Natural Gaits of the Non-Pathological Flat Foot and High-Arched Foot

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Abstract

There has been a controversy as to whether or not the non-pathological flat foot and high-arched foot have an effect on human walking activities. The 3D foot scanning system was employed to obtain static footprints from subjects adopting a half-weight-bearing stance. Based upon their footprints, the subjects were divided into two groups: the flat-footed and the high-arched. The plantar pressure measurement system was used to measure and record the subjects’ successive natural gaits. Two indices were proposed: distribution of vertical ground reaction force (VGRF) of plantar and the rate of change of footprint areas. Using these two indices to compare the natural gaits of the two subject groups, we found that (1) in stance phase, there is a significant difference ($p<0.01$) in the distributions of VGRF of plantar; (2) in a stride cycle, there is also a significant difference ($p<0.01$) in the rate of change of footprint area. Our analysis suggests that when walking, the VGRF of the plantar brings greater muscle tension to the flat-footed while a smaller rate of change of footprint area brings greater stability to the high-arched.

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Introduction

Foot arches are the result of the successive evolution of basic human activities such as walking [1–3]. Among the vertebrates, only humans have foot arches [4]. The anatomic structure of one transverse, one medial longitudinal and one lateral longitudinal arch can perform the functions of buffering, amortizing, stabilizing and generating propulsion in human activities [4,5]. Research into the shape, structure, and function of the foot arch has never ceased.

Differences exist in the shape and structure of each individual’s foot arches, which is related to factors such as age and weight [6,7]. The usual methods to collect the foot arch shape include footprinting, X-ray, plantar pressure measurement, laser scanning measurement and MRI scanning [8–12]. Using indices such as the footprint ratio and foot arch index, we can divide the foot shape into three categories: normal, high-arched and flat. The morphological flat and high-arched foot are asymptomatic. Some research results demonstrate that the non-pathological flatfoot (flexible flatfoot) does not affect one’s physiology or quality of life and therefore does not require therapy [7,13,14]. Others indicate that the flat foot exerts effects on velocity, stamina and/or balance [15,16] while those possessing the high-arched foot are unsuitable sprint athletes [17]. What difference exists in the gaits of people with the non-pathological flat foot and high-arched foot? Will this difference exert an effect upon walking? If so, how? As yet no satisfactory answers have been provided to these questions. Shape is a representation of structure. A 3D foot scanner can be used to record the footprint of a person while standing. According to footprint ratio [18], flat-footed or high-arched subjects can be selected. Structure affects function. The distribution of plantar pressure can qualitatively reflect such information as the structure and function of the foot as well as the control of the whole body in gait [19]. System Gait Analysis has been used to measure the natural gaits of both groups of subject. Differences in gait between these two groups have been detected by analyzing both the distributions of VGRF of foot and the rate of change of footprint area.

Materials and Methods

This study was approved by the Ethics Committee of Guangzhou Institute of Physical Education. Before the experiments, the subjects were informed of the objectives, requirements and procedures of the experiments. All gave informed written consent to participate in the study.

During the selection process, we examined the prospective subjects with help from the Orthopedics Department of our clinic to screen and exclude subjects with pathological flat foot or high-arched foot symptoms such as Talipes calcaneovalgus, Congenital talipes equinovarus (CTEV) (club foot), or planter flexion anomaly.

The subjects were asked to stand barefooted after both feet had been sterilized with 75% ethyl alcohol, and their footprints of half weight were captured with a 3D laser scanner.
The footprint-ratio method was used to analyze the foot shape. For the inner side of the podogram, a tangent was drawn from the heel to the inner edge of the metatarsophalangeal joint to measure the widest distance $AB$ of the hollow area of the footprint and the distance $ab$ between this line and the edge of the outer side of the foot. The width of the solid area was $bc$. The value of $ab/bc$ was calculated. When $bc=0$, let $ab/bc=1$. When $ab/bc \geq 0.786$, it was considered to be high-arched foot; when $ab/bc \leq 0.258$, a flat foot.

Twelve subjects for each group (flat foot and high-arched foot) were chosen (6 male and 6 female for each group). Their foot shape results are shown in Table 1.

The experiment started from the subject’s standing position (barefooted). After walking two or three steps, they stepped onto a platform. If the first step onto the platform was found to be incomplete or if the subject walked off the platform, or if the gait seemed apparently nonsuccessive, the subject was asked to try again. Data that met our requirements were collected. See Table 2.

The VGRF and the stride cycle from the subject were standardized (their weight was normalized as 1). According to the least-action principle in gait (the time of initial foot contact falls right in the middle of the other foot’s stride cycle) [20], the relationships between the forces (VGRFs of left and right foot and their resultant force) and the time were established. See Fig. 1.

### Results and Discussion

Table 1 shows that there exists significant difference ($p<0.05$) in the height of instep, as well as a significant difference ($p<0.01$) in the foot arch index and in the footprint-ratio index for both groups. Table 2 reveals there is no significant difference of foot arch shape in gait parameters such as stride frequency, length or velocity. Fig. 1 indicates a similar distribution of VGRF for both groups. (When VGRF is standardized according to weight, there is a substantial similarity of VGRF distribution between the two groups.) Since the VGRF exerted on the foot affects variations of acceleration, velocity, position and mechanical energy of the body’s center of mass vertically [21], while walking, the center of mass of the two groups shares almost the same kinetic and kinematic characteristics.

### Table 1. Basic information of subjects’ feet.

| Item (Unit)          | High-arched foot | Flat foot   |
|----------------------|------------------|-------------|
| Foot length (mm)     | 241.025±11.664   | 243.217±13.486 |
| Heel breadth (mm)    | 60.358±4.762     | 62.950±2.424 |
| Foot breadth (mm)    | 95.783±5.826     | 91.283±6.025 |
| Height of instep (mm)| 62.075±3.678     | 57.450±3.963 |
| Foot arch index      | 0.257±0.007      | 0.237±0.016**|
| Footprint ratio index| 0.908±0.098      | 0.246±0.092**|

*p<0.05, **p<0.01.

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### Table 2. Basic kinematic parameters of gait.

| Item (Unit) | High-arched foot | Flat foot |
|-------------|------------------|-----------|
| Step length (cm) | 68.740±5.400 | 68.158±6.547 |
| Step time (sec)   | 0.507±0.026   | 0.517±0.049  |
| Stance phase (%)  | 60.784±1.419  | 61.034±2.566 |
| Swing phase (%)   | 39.216±1.419  | 38.966±2.566 |
| Stride length (cm) | 137.000±10.736 | 136.783±12.989 |
| Stride time (sec) | 1.014±0.044   | 1.034±0.095  |
| Cadence (stride/min) | 59.313±2.496 | 57.680±5.885 |
| Velocity (m/sec)  | 4.884±0.528   | 4.751±0.761  |

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The foot print-ratio method was used to analyze the foot shape. For the inner side of the podogram, a tangent was drawn from the heel to the inner edge of the metatarsophalangeal joint to measure
Generally speaking, we cannot identify flat foot or high-arched foot from gait parameters. It is justifiable to say that based upon gait parameters such as stride length, frequency and GRF, neither the flat foot nor the high-arched foot lead to negative effects on physiology or living quality.

We are fully convinced that the principle that structure affects function is truthful. In order to discover the difference between the two foot arch types, we analyzed the distributions of VGRF of foot. The subject’s weight, foot length and stance time were standardized. The distributions of VGRF of foot were obtained. See Fig. 2.

Fig. 2 exhibits that for both groups of subjects, significant difference (p<0.01) exists in the peak value of VGRF in the heel and center. Virtually no significant difference can be identified under the first metatarsal bone, but significant difference (p<0.05) can be noticed under the first proximal phalanx bone. In order to analyze how these differences affect walking, a simplified foot arch structure model (triangle truss) was created by a foot arch index from two types of foot arch. See Fig. 3.

Fig. 3 indicates that when walking, the structural differences of both foot arch types produce differences in the muscle tension of the foot. When taking a long walk, the flat foot group will feel foot fatigue more easily while the high-arched foot group can walk longer and feel less foot fatigue. While walking, difference exists in the distributions of plantar pressure and the tension that the muscle group under the foot arch bears. This difference is again consistent with the principle that structure affects function.

Stability index plays an important role in gait analysis. Gait stability has been widely discussed by using the symmetry of gait parameters such as the VGRF or the stride length of both types of
foot [22]. Fig. 2 shows that the symmetry of gait parameters
of both types is very close, indicating the limitation of using such
a method to evaluate gait stability.

Stability analysis of human movement can often be evaluated by
the stance area index (for example, the stability is greater
when standing on both feet than on one foot.) From this viewpoint,
we analyzed the variations of plantar stance area while walking.
According to the least-action principle in gait, when the plantar
stance area of one stride cycle is standardized, the variation of
the plantar stance area of both types of foot can be obtained.
See Fig. 4.

Fig. 4 shows that in a stride cycle difference exists in the variations
of plantar stance area from both types of subject. In order to
evaluate this difference quantitatively, the following equation is
applied to assess the rate of plantar stance area while walking:

\[
\sigma = \frac{1}{fT} \sqrt{\sum_{t=0}^{T} (A(t) - \bar{A})^2}
\]  

(1)

where \( f \) stands for the collection frequency of the equipment, \( T \) the
stride cycle time of the subject, \( A(t) \) the plantar stance area at a
certain moment in a stride cycle and \( \bar{A} \) the average value of
footprint area in a stride cycle.

Calculation from Eq. 1 provides the variations of footprint areas
for the flat-footed and the high-arched groups respectively while
walking: 0.147±0.041, 0.084±0.034 (p<0.01). The fact that the
stability is greater when standing than when walking reveals that
the smaller the value from the calculation of Eq. 1, the better
the stability (the minimal value is zero). Accordingly, the rate
of change of footprint area of both types resulting from Eq. 1
quantitatively describes stability while walking.

Conclusion

The structural difference in these types of foot arch causes
significant difference of VGRF distribution of foot. The differences
in structure and in VGRF distribution have an effect on foot
muscle tension while walking. This offers important evidence to
analyze foot muscle fatigue. The VGRF distribution of foot can
well explain why the flat-footed experience pain more readily
when they walk for a long time. The smaller rate of the footprint
areas brings greater stability to the high-arched. The lack of
stability suffered by the flat-footed requires more consumption of
energy, and thus may well explain the fatigue felt by the flat-footed
on long walks.

In summary, the mysterious human gait is much more
complicated than we had expected. There exist so many unknown
phenomena, which we have not yet been able to discover. The
establishment of a new gait evaluation index could certainly be
employed as an important means to disclose the unknown. The
foot arch can not only lessen muscle fatigue, it can also reduce
energy consumption [23]. It was the unique foot arch that brought
the human being walk out of Africa (so to speak).

How to prevent seniors from falling has always been a key issue
in the biomechanical research of gait [24]. The analysis of these
two foot types may equally arouse attention to the gait of flat-
footed seniors. In addition, does the fact that walking can be
affected by foot type mean that we can enhance the gait stability
for flat-footed seniors by the design of their shoes [25]? In any
case, the VGRF distribution of foot and the rate of change of
footprint area can be employed as important evaluation indices.

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Author Contributions

Conceived and designed the experiments: Yifang Fan Yubo Fan. Performed
the experiments: Yifang Fan CL DL. Analyzed the data: Yifang Fan Yubo
Fan. Contributed reagents/materials/analysis tools: Yifang Fan Yubo
Fan ZL. Wrote the paper: Yifang Fan ZL Yubo Fan CL DL.
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