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ORIGINAL ARTICLE

The Comparison of the Difference in Foot Pressure, Ground Reaction Force, and Balance Ability According to the Foot Arch Height in Young Adults

[1]Jun-Young Song, [1]Sam-Ho Park, [2]Myung-Mo Lee*

[1]Department of Physical Therapy, Graduate School, Daejeon University, Republic of Korea. [2]Department of Physical Therapy, Daejeon University, Republic of Korea.

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ABSTRACT

Background. Human feet have important roles in supporting, moving and balancing the body. The feet must not only support the weight of the body but must also have the elasticity to absorb the burden associated with supporting excessive body weight. **Objectives.** The purpose of this study was to compare the difference of foot pressure, ground reaction force, and balance ability according to change of the foot arch during the weight loading. **Methods.** Total 60 healthy young adults were divided into flexible flat foot group (FFFG, n = 30) and normal foot arch group (NFAG, n = 30) by screening navicular drop test. To compare the foot pressure, the rate of change was calculated by measuring the foot contact area when walking against the foot contact area when standing. The ground reaction force measurement was performed to calculate the contact time of the foot, vertical force peak, and total GRF time-integral value during walking. Besides, a one-leg standing test was performed to measure postural instability according to the height of the foot arch. **Results.** The FFFG showed a significantly higher contact area than that of the NFAG. Also, there was a significant increase in contact area ratio in FFFG ($p < 0.05$). The vertical force peak results revealed no significant differences between the two groups. However, for contact time and total GRF time-integral values, the FFFG values were higher than those for the NFAG ($p < 0.05$). The FFFG had significantly greater COP, velocity, COP path length, and area values than those of the NFAG ($p < 0.05$). **Conclusion.** These results show that the flexible flat foot may reduce energy efficiency and increase instability during the dynamic performance and has a high risk of causing secondary problems.

KEYWORDS: ***Balance, Flexible Flat Foot, Ground Reaction Force, Foot Pressure.***

INTRODUCTION

Human feet have important roles in supporting, moving and balancing the body. The feet must not only support the weight of the body but must also have the elasticity to absorb the burden associated with supporting an excessive body weight (1). Foot elasticity is a function of the arched shape of the foot and the associated bone, ligament, tendon, and muscle structures, which form what is called the foot arch (2). Among those structures, the medial longitudinal arch (MLA) of the human foot has multiple functions, including absorbing and distributing load forces and providing stability (3). However, if the MLA structure collapses, which may be due to various causes such as posterior tibial tendon dysfunction or tight gastrocnemius-soleus complex, a flat-foot condition occurs (4, 5). In flat-foot cases, downward forces are

*. Corresponding Author:
Myung-Mo Lee, Ph.D, PT
E-mail: mmlee@dju.kr

deflected toward the inside of the foot, including the forefoot and the medial column, due to excessive pronation (hyperpronation) (6).

Flat-foot conditions can be divided into two types: rigid or flexible. A rigid flat foot is characterized by a stiff, collapsed arch in both weight-bearing and non-weight-bearing positions, whereas a flexible flat foot is characterized by a normal-appearing arch when the foot is not bearing weight but by a flattened arch when weight-bearing (7, 8). Flexible flat feet are the most common type of flat foot. Based on the classification approach of Harris and Beath, flexible flat feet account for approximately 2/3 of all flat-foot occurrences (9). A flexible flat foot results in hyperpronation, plantar flexion, adduction of the talus, and calcaneus eversion (8). If a flexible flat foot is neglected, it can worsen to become a rigid flat foot, resulting in a loss of flexibility, hindfoot eversion, and joint deformity with pain (10). From a biomechanical point of view, a flexible flat foot can cause some musculoskeletal problems because they require more energy consumption when performing movements such as walking, and running. (3, 11).

Among the various factors, the dynamic characteristics of flatfeet, ground reaction force(GRF) is a leading assessment metric to study vertical loading during walking. Changes in vertical load on the sagittal plane can be presented as an M-shaped graph (12). Several previous studies have reported that there is a significant correlation between the changes in vertical load and the function of the MLA (3, 8). As mentioned earlier, some studies have researched the structural dynamics of the flat-foot condition, but more study on a flexible flat foot, which has related to MLA, is needed. The purpose of this study was to compare the biomechanical characteristics of normal-arch feet with those of flexible flat feet by measuring ground reaction forces, changes in foot contact and pressure, and postural balance using a force plate. The results can be considered useful clinical data for characterizing the flexible flat-foot condition.

MATERIALS AND METHODS

Participants. 130 healthy adults in their 20s who are enrolled in D university were recruited through the recruitment promotion of research participants. Inclusion criteria were those who had no limitation of motion on the ankle joint and those who could perform single-leg standing over 30seconds (13). Those who experienced musculoskeletal diseases of the lower extremities within the last 6 months were excluded. The purpose of, and procedures used in, the study was explained to the participants, and only those who consented to participate were included in this study. This study was approved by the Ethical Committee of D University and is registered in the World Health Organization International Clinical Trials Registry Platform: KCT0004475.

Procedures. This study had a cross-sectional study design. Following the screening, the subjects were divided into a flexible flat foot group (FFFG, n = 31) and a normal foot arch group (NFAG, n = 99).

For screening purposes, a navicular drop test (NDT) was used to distinguish a flexible flat foot subject from a subject with a normal arch (14). The NDT, which indicates weight load changes on the sagittal plane, was introduced by Brody (1982). The NDT has been shown excellent validity (ICC > 0.94) when evaluating the height of navicular bone and also has high intra-rater reliability (ICC = 0.83) and inter-rater reliability (ICC = 0.73) (14-16). In this study, the NDT was used to evaluate the difference between the heights of the navicular tubercle obtained under resting and standing conditions. To perform the NDT, a subject sat on a chair with knees bent at 90°, their feet parallel and on the floor, and without any weight applied. Then the distance from the ground to the medial part of the navicular tubercle was measured. That same distance was also measured with the subject in a standing position under bodyweight-bearing conditions. Based on the difference in sitting and standing position values, a subject was considered to have a flexible flat foot if the difference was more than 10mm (Figure 1). To minimize intra-measurer variability, both measurements were obtained by the same person. After screening and group allocation, the ground reaction force (GRF) when walking, as well as foot contact area and postural stability parameters for each subject were determined to compare the mechanical properties of the two groups. Excluding the data of participants who disagree with the use of the measured data (NFAG, n = 4), the data of each of 30 individuals between groups were randomly collected. A flow chart for the experimental process is presented in Figure 2.

Foot Contact Area Ratio. The foot contact area was measured using the Gaitview® AFA-50 system (alFOOTs, Seoul, Republic of Korea).

The Gaitview measuring device included a force plate (550 mm × 480 mm × 35 mm) with a 410 mm × 410 mm × 3 mm active area, which contained 2304 (48 × 48) force resistance sensors. Each sensor had an area of 0.75 cm^2. Data were collected at 17 Hz.

During measurement, the subjects were asked to stand on the Gaitview device in an anatomically aligned position to allow measurement of the foot contact area under a static condition. To measure the foot contact area under dynamic conditions, the subjects were asked to start walking from 5 m in front of the Gaitview toward the Gaitview force plate and to step on the force plate with the dominant foot. The dominant foot was determined using the Revised Waterloo Footedness Questionnaire (17). An average dynamic contact area value was obtained by repeating this process 5 times and recorded the average data. An outline of the experimental process is presented in Figure 3. The recorded data were processed using Gaitview software version 1.0.1. The difference between the FFFG and the NFAG was based on a comparison of the groups' ratios for the contact area change between the dynamic condition and the static condition, expressed as a percentage and calculated as Contact area ratio = [(dynamic contact area – static contact area) / static foot contact area] × 100.

Ground Reaction Force. The difference in GRF values and postural instability between the FFFG and the NFAG was determined by using a Wii balance board. (WBB; RVL-021, Nintendo Co., Japan). The WBB contains a 52.07 * 33.53 * 8.12 cm force plate that senses changes in weight distribution and center of gravity of a subject via four load cells located at the board's corners. WBB is a low-cost, easy-to-use device that can measure the center of gravity and weight distribution in a clinical environment (18). Measurements obtained via the WBB are reported to have high validity (ICC = 0.701–0.994) and test-retest reliability (ICC = 0.676–0.946) compared to those obtained via a conventional force plate (19, 20).

To measure GRF while walking, we provided a walkway up to the height of the WBB, as shown in Figure 3, and the WBB was positioned within that walkway. For measurement, the subjects were asked to pass over the walkway at a comfortable walking pace and with an approach that would ensure the dominant foot would land on the WBB.

Data collected from the WBB were transferred via Bluetooth into Balancia software (Mintosys Inc., Republic of Korea) in a connected personal computer. The sampling data were collected at 100 Hz and 12Hz cut off pass filtering was applied. The data in Balancia were then sent to Microsoft Office Excel software (Microsoft, USA), and contact time, vertical force peak and total GRF time-integral values were calculated. Contact time is the period from heel contact of the WBB to toe-off the WBB, based on the time the weight value exceeded 0kg to when it returned to 0kg. During the gait cycle, the first vertical force peak of the contact phase and the second vertical force peak of the propulsive phase were defined as peaks 1 and 2, respectively. The total GRF time-integral value was calculated by adding the individual GRF values during the contact time. We described the contact time, peaks 1 and 2, and total GRF time-integral values in Figure 4.

Postural Instability. To compare postural instability between the groups, a single-leg standing test was performed on the WBB for 30 seconds using a dominant foot (21, 22). The parameters related to the center of pressure (COP) data, including COP path length, velocity, and area (95% CI) were measured. During the single-leg standing test, subjects were asked to keep their hands crossed on their shoulders and to flex the non-dominant hip by approximately 60 degrees. If the feet touched the floor or came off the WBB, the test was retaken. During testing, there was an assistant present to prevent falling. After repeating measurements 3 times, the average value was calculated.

Statistical Analysis. The SPSS 19.0 software (IBM, USA) was used for statistical analyses. Descriptive statistical tests were used to assess the distribution of the general characteristics of the two groups. The Kolmogorov-Smirnov verification was used to confirm the normality of the collected data; all were observed to be normally distributed. The independent t-test was used to compare the dependent variables between groups. Statistical significance was established when $p < 0.05$.

RESULTS

The general characteristics and measurement variables of the participants are shown in Table 1. Between the FFFG and the NFAG, there was no significant difference in their foot contact area ratios under static testing conditions; however, under dynamic testing conditions, the FFFG had a significantly higher contact area than that of the NFAG. Besides, there was a significant increase in contact area ratio in FFFG ($p < 0.05$). The vertical force peak results revealed no significant differences in peak1 or peak2 values between the two groups. However, for contact time and total GRF time-integral values, the FFFG values were higher than those for the NFAG ($p < 0.05$). The postural instability assessments showed that the FFFG had significantly greater COP, velocity, COP path length, and area values than those of the NFAG (Table 1).

Table 1. Comparison of Participants' General Characteristics and Measurements between Groups

Variables	FFFG (n = 30)*	NFAG (n = 30)*	t	*p*
General characteristic				
Age (years)	21.26 ± 1.831	22.10 ± 1.58	-1.882	0.230
Height (cm)	169.00 ± 8.02	169.36 ± 8.81	-1.168	0.512
Weight (kg)	66.50 ± 15.37	64.06 ± 12.78	0.667	0.428
Shoe size	248.33 ± 21.18	249.66 ± 17.31	-0.267	0.822
BMI (kg/m^2)	23.14 ± 4.44	22.21 ± 3.10	0.941	0.155
NDT (mm)	12.40 ± 2.10	4.76 ± 1.69	15.215	0.037 ‡
The contact area of the foot				
Static (cm^2)	92.51 ± 14.98	89.64 ± 13.43	0.783	0.437
Dynamic (cm^2)	115.10 ± 17.26	105.39 ± 14.23	2.385	0.021 ‡
Increase rate (%)	24.97 ± 8.31	18.01 ± 8.58	3.186	0.002 ‡
Ground reaction force				
Peak1 (W, %)	116.33 ± 12.12	109.88 ± 8.81	2.352	0.363
Peak2 (W, %)	121.70 ± 11.55	113.44 ± 8.65	3.131	0.791
Foot contact time (sec)	0.69 ± 0.09	0.61 ± 0.12	0.683	0.044 ‡
Time-integral SUM (W, %)	52.60 ± 5.63	48.82 ± 9.70	-1.071	0.048 ‡
Postural instability				
CoP velocity (cm/s)	7.96 ± 4.42	5.47 ± 0.95	3.019	0.021 ‡
CoP path length (cm)	237.87 ± 132.80	164.29 ± 28.25	2.968	0.021 ‡
CoP 95% area (cm^2)	19.29 ± 16.24	11.52 ± 6.80	2.417	0.044 ‡

*Data are presented as Mean ± S.D. **FFFG:** Flexible flat foot group. **NFAG:** normal foot arch group. **BMI:** body mass index. **NDT:** navicular drop test. **W%:** weight %. **SUM:** summation. **CoP:** center of pressure. **‡:** Significant difference between FFFG and NFAG ($p < 0.05$)

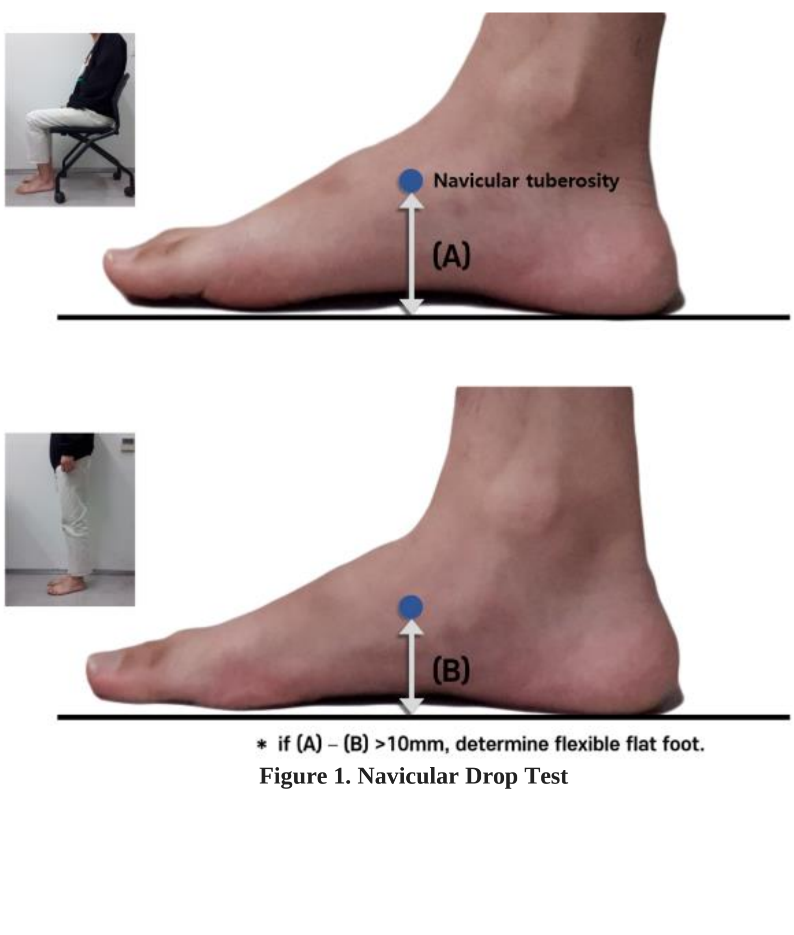

Figure 1. Navicular Drop Test

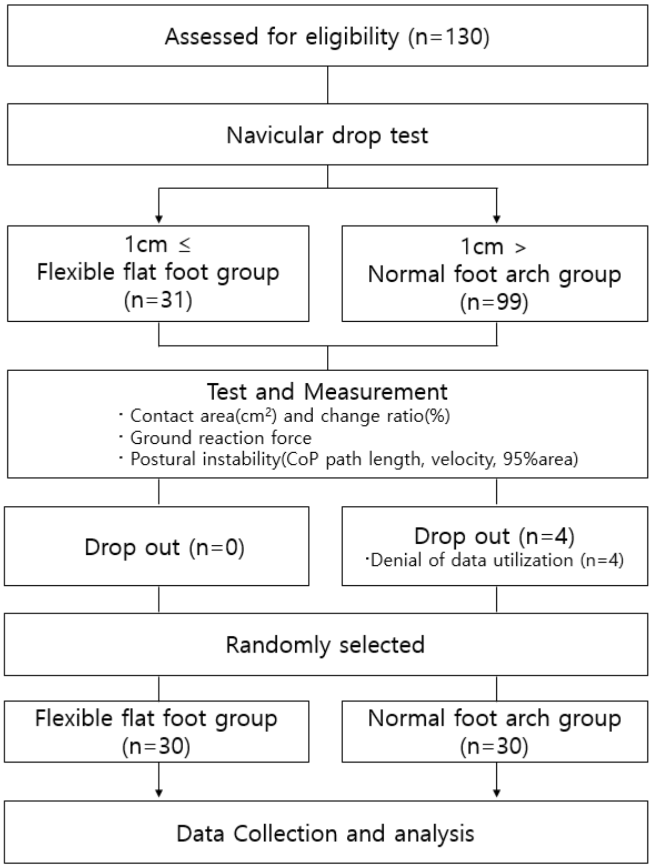

Figure 2. Flow Chart of This Study

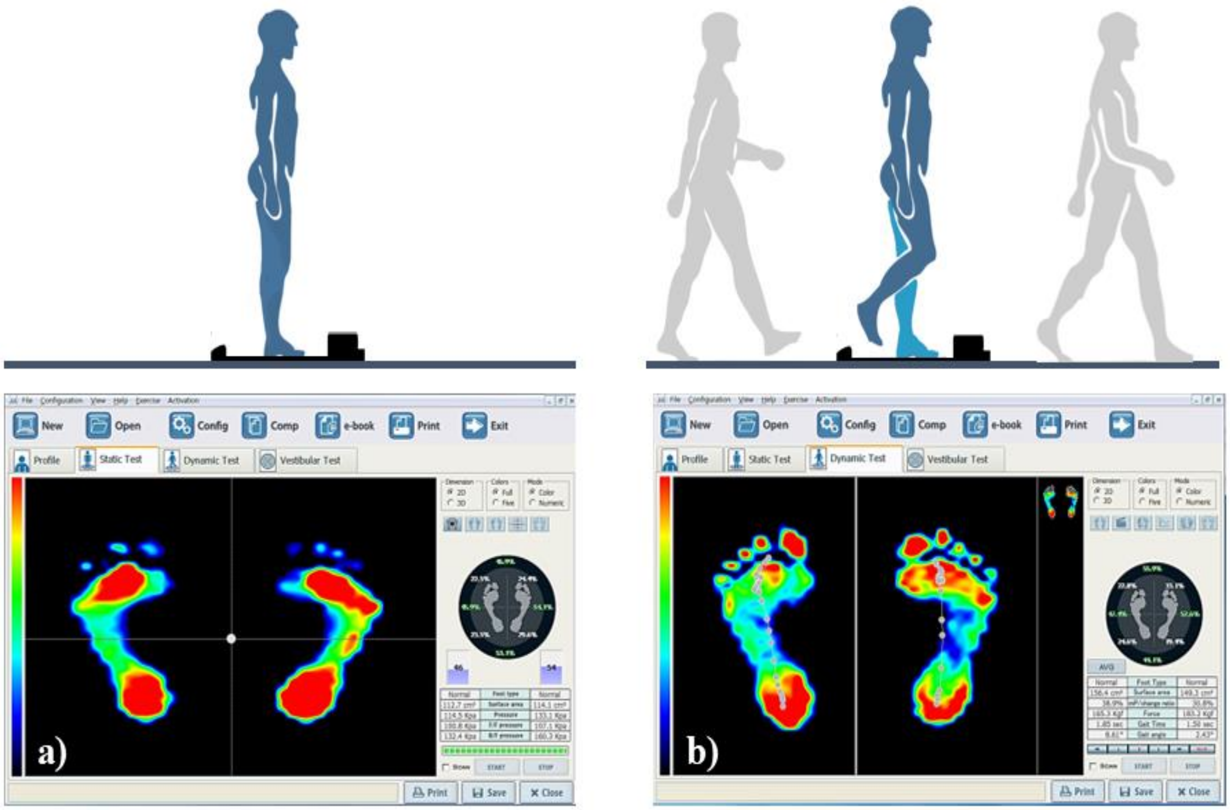

Figure 3. Measurement of foot contact area using Gait view system. a) Static position, b) dynamic condition (walking).

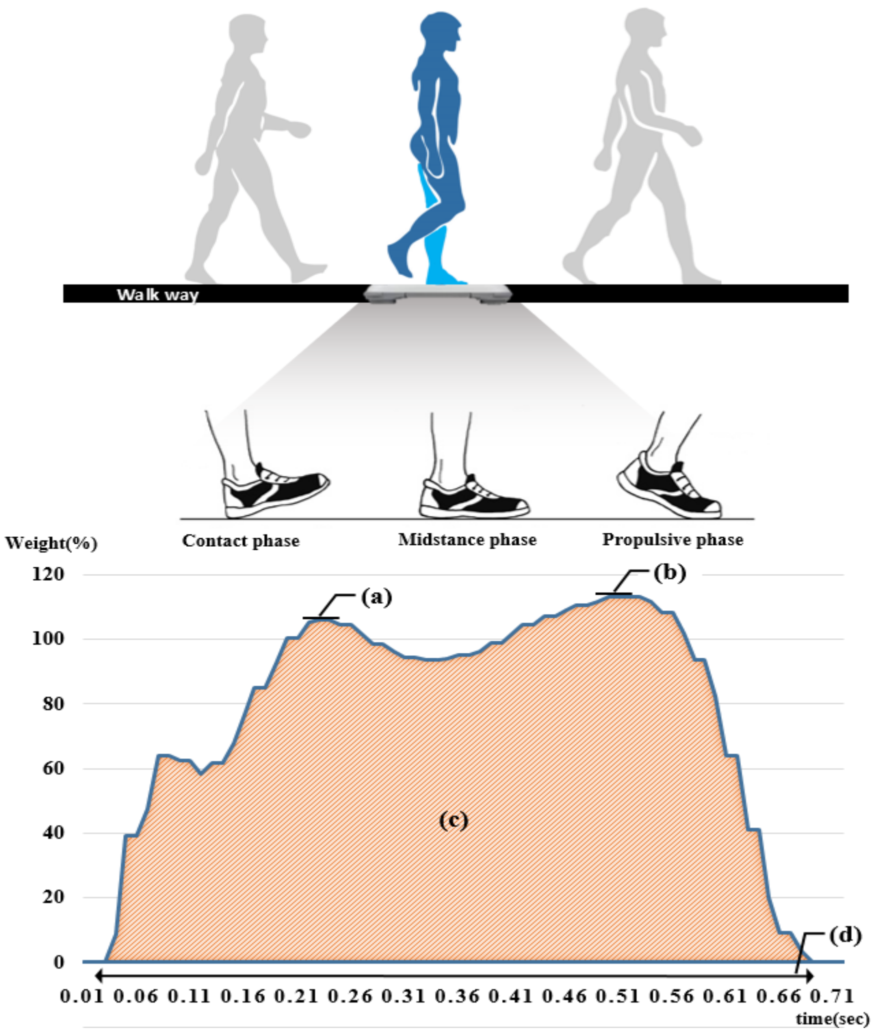

Figure 4. GRF measurement method using WBB and description of the parameters. **(a)** Vertical force peak1, **(b)** vertical force peak2, **(c)** total GRF time-integral values, **(d) contact time.**

DISCUSSION

The purpose of this study was to compare the biomechanical characteristics of subjects that have normal arches with those that have flexible flat feet while standing and walking by measuring their GRF, foot contact area, and posture instability parameters to provide clinically useful information.

The NDT, used in this study to identify subjects with flexible flat feet, was initially used to measure the degree of foot pronation of athletes, but later used to provide additional useful information about foot function in human gait (23). In this study, if the navicular tuberosity height difference between non-weight-bearing and weight-bearing conditions is more than 10 mm, the subject was assigned in the FFFG (24). The appearance of flexible flat feet has been investigated higher in the young age group (25). However, there was a slight difference in the reported appearance rates among researchers (24, 26). In our study, the prevalence of flexible flat feet was 23.8%, which showed similar results to the study of Aenumulapalli et al. (2017), which reported a 24.8% prevalence in the right foot in the same age group. Among the study subjects, the FFFG had a 12.4 mm average drop while the NFAG had a significantly smaller drop (4.76 mm average drop).

Plantar pressure and deformation of the foot are affected not only by body weight but also by gravitational acceleration (27, 28), reported that the FFFG increased the deformation of the foot when walking than the normal group, and reported that the deformation also increased when going down the stairs and as the height of the stairs increased. In our study, the foot contact area of FFFG in static posture was larger than that of NFAG, but the difference was not statistically significant. However, while walking, the ground contact area increased by 25% in the FFFG, while in the NFAG, the contact area only increased by 18%, indicating a significant increase in contact area in the FFFG. This means that in dynamic conditions, unlike in static conditions, the foot contact area increases with the weight load on the supporting foot from the initial contact to the mid-stance phase, causing the foot arch to collapse and the foot contact area to further increase.

As the weight load increases, the contact area to the forefoot and toe area increases, and the overall contact area also increases (29). The MLA is affected by the amount of GRF during weight support, and it must be able to withstand these loads and respond to various changing loads to avoid injury (30). Comparing the average difference between the two peak points of the GRF curve in this study, the magnitude of the weight load on the ground when walking was shown to be 10% greater in the FFFG than in the NFAG, but the difference was not significant. The absence of a significant difference between groups may be related to the characteristics of the WBB measuring equipment, which (only can) measure the magnitude of the force applied in the vertical direction. Previously, (31), also reported no difference in GRF in the vertical direction for male children with and without an orthosis.

Foot contact time in the FFFG was significantly longer than that in the NFAG. The drop of MLA extends the time that the feet contact the ground. Specifically, a decrease in MLA height delays the time that navicular drop during the initial stance phase and return during the terminal stance phase (29, 32). Also, the reduced arch height inhibits conserving metabolic energy expended during walking or running (33). In this study, the total GRF time-integral was significantly higher in the FFFG than in the NFAG, which could be considered to have the greatest effect of vertical force and contact time applied to the feet. Boozari et al. (2013) observed a correlation between fatigue and GRF in a study of the normal foot arch and flexible flat foot subjects and reported that there was no significant difference in peak GRF values between the two groups, but there were significant changes in peak values. The presence of a flexible flat foot increases the load transmitted to the body tissues and joints of the body, which can lead to higher energy consumption and faster muscle fatigue when walking, ultimately resulting in pain and various diseases (11, 23, 34).

Postural instability can be determined by measuring the COP path length, velocity, and area. In this study, the postural instability results according to the height of the foot arch showed that the FFFG had 45% greater COP movement distance and speed and 67% greater area compared to those of the NFAG. The results suggest that a flexible flat foot produces a postural imbalance as compensation for the difference in height of the foot arch, resulting in an unstable center of gravity. This result was similar to that reported by Tahmasebi et al. (2015) (35) which showed significant differences in the COP path length and velocity in subjects with flat feet. In those with flat feet, excessive foot pronation occurs in the stance phase during walking, and MLA tension is increased by the excessive stretching of the supinator muscle of the foot and the excessive use of the foot's intrinsic muscles, resulting in a reduction of the ability to store and release elastic energy at the beginning of the stance phase. Also, the elastic restoring ability of the MLA is significantly lowered, further reducing the stability of the foot.

The results of this study support those in several previous studies that showed that, compared to a normal-arch condition, the flat-foot condition increases the number of steps and double-limb support times, reduces the stride length, and increases energy consumption, GRF, and repulsive forces of the lower extremity (36, 37).

CONCLUSIONS

This study assessed differences in the ground contact area, ground reaction forces, plantar pressure, and static balance ability in 60 male and female adults in their twenties that were classified into the normal arch and flexible flat foot groups according to differences in the height of the foot arch. As a result, Subjects in the flexible flat foot group showed more contact area, contact time, ground reaction force, and static instability than those of subjects in the normal arch group. Based on these results, subjects with flexible flat feet may be more unstable and perform more unnecessary movements when executing normal day-to-day movements than those of subjects with a normal foot arch. The results of this study should be useful data in future follow-up studies.

APPLICABLE REMARKS

- The normal posture alignment of the feet and lower limbs, as well as the stability of the feet, directly affects our body stability and walking ability in our daily lives. Therefore, it is necessary to check the condition of the foot arch to prevent secondary musculoskeletal problems caused by deformation of the foot arch.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

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