Title: The ankle energetic effect of carbon fiber insoles on Walking

Short Title: Ankle energetic effect of carbon fiber insoles

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Abstract

Background & Aims

Various insoles have been developed, but little objective evaluation of their effectiveness has been conducted. We investigated the effect of insoles supporting the cuboid bone and anterior part of the calcaneus in healthy individuals.

Methods:

The subjects included 18 healthy males and females. They walked in standardized shoes with a flat insole (hereinafter, FI, a flat insole made of polyurethane without an arched shape on the surface) and a carbon fiber insole (hereinafter, CFI, made of carbon and supporting the cuboid and anterior part of the calcaneus). We used a three-dimensional motion analysis device and a force plate to analyze gait and quantitatively compared the effect of CFI.

Results:

The CFI reduced ankle power without reducing walking ability. In particular, with regard to the left-right difference in ankle joint sagittal plane power, we found that when the left-right difference was large, the use of CFI reduced the left-right difference in power.

Conclusion：

The burden on the muscles of the lower limbs on one side is reduced, and sports performance, including walking, can be maintained.

Key words：carbon fiber insole, gait analysis, three-dimensional motion capture, biomechanical relevance, ankle power

1. **Introduction**

Although insoles made of various materials and shapes have been developed to improve performance in sport activities, few objective evaluations on their effectiveness have been conducted. Moreover, the functions required for insoles are not only shock absorption and support for the foot arch, but also improvement of performance in sport activities. Although sport performance is often evaluated through breaking competition records, etc., few kinematic quantitative evaluations have been conducted, so the effects thereof remain unclear.

Regarding the effects of insoles other than in terms of sport activities, reports have been made on whether the use of insoles affects the standing balance of the elderly. Several studies on flat and textured insoles have reported no difference in standing balance using textured insoles compared to flat insole (hereinafter "FI"). Among these, insoles with a pyramid-shaped projection on the surface [1], those with raised edges [2,3], those with round plastic bumps [4], those with granules [5], and sandals equipped with spike insoles [6,7] are reported to improve standing balance. As a reason for this, one common effect of aging is a loss of skin sensation, which is thought to be correlated with impaired posture control and an increased risk of falling.

Clinically, insoles have been prescribed to protect the plantar fascia and reduce pain in patients suffering from plantar pain [8]. Lateral wedge insoles are prescribed to prevent bowlegs in patients with varus arthrosis deformans [9]. As a treatment for flat feet, insoles are also prescribed as arch support to prevent the medial arch from being flattened and everted [8]. These cases are often subject to subjective evaluations such as comfort and pain reduction, with few quantitative analyses having been conducted.

It has been reported that regarding the left-right difference in movement of the lower limbs of healthy individuals, movement is symmetrical while walking on a treadmill, with the left-right difference decreasing with increased speed among individuals suffering from vertical displacement of the knee [10]. Regarding left-right differences in the percentage of time standing on each foot during one walking cycle, it has also been reported that the time standing on the non-dominant leg was significantly longer than that on the dominant leg during the standing phase III (from heel landing to toe rising) [11]. In other words, it appears that left-right differences exist in the movement of the lower limbs during normal walking. From these reports, although a dynamic evaluation has been conducted on the balance of the lower limb movement, no evaluations into further details have been conducted.

In this study, we captured an opportunity to evaluate carbon fiber insole (made of carbon and supporting the cuboid and anterior part of the calcaneus (hereinafter "CFI")) developed to improve performance in sport activities. The CFI used herein are expected to improve the balance of the standing posture via the structure of foot support. We will verify the improvement of left-right balance when walking by measuring the ankle moment and power on sagittal plane. Assuming that there is a difference in the left-right moments and power on sagittal plane during normal walking of healthy individuals, we conducted a kinematic analysis on the effects of using insoles from the data of the three-dimensional motion analysis device and the force plate to investigate the effects on walking.

2. Methods

2.1. Participants

The subjects included healthy individuals aged 20 to 63, excluding those who require walking aids such as canes, as well as those with neuromuscular diseases, cardiovascular diseases, respiratory diseases, or motor neuron diseases that may influence their walking. The study was discontinued if a subject complained of pain or discomfort when using the insole. 18 males and females (9 males, 9 females, from 20 to 63 years old, average 43.9 ± 14.4 years old) satisfying the above criteria were selected.

2.2. Procedures

For comparison of the insoles among subjects, we asked subjects to walk wearing standardized shoes (no heel counter and shank) with normal FI without an arched shape on the surface and made of polyurethane and wearing CFI (BMZ insole, BMZ. Inc, Gunma) (Fig.1A and Fig.1B) and conducted a gait analysis using a three-dimensional motion analysis device (Vicon MX, Vicon Motion Systems Oxford. UK,) and a force plate (AMTI, Watertown, MA, USA).

For the three-dimensional movement analysis, analysis markers were attached to a total of 28 points: 4 points at the head, C7, Th8 spinous processes, the midpoint of the left and right superior posterior iliac spines, the acromion, the external humerus condyle, the radial styloid process, the superior anterior iliac spine, the point 1/3 from the greater trochanter on the line between the superior anterior iliac spine and the greater trochanter, the external femoral condyle, the midpoint of the line shape between the external femoral condyle and the ankle lateral malleolus, the ankle lateral malleolus, the midline of the facies posterior to the calcaneus, and the head of the second metatarsal bone.

Patients walked normally in standardized shoes on a walkway of approximately 10 m without knowing which insole they are wearing. The insoles to be worn were randomly chosen. No instructions on walking speed were given and the subjects walked at their optimal speed. After two trials each with both the CFI and the FI, a total of three measurements were taken.

In order to investigate any correction due to the insoles, a past study compared the control conditions wearing the shoes the subjects regularly wore with 3 mm FIs and wearing standardized shoes with the same insoles [12]. As a result, the conclusion recommends using the footwear of the participants as the control condition, because standardized shoes, compared to the usual shoes, significantly affect the knee adduction impulse, ankle abduction moment, and vertical grounding reaction load factor at the time of knee abduction. However, since walking needs to be evaluated with "shoes + insole", this study focused on the difference in the function of insoles by using the same shoes (no heel counter and no shank).

2.3. Ethics approval and consent to participate

This study was approved by the medical research ethics review committee for individuals at Gunma University (study number HS2017-229).
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2.4. Data analysis

All subjects completed the measurements without any adverse events. The obtained data were imported into the Visual 3D software program, ver. 6 (C-Motion, Inc., Germantown, MD, USA) to calculate the walking parameters and kinematics data.

Walking speed, cadence, step length, and stride length were recorded as walking parameters. Walking speed was defined as the speed of movement of the center of gravity in the direction of travel, calculated as the average of 5 m as the middle point during walking. Cadence was also calculated at 5 m as the midpoint during walking. The step length and stride length were also calculated as the average of 5 m as the midpoint during walking.

We calculated hip and ankle moment on the sagittal plane at terminal stance, and analyzed them. The peak values of hip flexion moment, hip power on the sagittal plane, ankle planter flexion moment, and ankle power on the sagittal plane were recorded.

2.5. Statistical analysis

We compared the data when wearing FI and that when wearing CFI. Group A (n = 7) included those with a left-right difference of more than 20% in ankle power when using FI, while Group B (n = 11) included those with a difference of less than 20%. We compared the subjects within each group. Table 1 shows the physical characteristics of the subjects. There was no difference in the physical characteristics between Group A and Group B.

Regarding statistical processing, we performed a paired t-test for the walking parameters and Wilcoxon's signed rank test for left-right differences in joint moment, power, and ankle power, with <0.05 considered to be a significant difference.

3. Results

The three-dimensional motion analysis revealed no significant difference in the walking parameters (gait velocity (m/s), cadence (steps/minute), step length (m), stride length (m)) between the FI and the CFI. No differences in hip flexion moment or ankle plantar flexion moment were observed between the two groups. The CFI significantly reduced ankle power on sagittal plane compared to the FI ($P < 0.05$). There was no significant difference in hip power on sagittal plane between the CFI and the FI (Table 2).

We then examined the left-right difference in peak ankle power in the sagittal plane when wearing FI. We found that there were two groups, one with a large difference between the left and right sides and the other with a small difference. The group with the largest difference was designated Group A, and the group with the smallest difference was designated Group B. The difference in peak ankle power in the sagittal plane was defined as 1.0 w/kg.

In Group A, walking with carbon insoles significantly decreased the left-right difference in the power compared to walking with FI (Fig.2A). However, the insoles caused no difference in Group B, in which the left-right difference in power was small (Fig.2B).

4. Discussion

We found that the CFI reduced ankle power without affecting walking ability. The reduced power immediately before raising the toe means reduced power of the gastrocnemius muscle and the soleus muscle, which create the ankle's plantar flexion force. Reduced muscle power may reduce muscle fatigue and prevent a decline in sports performance, including walking, can be maintained.

Reduced ankle power during "kicking the ground to move the foot forward" is known to increase the hip joint power as a trade-off [13]. However, no change in hip power was observed in this study. Reduced ankle power without increased hip power may also lead to a decrease in overall energy consumption.

Since walking is performed symmetrically, the ankle power while walking is considered to involve no left-right difference. However, it is known that dominant and non-dominant legs have different reaction time and muscle strength [14]. In this study, 7 out of 18 subjects had a left-right difference of more than 20% in ankle plantar flexion power during walking with the FI. In these 7 subjects, we confirmed that the use of CFI reduced the difference in ankle plantar flexion power. In other words, the use of CFI equalized the left-right power. The burden on the muscles of the lower limbs on one side is reduced, and sports performance, including walking, can be maintained. CFI may reduce the burden on the muscles of the unilateral lower limbs and prevent the deterioration of sport performance.

The insoles used in this study provide support to the cuboid bone and the anterior part of the calcaneus and are made of light and thin highly rigid carbon. Directly pushing the medial longitudinal arch up, as with polyurethane insoles, is effective for postural stability at rest, but it may hinder the original functions of the arch, such as shock absorption, by changing the arch height and momentum to move forward. The carbon insole used in this study is designed to directly support the cuboid bone. Especially for athletes, it is more useful to hold the arch by supporting the cuboid bone than directly pushing the medial longitudinal arch up.

A recent study concluded that two unique arches on the human foot enabled bipedal walking [15]. Most previous studies have focused on the medial longitudinal arch (hereinafter, MLA), which extends from the heel to the ball of the foot. However, it was revealed that the transverse tarsal arch (hereinafter, TTA) transecting the foot is related to more than 40% of the rigidity of the foot. Only the genus Homo have a fully developed MLA and TTA. These findings suggest that the combination of two adjacent arches creates the longitudinal rigidity of the foot. The findings that two unique arches in human feet enabled efficient upright walking indicate that support of the arch by the insole not only affects the MLA but also the TTA derived therefrom.

In this way, the joint group around the heel plays a role of a torque converter (force converter) that controls the height of the arch, the actions of the toes of the foot, and the direction and inclination of the lower limbs. Therefore, we believe that the foot can do its job more effectively when the major joints in the foot work at their full potential.

For the treatment of flat feet, one common deformation in young individuals, a previous study evaluated the hardness of insole materials and the height of the arch support. The results indicated that correction of the height of the arches involved increases in both the hardness of the material and the height of the support [16]. Therefore, while static insoles are suitable for the treatment of flat feet, such insoles are inappropriate for sport because they are related to the movement of the articulatio subtalaris. The reason for this is, if the insoles are hard, the subtalar joint may open (the arch is bent and absorbs shock) or close, making it difficult to evoke the locking system of the midtarsal joint and stabilize the foot. In addition, sport insoles require thinness and high rigidity to improve performance. For this reason, we used carbon insoles (made from carbon fiber consisting primarily of carbon) that combines the two functions as CFI.

We have some limitations. First, we need to think about "What made the adjustment?". Why did the left-right difference of Group A become smaller? While the FI required large force, the carbon insoles required less power. Although we found the use of carbon insoles lead to the equalization of left-right power, further quantitative evaluation is necessary. Second, the small number of cases may affect the results. Third, this study was conducted on healthy subjects and cannot be generalized to patients with gait disorders.

5. Conclusion

The CFI reduced the power of the ankle plantar flexion muscles. Regarding the ankle power obtained from the force plate, the use of CFI in the group with a large difference in left-right power significantly reduced the left-right difference in power, equalizing the left-right power of the ankle plantar flexion muscles. In sport activities, the CFI are believed to function to reduce the fatigue of the lower limbs muscles as well as the burden on the unilateral legs, and maintaining long-term sports performance, including walking.

List of Abbreviations

CFI：carbon fiber insole；FI：flat insoles；MLA：medial longitudinal arch；TTA：transverse tarsal arch；PAN：polyacrylonitrile;

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Figure legends

Fig. 1A: Carbon fiber insoles(CFI).Top view(left) and side view(right).

The CFI is made of carbon, which is thin and highly rigid, with a structure that supports the cuboid bone and the anterior part of the calcaneus.

Fig. 1B: Longitudinal sectional view illustrating the relationship between the insole and the foot

F: Weight of user

The moment acts on the calcaneus with the fulcrum P2 as the center

The moment acts on the cuboid bone with the fulcrum P3 as the center

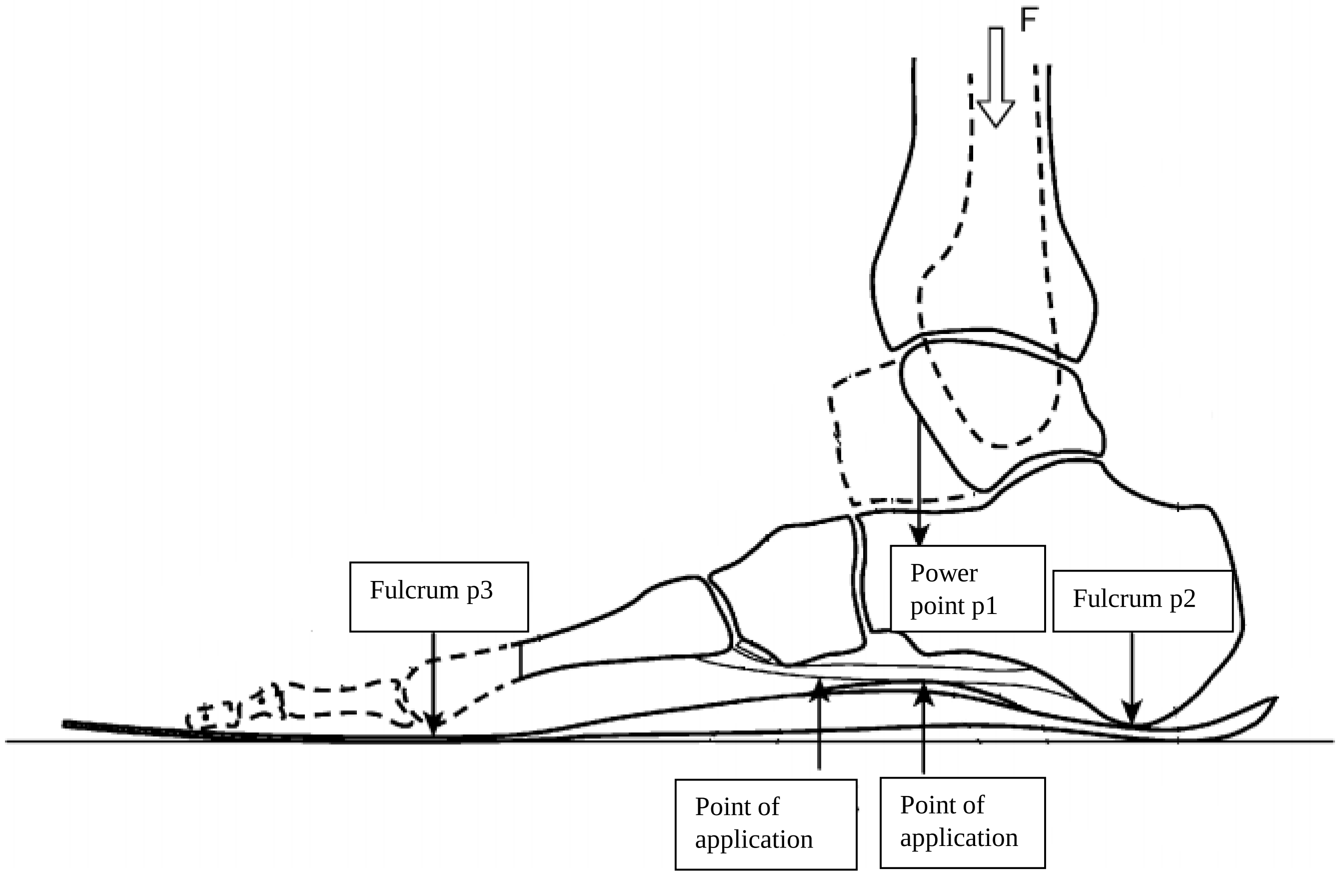
Fig. 2A: Differences in ankle power on sagittal plane in right and left ankle at Group A

In Group A, in which the left-right difference in power is large with polyurethane insoles, walking with carbon insoles significantly decreased the left-right difference in power compared to walking with polyurethane insoles.

Fig. 2B: Differences in ankle power on sagittal plane in right and left ankle at Group B

The insoles caused no difference in Group B, in which the left-right difference in power was small.

Fig. 1A　Carbon fiber insoles(CFI).Top view(left) and side view(right).



F: Weight of user
The moment with fulcrum P2 as the center acts on the calcaneus, while the moment with fulcrum P3 as the center acts on the cuboid bone

Fig1B : Longitudinal sectional view illustrating the relationship between the insole and the foot

Table1 The physical characteristics of the subjects

	Group A (n=7)	Group B (n=11)	p-value
Age (y)	38.6 ± 15.7	47.3 ± 13.9	0.369
Sex (M/F)	3/4	6/5	0.192
Height (m)	1.67 ± 0.1	1.64 ± 0.1	0.722
Weight (kg)	63.1 ± 13.4	58.8 ± 9.1	0.333
BMI (kg/m^2)	22.5 ± 3.4	21.8 ± 2.7	0.381

Data are presented as Means ± SD
BMI: body mass index

Table2 Comparison of gait parameters between flat insole and carbon fiber insole

	Flat insole	Carbon fiber insole	p-value
Gait velocity (m/s)	1.28 ± 0.14	1.34 ± 0.14	0.228
Cadence (steps/minute)	116.8 ± 7.9	116.6 ± 7.8	0.815
Step length (m)	0.61 ± 0.07	0.62 ± 0.08	0.139
Stride length (m)	1.32 ± 0.09	1.34 ± 0.08	0.123
Peak hip moment (Nm/kg)	0.94 ± 0.25	0.93 ± 0.28	0.870
Peak hip power (w/kg)	1.55 ± 0.60	1.54 ± 0.58	0.950
Peak ankle moment (Nm/kg)	1.53 ± 0.16	1.52 ± 0.22	0.085
Peak ankle power (w/kg)	5.06 ± 1.14	4.65 ± 1.19	0.023*

Data are presented as Means ± standard deviation