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Original Paper

Relationship between Standing Balance Ability and Ground Contact Area

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Abstract

In this study, the standing balance abilities of 10 healthy adult men were biomechanically analyzed barefoot and while wearing arch supports. At first, the ground contact condition of the foot was compared before and after standing on the arch supports for 1 min in a standing position, and the results revealed a significant decrease in the ground contact area and contact area ratio after wearing. Then, the sway area and total trajectory length (LGN) of the center of pressure (COP) and the head vertex when barefoot and wearing arch supports were compared under open and closed eye standing conditions. With eyes open, both the sway area and LGN of the COP significantly increased when wearing the arch supports. In contrast, the LGN of the head vertex was significantly increased only with the eyes close. Under the eye-opened condition, the percentage of the area ratio between head vertex and COP, which indicates the stability of the standing balance, decreased significantly when wearing arch supports. Within the LGN ratio, the results also showed a significant decrease in the percentage when wearing arch supports with open and closed eyes. To assess standing balance stability, sway area and LGN of the COP are mainly used as parameters; however, this study proposes that comparing parietal sway with conventional data provides a more accurate representation.

1. Introduction

During biological evolution, life was born in the sea and expanded its range to the ground in the evolutionary process. It is widely known that each life form has to adapt themselves to the environment under complex interactions between gravity and ground reaction force to maintain their daily activities.

Humans are the only animals that have obtained upright bipedals through evolution. Thus, we are required to control the body to maintain the high position of the center of gravity on a small base of support; therefore, it is considered to be a cause of why humans have gained specific foot arch structures[1].

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According to Hirasawa, human upright bipedals are under the influence of constant gravity and there are important interactions between not only the sole shape and area as a human plane but also parameters such as the centroids falling on it, equilibrium capability, muscle economy of antigravity muscles, and body fluid circulation[2].

Previous research evaluating pedoscopy and footprints shows that over 50% of both children and adults have floating toes in some way and it occurs more often on the outside of the heel[3,4].

However, researchers studying floating toes consider that toe strain itself is not an issue but secondary effects of floating toe are serious issues. Specifically, they suggest that an abnormal alignment due to floating toes causes back pain, stiff shoulders, and neck pain, which induces walking efficiency reductions and, in the elderly, the increasing risk of falls due to balance problems. Nevertheless, there are few reports on this cause and effect relationship. Therefore, we conducted a comparative experiment on static standing balance barefoot and with arch supports supporting a foot arch structure at three points (Figure 1, LOFE Arch support, Joylife Ltd.).

The purpose of this study is to clarify the relationship between standing balance ability and ground contact area.

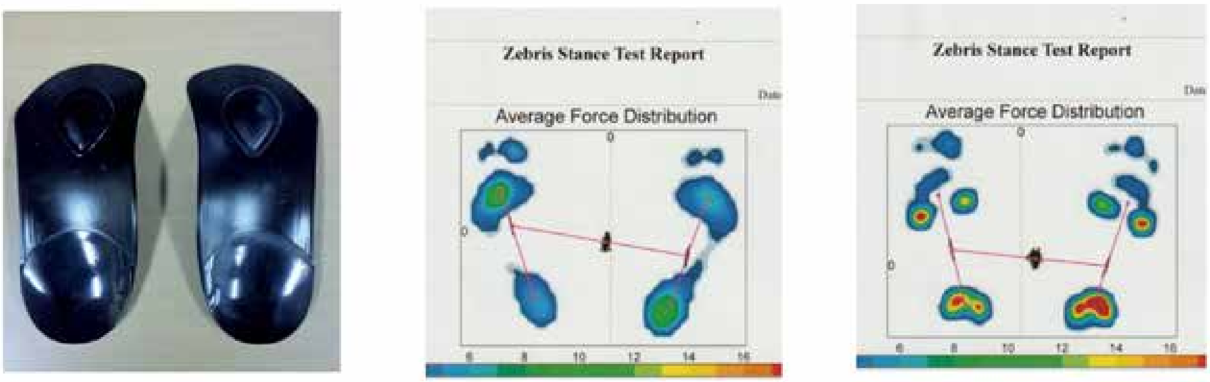

Figure 1 Arch support

The figure on the right shows the foot pressure distribution between barefoot (left) and arch support (right) during static standing of the same subject using the zebris high-performance pressure distribution system (manufactured by InterReha Co., Ltd.).

2. Methods

2. 1 Subjects

The subjects consisted of ten healthy Japanese males who volunteered to participate in the study.

Their age, height, and body weight were 33.6 ± 6.9 years, 171.7 ± 4.4 cm and 72.3 ± 10.2 kg, respectively [mean ± standard deviation (SD)]. All subjects signed informed consent forms prior to participation in the study. All procedures were approved by the Ethics Committee of the Kawasaki University of Medical Welfare (No.19-028) and were in accordance with the Declaration of Helsinki.

2. 2 Procedures

2. 2. 1 Measurement of the ground contact area of the plantar surface

The ground contact area of the foot and toes using foot pressure distribution measuring instruments were measured using Foot Look (FLK1: Foot look Co., Ltd.). The subjects were instructed to stand barefoot on the foot scanner, place both upper limbs on the body side, and look at the marker at the same height as their eyes 2 m in front of them.

Data were entered into a personal computer to calculate the plantar surface of both feet, the ground contact area, the ground contact area ratio (ground contact area/plantar surface area), and the floating index[5,6]. The measurements were taken barefoot before and after wearing arch supports for 1 min.

2. 2. 2 Measurement of standing balance ability

The subjects had a 1 cm diameter reflective marker attached to the head vertex and were subjected to a 30-second standing posture on a force plate (KISTLER 9281CA, size 600 × 400 × 100 mm). The subjects were instructed to keep the inner edges of the feet parallel, leave one fist width between their feet, and look at the same marker at eye height 2 m ahead.

A force plate was used to measure ground reaction force at a frequency of 200 Hz and measure the total length of COP (LGN), environmental area (ENV.area), and rectangle area (REC.area).

At the same time, two high-speed video cameras (IEEE1394b: for-assist) were used to shoot videos at 30 frames per second (shutter speed: open, shooting time: 30 seconds) from two directions.

The measurements had to consider the repeatability of standing movements and the trainability of the arch supports. Therefore, the average value was calculated by order of : open eyes barefoot, open eyes with arch supports, closed eyes barefoot, closed eyes with arch supports and closed eyes with arch supports, closed eyes barefoot, open eyes with arch supports, open eyes barefoot.

Figure 2 Measurement of standing balance ability when wearing arch support

2. 2. 3 Analysis

Analysis of ground reaction forces was determined using TRIASII. software (Q'sfix Co., Ltd.), LGN, ENV. area, and REC. area.

For the analysis of the head vertex, the coordinates of the top of the head were extracted using the three-dimensional motion analysis system Frame-DIASSV. Using video obtained from Q'sfix co., Ltd., the straight moving distance from the LGN and the starting point of the operation to the X and Y directions was measured. The REC.area was calculated from the data. COP sway and head vertex sway were compared, and the standing balance ability was judged.

2. 2. 4 Statistical analysis

All the obtained data are expressed in means and standard deviations. A paired t-test was used to test the difference between each data, and the significance level was less than 5%.

The statistical software used Excel statistics (2015, Excel stats, Social Survey Research Information Co, Ltd., Tokyo, Japan).

3. Results

3. 1 Morphological changes in foot and toe ground contact conditions

Table 1 shows the changes in sole ground contact conditions immediately after wearing arch supports for 1 min.

The plantar surfaces of both feet were not significantly different before and after wearing arch supports for 1 min. However, the sole ground contact area significantly decreased after wearing arch supports (203.12 ± 29.88 cm^2, P<0.05) compared to before (225.18 ± 29.46cm^2). As a result, the ground area ratio, which shows the ratio of the ground contact area to the entire foot bottom, showed a significant decrease immediately after wearing arch supports (55.5 ± 8.4 %, P<0.05) compared to before (63.8 ± 6.6 %). The grounding situation of the foot was calculated for a score of 20 points as a floating score (2 points with clear footmarks, 1 point of the blurred foot, 0 points without a picture at all) according to the previous study[5,6].

The floating score decreased after wearing arch supports (12.0 ± 4.22 %) compared to before (14.82 ± 4.29 %), but there was no significant difference.

Table 1 Morphological changes in the sole before and after wearing arch supports

		Plantar surface (cm^2)	Ground contact area (cm^2)	Ground contact ratio (%)	Floating score
Before	Mean	352.6	225.18	63.8	14.9
	SD	25.76	29.46	6.6	4.51
After	Mean	366.47	203.12 *	55.50 *	12.5
	SD	17.75	29.88	8.4	4.09

＊ P ＜ 0.05

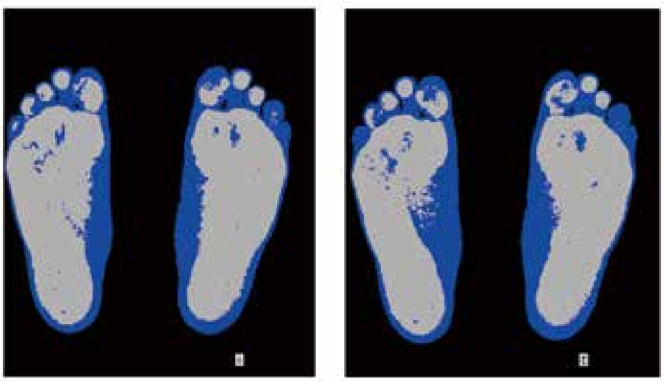

Figure 3 Changes in the sole ground contact area before and after wearing arch supports under static standing conditions (left : before, right : immediately after)

3. 2 Head vertices and COP changes during static standing

3. 2. 1 LGN and ENV.area of COP

Table 2 shows the LGN and ENV.area when barefoot (BF) and wearing arch supports (AS) under open and closed-eye standing conditions.

ENV.area significantly increased when arch supports were worn in both conditions compared to being barefoot (open-eye 2.14 ± 1.27 cm^2, P<0.01 ; closed-eye 3.28 ± 1.25 cm^2, P<0.05).

LGN showed a significant increase in both standing conditions when arch supports were worn (open-eye 47.59 ± 6.33 cm^2, P<0.01, closed-eye 73.62 ± 12.44 cm, P<0.01).

In addition, the amount of change from being barefoot to wearing arch supports for closed eyes (23.15 ± 10.30 cm, P<0.01) was significantly higher than the value for opened eyes (1.97 ± 2.71 cm).

The REC.area of the head vertex when opened (BF 6.62 ± 2.53 cm^2, AS 7.89 ± 3.33cm^2, P<0.01), or closed-eyed (BF 11.1 ± 4.11cm^2, AS 14.54 ± 5.63cm^2, P<0.05) both showed significant increases when arch supports were worn. In the LGN, there was no significant difference between being barefoot (30.02 ± 7.02 cm) and arch supports (32.70 ± 5.87 cm) with open eyes.

There was a significant increase in the closed eye condition (BF 39.75 ± 9.92 cm, AS 47.32 ± 11.80 cm, P<0.05) when arch supports were worn.

Table 2 ENV.area and LGN when barefoot (BF) and wearing arch supports (AS) under open-eye and closed-eye standing conditions

	ENV.area (cm^2)				LGN (cm)			
	Open-eye		Closed-eye		Open-eye		Closed-eye	
	BF	AS	BF	AS	BF	AS	BF	AS
Mean	2.41	3.28 **	4.54	6.51 *	37.12	47.59 **	50.47	73.62 **
SD	1.27	1.25	2.16	2.69	7.00	6.33	9.51	12.44

* $P < 0.05$ ** $P < 0.01$

Table 3 Head vertex REC.area and LGN when barefoot (BF) and wearing arch supports (AS) in an upright position

	REC.area (cm^2)				LGN (cm)			
	Open-eye		Closed-eye		Open-eye		Closed-eye	
	BF	AS	BF	AS	BF	AS	BF	AS
Mean	6.62	7.89 **	11.1	14.54 *	30.61	32.72	40.45	48.85 *
SD	2.53	3.33	4.11	5.63	7.11	6.19	10.17	11.23

* $P < 0.05$ ** $P < 0.01$

3.2.2 Head vertex REC.area ratio and LGN ratio for COP

Table 4 shows the REC.area ratio and LGN ratio of the head vertex to COP.

Arch supports worn with open eyes significantly reduced the REC.area ratio (BF 127.7 ± 34.6%, AS 110.7 ± 23.3%, P<0.05). However, closed eyes tended to decrease when wearing arch supports, but overall there was no significant difference (BF 123.3 ± 36.3%, AS 104.1 ± 31.7%).

Worn arch supports significantly reduced the LGN ratio compared to being barefoot in both open (BF 83.2 ± 15.7%, AS 9.0 ± 11.8%, P <0.05) and closed eyes (BF 80.8 ± 16.5%, AS 66.5 ± 10.9%, P <0.01).

4. Discussion

Conventionally, the gravity center sway test using a stabilometer has been used for quantitative assessments of static standing balance ability. Many studies conclude that with lower COP sway area and LGN, which are the evaluation indices, the higher the balance ability[7].

However, patients with Parkinson's disease who have a specific balance disorder do not show a large

Table 4 Comparison of head vertex REC.area and LGN for COP when barefoot (BF) and Arch Supports (AS) worn in the upright position

	Head vertex ／ COP REC.area (%)				Head vertex ／ COP LGN (%)			
	Open-eye		Closed-eye		Open-eye		Closed-eye	
	BF	AS	BF	AS	BF	AS	BF	AS
Mean	127.7	110.7 *	123.3	104.1	83.2	69.0 *	80.8	66.5 *
SD	34.6	23.3	36.3	31.7	15.7	11.8	16.5	10.9

＊ $P < 0.05$

increase in the sway area of the center of gravity[8,9], and similarly, no difference is reported on the oscillation of the standing trajectory length between a gymnast who requires a high degree of balance ability and a general university student[10]. Furthermore, some studies have questioned the validity of whether simply measuring the center of gravity oscillating area and sway trajectory length using the stabilometer in a static standing position is appropriate when evaluating balance ability and posture stability[10].

One of the factors for why prior studies have failed to establish a common evaluation for the results in the study of the oscillation of the gravity center test for healthy adults with no balance disorders is the lack of considerations of the variety of the foot sole structure, only contacting surface on the ground when standing, and of the ground contact states of the sole. Previous studies reveal that the sensation of the plantar region plays a feedback role, such as the degree of force exerted by the ankle joint, the load distribution between both lower limbs, and the material of the floor surface to the upper central nervous system. Moreover, many reports show that sole sensation is closely related to balance ability[11].

4. 1 Immediate morphological changes of the foot contact surface induced by arch supports

In a previous morphological study comparing the feet of preschoolers in two groups with and without functional sandals, there was no significant difference found in the contact surface area of the preschoolers' feet before adopting the functional sandals. However, after five months of wear, there was a significant difference found in their foot arch formation[12].

Thus, this previous study implies that footwear has some effect on arch structure; however, it should be considered that the subjects were children whose foot arches are still developing, and it took 5 months to induce morphological changes on their foot arches.

The arch supports used in this study are made of a special hard material called engineering plastic. Because of this particular material, the arch supports have unique characteristics.

Specifically, they have both flexibility and rigidity so that the shape, which supports the plantar with three points (a thenar part, a hypothenar, and calcaneus), does not change even under the load of the human body.

In a previous study of foot-shape in adults, it was reported that the arch height tended to decrease with aging[4,13], but in this study, the foot contact area significantly decreased immediately after wearing the arch supports for 1 min. Thus, it is presumed that the arch formation may be facilitated by pressure stimulation from the three-dimensional shape of the arch supports even in adults.

It is noteworthy that such a temporary effect of pressure stimulation on the sole resulted in a change in the foot contact area and the foot contact area ratio, and this phenomenon is an essential element in conducting the comparative research between being barefoot and wearing arch supports.

4. 2 Changes in COP and the head vertex sway area and the LGN

In this study, the stability in the static standing posture was determined by calculating the ratio of how much the head vertex sways, which corresponds to the top of a building, and to the COP sway of the sole, which corresponds to the base of a building.

Human postural control involves information from the visual system, somatosensory system, and vestibular labyrinth system. Besides, when considering daily human movements, it is assumed that visual information plays a significant role.

Murase et al. describe that humans perform two types of postural control to maintain an upright posture[14]. They have clarified the following two phenomena via experimentation in which the subjects were to stand on a table that vibrates back and forth and left and right. When the frequency of vibration of the table is low, the center of gravity is moved in the same direction as the vibration of the table, which means the movement of the parietal region also follows the inertia. In contrast, when the frequency is high, the body is controlled to reduce the movement of the center of gravity to the gravitational field of the earth by moving the center of gravity in direct opposition to the table. In other words, the movements occur only in body parts below the waist, and the head vertex is moving little when viewed by the outside world. Despite that, it is established that postural control is performed in the same way as when the frequency is high with eyes open, which is by moving the whole body in the same direction as the table, even at high-frequency when the visual information is blocked by closing eyes[15].

From the results obtained in this study, there was a significant increase in the ENV.area of COP when wearing arch supports compared to BF in both open and closed eyes. REC.area at the top of the head also significantly increased after wearing arch supports.

In the LGN of COP, a significant increase was seen when barefoot and compared to when arch supports were worn in the open-eye standing conditions, but there was no significant increase in LGN at the head vertex. This means that the head position maintains stability while the instability of the soles has increased.

On the other hand, in the closed-eye standing condition, there was a significant increase in the head vertex LGN with worn arch supports compared to being barefoot. These results indicate that vision is greatly involved in posture control against a head position.

The REC.area ratio of the head vertex/COP and the LGN of the head vertex/COP were also investigated as indices to quantify the posture stability. Under observation with the eyes open conditions, both the REC. area ratio and the LGN ratio of the head vertex/COP showed a significant decrease when wearing arch supports. This suggests that as compared with being barefoot, the arch supports provide postural control performed by movement of body parts below the waist and the stability of the head when standing is increased. Similarly, with eyes closed, the REC.area ratio of the head vertex/COP showed a decreasing tendency when wearing arch supports, and the LGN of the head vertex/COP showed a significant decrease. Therefore, it is assumed that even under conditions of standing with eyes closed without relying on vision, the postural control ability of the somatosensory system was enhanced by arch support-applied stimulation to the plantar ground surface.

For example, in human upright bipedal walking, when considering the movements of standing and walking, contradictory characteristics such as "stillness and movement" and "stability and mobility" are required. From a physics point of view, the wider the lower part of the object, the more the stability is improved, and the higher the center of gravity and the narrower the contact with the ground, the more efficient it is to improve movement.

Inuzuka states that vertebrates have evolved to have a higher center of gravity of the body. According to him, the higher the position of the center of gravity, the more unstable; however, humans change this falling force into propulsion, and the movement of walking means to continue to fall with the help of gravity[16].

Human motion is triggered by moving the center of gravity to the outside of the base of the support (BOS) and occurs by replacing the center of gravity within the BOS again. Walking and running are the continuous types of these movements.

In this study, the foot contact area immediately decreased after wearing arch supports as compared with being barefoot. Moreover, the parietal head vertex/COP sway ratio significantly decreased, although COP sway area and the LGN increased when wearing arch supports with both eyes open and eyes closed.

Hence, the arch structure of the foot appears to play an important role in enabling the contradictory posture strategies of stability and mobility.

Only the immediate effects of wearing arch supports were evaluated in this study. Further studies are needed to evaluate the changes in foot contact surface and the related standing balance abilities of wearing arch supports in the medium to long term span.

5. Conclusions

This study aims to investigate the morphological changes of the ground contact area of the foot immediately after wearing arch supports and the differences in the head vertex and COP sway between being barefoot and wearing arch supports under conditions of both eyes open and eyes closed. The morphological experiment of the foot using Foot Look confirmed that the ground contact area and ground contact area ratio were significantly reduced even after wearing arch supports for a short time of one min and showed immediate effects.

Therefore, this study suggests that foot arch structure must be included as a factor when evaluating standing balance ability. Judging balance ability and stability while standing, and using only the results of the COP sway area and LGN of COP by the center of gravity sway test, is difficult. This study demonstrates the effectiveness of calculating the parameters of head vertex sway/COP sway as an evaluation index of stability. We calculated the sway area of the head vertex by the REC.area ; however, it is undeniable that more accurate analyses may be possible via estimation of the ENV.area. This is a subject for further studies. The results of these experiments clearly show that the structure of the foot arch plays an essential role in performing contradictory postural strategies of stability and motility for the upright bipedals of humans.

References

1. Hashimoto T : Kinematic study of the foot arch. *Journal of Joint Surgery*, 34(1), 28-32, 2015. (In Japanese)
2. Hirasawa Y : Static upright ability of Japanese people from the point of view of stasiology. *Journal of the Society of Biomechanisms Japan*, 6(3), 7-14, 1982. (In Japanese, translated by the author of this article)
3. Iwase H, Murata S, Yumioka M, Abiko T, Nakano H and Matsui H : Foot and toe morphology in first-grade elementary school students. *Japanese Journal of Health Promotion and Physical Therapy*, 7(3), 115-119, 2017. (In Japanese with English abstract)
4. Yumioka M, Murata S, Iwase H, Naito K, Abiko T, Shiraiwa K and Horie J : Foot and toe morphological abnormalities in the elderly. *Japanese Journal of Health Promotion and Physical Therapy*, 7(2), 79-83, 2017. (In Japanese with English abstract)
5. Fukuyama K and Maruyama H : The determination of floating toes and the reliability of its assessment. *Rigakuryoho Kagaku*, 27(4), 497-502, 2012. (In Japanese)
6. Fukuyama K, Osanai M and Maruyama H : Adult toe contact and the function of floating toes. *Rigakuryoho Kagaku*, 24(5), 683-687, 2009. (In Japanese)
7. Nakatani T, Nadamoto M and Morii H : Effects of barance-ball training on postural sway. *Japanese Journal of Physical Fitness Sports Medicine*, 50, 643-646, 2001. (In Japanease)
8. Inoue R : Changes in the position and shift of the center of grayity and body sway in patients with Parkinson disease and Parkinson syndrome. *Physiotherapy*, 19(6), 546-550, 1992. (In Japanese)
9. Oku T, Amimot K, Watanabe S, Makita M and Okamoto S : Equilibrium function in patients with Pakinsonism -analysison the center of pressure (COP) in static and dynamic standing position-. *Physical Therapy Japan*, 18(2), 125-130, 1991. (In Japanese)
10. Fujiwara K and Ikegami H : A study on the relationship between the position of the center of foot pressure and the steadiness of standing posture. *Japanese Journal of Physical Education*, 26(2), 137-147, 1981. (In Japanese with English abstract)
11. Mochizuki H and Mineshima T : Reliability and validity of the index of postural stability using

forceplates. *Physiotherapy*, 27(6), 199-203, 2000. (In Japanese)

12. Miyaguchi K and Demura S : Influences of wearing Japanese-style sandals on standing postural sway and posture in preschool children. *Physical Education Measurement and Evaluation*, 14, 43-52, 2015. (In Japanese with English abstract)
13. Tateshige H and Ichihashi N : Influence of plantar sensation, plantar pressure, and ground contact condition of the sole on standing balance in elderly. *Department of Health Sciences, Kyoto University School of Medicine*, 4, 24-30, 2007. (In Japanese with English abstract)
14. Ichikawa S and Kusumi H : The foot of a human and mophological changes. *Journal of the Society of Biomechanisms Japan*, 43(2), 89-94, 2019. (In Japanese)
15. Murase K, Saito S and Tsukahara S : Visual and posture control. *Biomechanism*, 4, 149-156, 1978. (In Japanese)
16. Inuzuka N : Morphology of the spinal column and vertebrae. *Spinal Surgery*, 28(3), 239-245, 2014. (In Japanese with English abstract)