, where P is the period of oscillation (Cavagna, 2006; Cavagna et al., 1988; Cavagna et al., 2005).

Statistical Analysis

A 2 (Insole: carbon, traditional) x 2 (Sex: male, female) analysis of variance (ANOVA) with repeated measures on insole was performed on RSI, K_{vert}, peak vGRF, ground contact time (GCT), speed, knee angle at contact, and knee angle at toe-off. The statistical analysis was conducted using SPSS IBM 22. Means were considered significantly different when the probability of a type I error was.05 or less. If the sphericity assumption was violated, Huynh-Feldt corrections for the *p*-values were reported. Partial eta-squared (η_p^2) values were computed to determine the proportion of total variability attributable to each factor or combination of factors. With a moderate effect size of approximately 0.5, a probability of type I error value of 0.05, and 80% power, the recommended sample size by G*Power 3.1 was 12.

RESULTS

In the drop jump, there were primarily main effects on insole for K_{vert}, $F(1, 13) = 6.69$, $p < .05$, $\eta_p^2 = .34$; and vGRF, $F(1, 13) = 20.62$, $p < .01$, $\eta_p^2 = .613$ (Table 2). However, there were no main effects on sex and no interaction, $p < .05$. The RSI had neither main effects nor interaction, $p > .05$. The RSI is 1 when the flight time and the contact time are equal. There was no significant difference in RSI between carbon and traditional insole despite the RSI in carbon insole being 11% greater compared to the RSI in traditional insole. However, the peak vGRF was also 11% greater in carbon than that in traditional, yet with a significant difference. The K_{vert} demonstrated a nearly 40% higher stiffness differential between the carbon and traditional insole (Figure 1).

In the sprint, besides the GCT, $F(1, 13) = 4.02$, $p = .066$, $\eta_p^2 = .24$; and the knee angle at contact, $F(1, 13) = 4.07$, $p = .067$, $\eta_p^2 = .25$, reaching close to significant effect on insole, none of the variables showed any main effects or interaction, $p > .05$. The GCT was 6.8% longer and the knee angle at contact was 13.9% greater in carbon insole compared to traditional insole. Table 3 shows that all other variables were either the same as traditional insole or slightly higher in carbon insole. Nonetheless, the overall running speed was not enhanced with carbon insole.

The K_{vert} in sprint was much greater than that in drop jump as the period of oscillation of the body center-of-gravity would be much shorter in sprint, which increases the stiffness. On the other hand, as expected, the peak vGRF in sprint was smaller in sprint compared to the drop jump from a 68-cm tall box.

DISCUSSION

It was hypothesized that adding carbon insoles to running shoes would increase reactive strength and leg stiffness, hence boosting vertical force. Some advantages were identified in drop jump but not in sprint. The K_{vert} was greater in carbon insole over traditional, albeit this difference was not statistically significant and came at the cost of longer ground contact time (GCT). As a result, the running speed was unaffected. Biological sex effect was found to be only a factor when comparing men's and women's ground reaction forces, due primarily to mass discrepancies (males = 79.1 kg, females = 65.07 kg). Once the participants' body masses were taken into account, the difference became nonsignificant.

One part of this study was to examine the effects that carbon insoles would have on an athlete's reactive strength. Reactive strength is measured through reactive strength index (RSI) that is closely related to sprint performance (Healy et al., 2019). Reactive strength assessments are also

Table 2. Drop jump data

Variables	Carbon		Traditional	
	Male	Female	Male	Female
RSI	1.2±0.35	1.1±0.43	1.2±0.38	1.0±0.27
K_{vert} (kN/m)*	9.8±5.6	6.7±3.4	7.3±3.3	4.7±1.7
vGRF (N)*	4.8±0.76	4.2±0.90	4.2±0.84	3.9±0.73

All data are presented as mean±standard deviation. * = significant difference between Carbon and Traditional insole. RSI=Reactive Strength Index, K_{vert}=vertical stiffness, vGRF=peak vertical ground reaction force

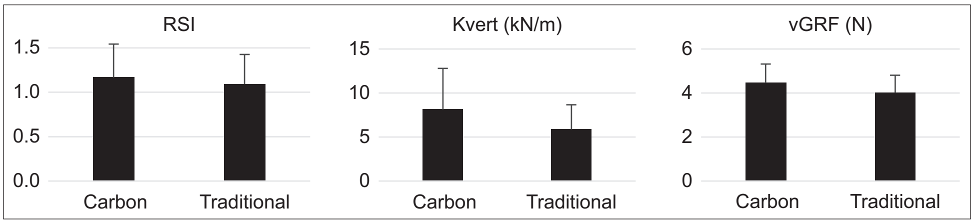

Figure 1. Reactive strength index (RSI), vertical leg stiffness (K_{vert}), and peak vertical ground reaction force (vGRF) between carbon and traditional insole

Table 3. Sprint data

Variables	Carbon		Traditional	
	Male	Female	Male	Female
K_{vert} (kN/m)	56.3±29.0	35.0±10.6	52.6±23.5	34.1±4.9
vGRF (kN)	2.0±0.11	1.6±0.17	2.0±0.22	1.6±0.16
GCT (ms)	185±50	193±19	166±41	186±17
Speed (m/s)	6.0±1.9	5.0±0.6	5.8±1.8	5.0±0.5
Knee Angle at Contact (deg)	20.3±11.0	22.3±10.6	16.4±11.5	21.0±7.9
Knee Angle at Toe-Off (deg)	13.0±8.1	14.6±5.3	12.5±8.8	12.8±5.3

All data are presented as mean±standard deviation. K_{vert}=vertical stiffness, vGRF=peak vertical ground reaction force, GCT=ground contact time

a common indicator of an athlete's ability to use their stretch-shortening cycle (SSC) to increase force production. Drop jumps are frequently used as a method of evaluation. The aim of the drop jump exercises is to increase muscle-tendon unit's capacity to store and release elastic energy when exposed to high stretching forces such as those present during jump landings and stance phases in sprinting (Ball & Zanetti, 2012).

The drop jump results of this study revealed no significant difference in RSI between the two types of insoles despite the carbon insole having a slightly higher index score compared to the traditional insole. However, K_{vert} was significantly greater in the carbon insole (8.16 kN/m) over the traditional insole (5.88 kN/m) and it directly impacted peak vGRF to be greater in the carbon insole as expected (Derrick, 2004). The carbon insole generated 11% greater peak vGRF than the traditional insole (Figure 1). It is unexpected that while K_{vert} showed significance between the two insoles, RSI did not. Increasing lower limb stiffness with the carbon insoles was expected to increase reactive strength also due to the prevention of excessive lengthening of muscles under high stretch loads which would help to increase force production during subsequent muscle activation through utilization of the elastic structures within the SSC.

These effects found in the drop jump were not present in the 20-yard sprint. The vertical stiffness was assessed during the initial acceleration phase (0 - 10 m), as opposed to the maximal velocity phase due to the restriction of lab space. This is an important distinction to point out as the running mechanics are vastly different between these two phases. One of the largest distinctions between acceleration phase and the max velocity phase is the ground contact time which normally ranges between 152 and 196 ms in initial acceleration and between 94 and 119 ms at max velocity (Wild et al., 2011). In this study, the GCT was190 ms in the carbon insole and 181 ms in the traditional insole. The difference is similar to what Cigoja et al. (Cigoja et al., 2019) found (Stiff = 252.0 ms, Control = 239.6 ms) although those results were substantially higher in that study due to submaximal pace. Another significant difference between initial acceleration and max velocity phase is the flight time (acceleration = ~0.06s, max = ~0.126s). These are important distinctions to make due to the characteristics of each phase containing properties that would require different carbon stiffness. The carbon insoles used in the treatment group were significantly stiffer and it was noted by some athletes to be uncomfortable.

We believe that a less stiff insole that would have taken into account the participant's weight should have been used in the sprint task due to significant findings that were only found in the drop jump activity, where the relative vertical force exceeded 4-6 times their body weight. Additionally, it should have been tested during the maximal velocity phase of the sprint task rather than the acceleration phase, when there are more joint flexion angles, longer ground contact times, and a greater emphasis on horizontal ground reaction forces (Wild et al., 2011). Future research could benefit from giving participants a break-in period to become accustomed to the firmer insole and become less aware of the feel difference.

CONCLUSION

It is premature to determine the immediate effect of carbon insole in the early acceleration stage of sprint as cumulative effect may arise much later. In addition, there are greater joint flexion angles and, with the body leaning more forward, there is a greater emphasis on horizontal ground reaction forces rather than vertical force to accelerate (Wild et al., 2011). Therefore, future studies may discover the benefits of carbon insole benefits after the athletes have attained their top speed. Improvements in the overall sprint time of even a few milliseconds can mean the difference between winning and losing.

AUTHOR'S CONTRIBUTION

B.S.: Conceptualization, study design and protocol, data collection, data analysis, writing original draft, editing. J. S.: Contributed to the conceptualization, study design and protocol, writing original draft, editing. J.R.: Contributed to the conceptualization, study design and protocol, editing.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

DECLARATIONS

Ethics Approval and Consent to Participate

The study was approved by Baylor Institutional Review Board (protocol #: 1633228-4, approved 08/05/2021, Baylor University). The details of the study was explained to all the participants prior to study recruitment. A written Informed consent was obtained from all the participants. The procedures of the study were conducted according to the Declaration of Helsinki.

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