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Qualitative Analysis of Pressure Intensity and Center of Pressure Trajectory According to Shoe Type

Kyung-Ock Yi[1]

[1]*Division of Human Movement Studies, College of Health Science, Ewha Womans University, Seoul, Korea*

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ABSTRACT

The purpose of this study was to qualitatively analyze pressure intensity and the center of pressure(COP) trajectory according to shoe type. Subjects were ten first-year female university students. The EMED-AT 25/D(Novel, Germany) was used to measure pressure intensity and COP trajectory. The COP Excursion Index(CPEI) was used for within subject test design. Independent variables were bare feet and six types of shoes. Dependent variables were center of pressure trajectory and pressure intensity. Barefeet and five toed shoes had a similar pressure intensity and COP trajectory. COP trajectory for all other shoe types showed a medial wobble at the heel. Pressure intensity for all other shoe types was related to the structure of the shoes. In conclusion, different shoe types can not only affect gait, but they can also influence foot deformities, pain, and dysfunction.

Keywords : Center of Pressure Trajectory, Pressure Intensity, Shoe type, Bare Foot

Ⅰ. Introduction

In modern society people are increasingly experiencing an assortment of foot problems(Bergmann, Kniggendorf, Graichen, & Rohlman, 1995) including deformity, pain, dysfunction (Robins, Gouw, & Hanna, 1989; Fuzhong et al., 2005). These problems likely result from two factors: shoe(Yi, 2007; Robbins et. al., 1989; Andrew & Dudley, 2004), and hard, flat, even walking surfaces(Robbins & Gouw, 1991). Although shoes have been designed to protect the feet, it seems that protective footwear is actually having the opposite effect. Restrictive padded footwear forces the foot, and especially the toes into an unnatural configuration, restricting movement and causing muscle atrophy and joint degeneration in the foot. In addition, leaning on padded or elevated shoe structures during walking changes natural human gait.

The ubiquity of foot deformities such as hallux valgus, hammer toes, twisted or impacted toes(especially the 4th and 5th phlanges) and pes planus/pes cavus(Coughlin & Kaz, 2009) implies that shoes are having markedly negative effects on the feet.

Footwear also exaggerates natural movement tendencies in the foot, causing abnormal movement. For example, the medial arch is higher than the lateral arch, and the first toe is stronger than other toes, therefore many people have a tendency to shift their weight medially while walking and running(Cock, Vanrenterghem, Willems, Witvrouw, & Clercq, 2008). Elevated heels act as a lever, magnifying any deviation from the vertical and exaggerating this medial tendency. This tendency is reflected in studies by Andrew and Dudley(2004), which show high levels of pes planus. Since pes planus causes fallen arches, this is another example of how footwear can negatively affect the feet. Lastly, footwear interferes with the one of the major functions of the foot, proprioception. Since heavily padded shoes act as a barrier between the foot and the ground, the nervous system is unable to obtain precise information about foot positioning and terrain type. Consequently, the nervous system is unable to accurately self correct foot position during gait. Robbins's et al.(1991) study demonstrated that in dividuals will

Corresponding Author : Kyung-Ock Yi
Division of Human Movement Studies, College of Health Science, Ewha Womans University, 52 Ewhayeodae-gil, Seodaemun-gu, Seoul, Korea
Tel : +82-2-3277-2553 / Fax : +82-2-393-2848
E-mail : yikok@ewha.ac.kr

increase pressure when stepping onto a padded surface.

This increased pressure indicates the foot's need for greater proprioceptive feedback from padded walking surfaces. This study will examine how different shoe types alter gait, and investigate the mechanisms between shoe type and foot deformity, pain, and dysfunction. Thus, the purpose of this study was to perform qualitative analysis of pressure intensity and the center of pressure trajectory according to shoe type.

Ⅱ. Methods

1. Subjects

The subjects were ten first-year female university students with no observed foot deformity and gait abnormalities. Freshmen were selected specifically because they have spent less time in high heels compared to senior students(and thus have fewer potential gait abnormalities from high heels). There were different center of pressure trajectory according to foot type(Walker & Fan, 1998; Benedetti et al., 1997), the resting calcanael stance position for subjects was less than ±2 degrees, classifying them as "normal" or pes rectus rear foot type.

2. Equipment

EMED-AT 25/D(Novel, Germany) was used to measure pressure intensity and center of pressure trajectory according to shoe type.

3. Variables

Independent variables were six types of shoes: flip flops, canvas shoes, running shoes, elevated forefoot walking shoes, elevated mid foot walking shoes, and five-toed shoes. barefeet served as the control. Dependent variables were center of pressure trajectory and pressure intensity.

4. Center of pressure trajectory

In order to analyze foot center of pressure trajectory the foot was divided into four sections: rear foot, mid foot, forefoot, and toes. These areas were then subdivided into the following sections: medial/lateral rear foot, medial/lateral mid foot, 1st-5th metatarsals, 1st-5th phalanges, for a total of 14 different sections.

5. Pressure Intensity

Eight different colors were used to designate pressure intensity. The colors were as follows: White(no pressure), Black(1 newton per cm^2), dark blue(3 newtons per cm^2), blue(6 newtons per cm^2), green(10 newtons per cm^2), yellow(15 newtons per cm2), red(22 newtons per cm^2), and hot pink(30 newtons per cm^2).

6. Procedure

Subjects walked normally(1.28 m/sec) across a room(8 m) ten times with each type of shoe, making sure to walk directly over the pressure plate each time. The Center of Pressure Excursion Index(Song, Hillstrom, Secord, & Levit, 1996; Wong, Lilian, Adrienne, Joshua, & Jack, 2008; Raquel, Alfonso, Elena, & Juan, 2012) was used to identify the individual with most "normal" barefeet gait pattern. According to within subject test design, this subject's results were analyzed. Therefore the most representative gait pattern from the ten pressure plate trails for each shoe was compared.

Ⅲ. Results

1. Pressure trajectory

1) Bare Foot

Barefeet were used as the control for this study, therefore, barefoot walking patterns were regarded as normal movement, since

Figure 1. Type of shoes

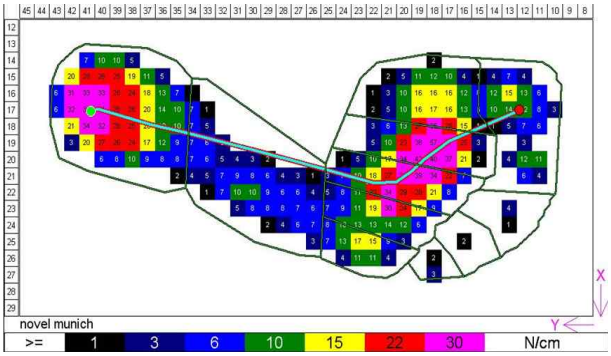

Figure 2. 14 sections of the foot

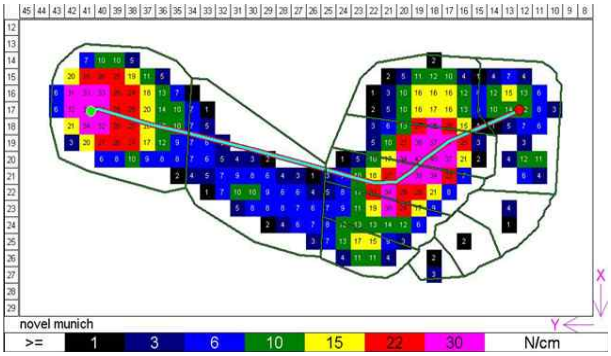

Figure 3. Center of pressure trajectory for barefoot

movement or foot position was unaffected by shoes. The pressure trajectory for barefoot started at the center of the heel and moved forward along the foot's centerline until it reaches the middle of the third metatarsal. There it moved medially towards the 1st toe until toe-off. This medial shift in COP trajectory is also known as excursion(Wong rt al., 2008).

2) Five Toed-shoe

Five toed shoes had a similar center of pressure excursion pattern as bare feet.

3) Athletic Shoe

The center of pressure trajectory for athletic shoes was dramatically different than barefoot movement. At heel contact center of pressure began lateral of the centerline but immediately shifted medially past the centerline. Shortly afterwards, the center of pressure shifts back to the centerline. This movement can be described as a "medial wobble." From the middle of the heel until toe off the center of pressure travels in more or less a straight line along the foot's center line. Unlike barefoot movement, there was no excursion pattern.

4) Canvas Shoe and Flip Flops

Canvas shoes and flip flops demonstrated a similar pattern as athletic shoes. Both had the same medial wobble at heel contact as the center of pressure begins lateral of the centerline, shifts medially, and realigns itself with the centerline at the middle of the heel. For both shoes, center of pressure travelled slightly medial to the centerline until it moved to the center of the forefoot. There, the center of pressure travelled laterally to the centerline at toe off.

5) Elevated forefoot and elevated midfoot walking shoes

Elevated forefoot and elevated midfoot walking shoes also demonstrated a similar pattern to athletic shoes. both shoes showed a medial wobble at the heel. Then the center of pressure moves in more or less of a straight line to the along the foot's centerline until toe off.

2. Pressure Intensity

1) Bare Foot

In barefeet, pressure was highest at the heel and in the forefoot at the second and third metatarsal. Pressure was lowest throughout the entire midfoot as well as in the last three toes(Figure 3).

2) Five Toed Shoes

Foot pressure was very similar between five toed shoes and barefeet. Pressure was highest at the heel but this high pressure was anterior compared to barefeet. Similar to barefeet, there was high pressure at the forefoot, but in five toed shoes this was highest at the first and second metatarsal. Finally unlike barefeet. there was high pressure at the first toe. Furthermore, there was more pressure at each toe compared to barefeet. Pressure was lowest at the midfoot -even lower than in barefoot(Figure 4).

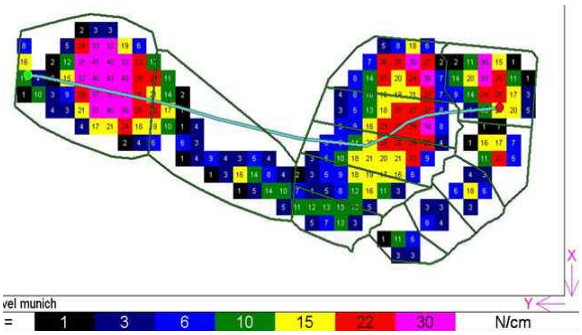

Figure 4. Pressure trajectory for five-toed shoe

3) Athletic Shoes

For athletic shoes, pressure was highest at the circumference of the heel and at the first metatarsal. Pressure at the heel was in a

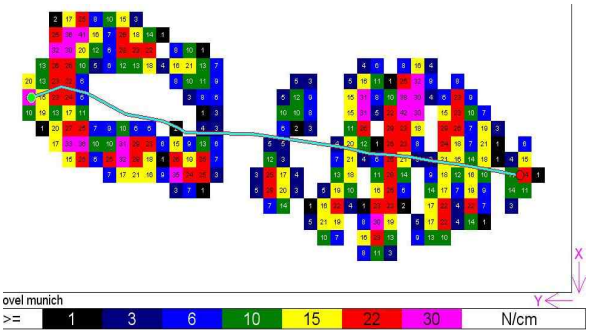

Figure 5. Pressure trajectory for athletic shoe

distinct ring pattern. Pressure was lowest at the midfoot. At toe-off, pressure at toe of was actually in front of the toes (Figure 5).

4) Canvas Shoes

Canvas shoes exhibited the widest area of foot pressure. Pressure was highest at the heel, although it was centered much more medially compared to barefeet.

Pressure was lowest at the midfoot. At toe off pressure was in front of the second and third toes (Figure 6).

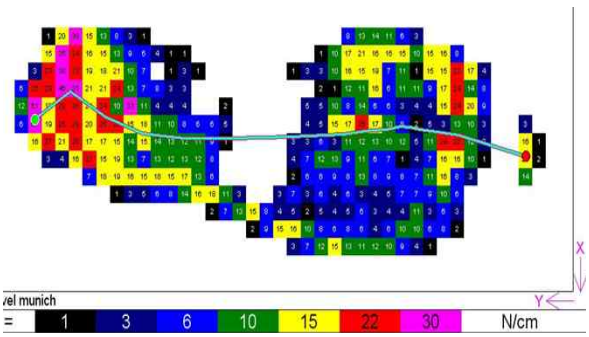

Figure 6. Pressure trajectory for canvas shoe

5) Flip Flops

Flip flops showed a high level of pressure on the medial aspect of the heel and toes. Pressure was lowest at the midfoot (Figure 7).

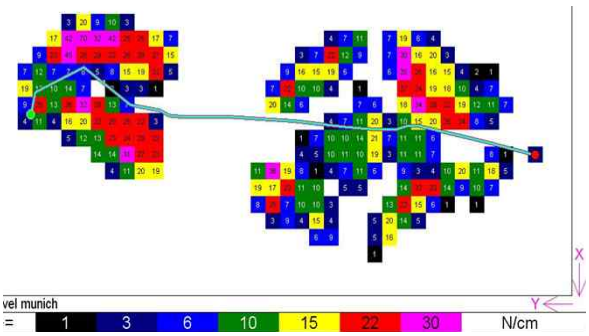

Figure 7. Pressure trajectory for flip flops

6) Elevated Forefoot

Elevated forefoot walking shoes displayed the highest levels of pressure at the heel and forefoot. Heel pressure was at the anterior portion of the heel compared to barefeet. In both the heel and forefoot, pressure was distributed relatively evenly throughout the foot. The lowest area of pressure was at the midfoot, and furthermore the elevated forefoot shoes had the lowest amount of pressure compared to any other shoe(Figure 8).

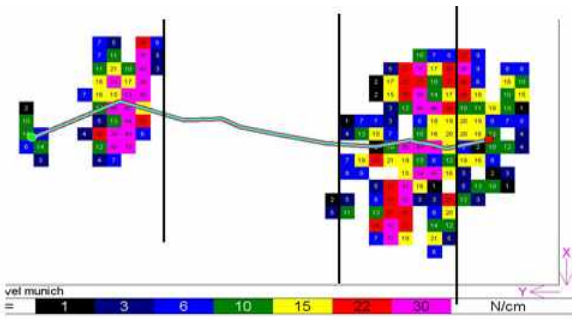

Figure 8. Pressure trajectory for elevated fore foot walking shoe

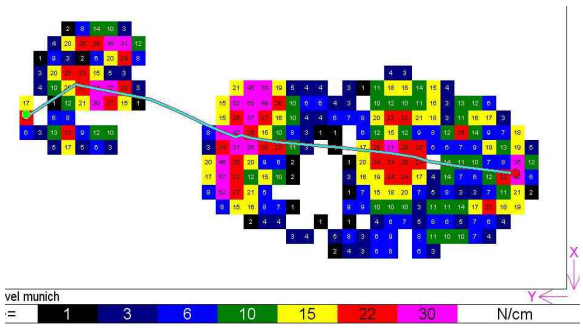

Figure 9. Pressure Trajectory for Elevated Mid Foot Walking Shoe

7) Elevated Midfoot

Elevated midfoot shoes showed high levels of pressure at the medial aspect of the heel, anterior portion of the midfoot, second metatarsal, and in front of the second toe.

Ⅳ. Discussion

A. Center of Pressure Trajectory

1) Barefeet and Five Toed Shoes

a) Contact Point

There were two different contact points for the center of pressure trajectory amongst the six different shoe types. The point

of contact for the center of pressure trajectory for barefeet(Wong et al., 2008) and five-toed shoes was at the centerline of the heel.

b) Trajectory

The center of pressure trajectory for barefeet in this study was similar to other studies which have documented "normal" barefoot center of pressure trajectory(Claudia et al, 2002; Wang et al., 2011). The center of pressure trajectory for barefeet and five toed shoes moved in a straight line from the heel to the middle of the third metatarsal. At the forefoot the center of pressure moved inwards dramatically until it reached the first toe in a process called excursion(Wong et al., 2008). There was no medial wobble at the calcaneus with barefeet and five toed shoes because there is negligible heel elevation with either shoe type.

c) Foot Alignment

Individuals usually rotate their toes at a -2 to +15 degree angle away from the direction of movement while walking(Staheli, 1985, 1993). For barefoot subjects, this aligns their heels and first toes parallel to the direction of movement. Thus, the hip, knee, and ankle are aligned during gait(Haim, Amir, Nimrod & Alon, 2010).

2) Padded Shoes

a) Contact Point

For padded shoes(athletic shoes, canvas shoes, flip flops, elevated forefoot shoes, elevated midfoot shoes) the point of contact for the center of pressure trajectory was lateral to the calcanael centerline(Young, Craig, Mark, George & Kevin, 2005). A possible reason for this lateral contact is related to the padded heels on all of these shoe types. In padded heels subjects required greater dorsi flexion to duplicate the barefoot sagittal impact angle at the heel. However, subjects likely compensated for this by making contact lateral to the calcaneal centerline(Pisciotta et al., 2011). This gait characteristic is reflected in the uneven wear pattern on the heel of most shoes(most people's heels show more wear at the lateral portion of the heel). It is likely that the lateral compensation at heel contact corresponds with outward rotation of the foot, so future studies should include kinematic analysis to compare foot position to center of pressure trajectory.

b) Trajectory

Athletic shoes, canvas shoes, flip flops, elevated forefoot shoes, and elevated midfoot shoes all had similar center of pressure patterns, likely due to the padded heel on all of these shoes. After initial heel subject's demonstrated a medial wobble (Pisciotta et al., 2011; Young, Craig, Mark, George & Kevin, 2005) in all shoe types. After the wobble the center of pressure travelled in an approximate straight line along the foot's centerline until toe off.

The initial medial foot wobble(Cock, Vanrenterghem, Willems, Witvrouw & Clercq, 2008) reflects the reduced proprioceptive control of the heel due to padding(Robbins & Gouw, 1991). Padded heels acted as a lever, naturally exaggerating the side to side shift of body weight that coincided with forward movement. Furthermore, with padded heels, the foot must orient itself to both the shoe and the ground. The foot had direct contact with the padding of the shoe and only made contact with the ground through the shoe(Robbins et al., 1991). The time in which the foot wobble occurred likely reflected the extra time necessary for the foot to sense that it was out of position and compensate.

Another reason for the medial wobble in padded shoes was that subjects were using the foot padding to correct their foot positioning. Subjects could be leaning on the foot padding to stop their medial momentum and afterward correcting their foot positioning, resulting in the wobble. The medial wobble changed the position of the foot during gait, causing pronation at the heel. This in turn could result in increased medial torsion force at the ankle, the heads of the fourth and fifth metatarsals(Gastwirth, 1996; Hlavac, 1970) and the knee.

This medial wobble in the heel demonstrates why there are more pronators than supinators. This study shows that placing padding between the feet and the ground and restricting individual metatarsal and toe articulation creates an unnatural gait pattern. Comparing center of pressure trajectory in barefeet and with shoes shows exactly how gait is changed.

c) Foot Alignment

As cited above, most individuals usually position their foot laterally between -2 and 15 degree to their direction of movement (Reynolds, 1995). However, since the COP trajectory in padded shoes moves in a straight line to the third metatarsal, the COP trajectory is not parallel with the direction of movement(Reeves & Bowling, 2011). Thus, there must be torsion force in the toes, ankle, knee and hip to realign COP trajectory with movement direction at toe off(Donatelli, 1996; Valmassy, 1996).

2. Pressure Distribution

1) Barefeet and Five Toed Shoes

Similar to Center of Pressure Trajectory, barefeet and five toed

shoes exhibited a parallel pressure distribution patterns. Both had the highest concentration of pressure at the heel and the forefoot. However in five toed shoes, heel pressure occurred slightly anterior to barefeet. This was caused by increased dorsi flexion while wearing five toed shoes. In addition, for five toed shoes, forefoot pressure was concentrated in the 1st and second metatarsal, compared to the 2nd metatarsal for barefeet. Furthermore, five toed shoes showed less pressure along the midfoot, but their was visibly more pressure throughout all the toes. Finally compared to bare feet, five toed shoes showed more pressure in each metatarsal. Since five toed shoes act as a brace, holding the toes separately during movement, users engaged their toes more than when barefoot.

2) Athletic Shoes

It is likely that the structure of athletic shoes effected the center of pressure graph. These athletic shoes featured an o-shaped heel with an empty center, which is reflected in the pressure distribution. It is likely that this pressure distribution was a deliberately engineered into the shoe design. If shoe designers assume that the foot is weak and vulnerable to injury due to high pressure, the o-shaped heel redistributes pressure to the outer circumference of the heel. In theory, this would lead to less heel injuries and pain. However, since the center of the heel evolved to absorb the most impact from walking, this pressure redistribution is likely to exacerbate problems, as the outside of the heel did not evolve to withstand high pressure. Furthermore, toe pressure reflects the unnatural configuration of athletic shoes as each toe loses its distinct ability to apply pressure separately, resulting in a foot pressure graph that reflects the shape of the shoes instead of the shape of the foot.

3) Canvas Shoe

Canvas shoes had the widest area of pressure distribution compared to any other shoe. This wider area of pressure distribution likely coincides with greater foot muscle activation. Therefore subjects using canvas shoes might experience muscle fatigue earlier than with other shoe types.

4) Flip Flops

High medial heel pressure likely reflected the dangling heel of flip flops. In order to compensate for the lower heels, walkers rotated their heels laterally.

5) Elevated Forefoot Walking Shoe

The high pressure throughout all of the metatarsals at the forefoot indicated toe dorsi flexion and abduction. Toe dorsi flexion and abduction is important, since the structure of most shoes inhibits movement in this range of motion.

6) Elevated Midfoot Walking Shoe

Unlike any other shoe type, elevated midfoot shoes had high pressure at the midfoot. This pressure corresponded to the elevated midfoot structure of the shoes. After making contact with the heel, the elevated midfoot also makes firm contact with the ground.

7) Influence of Shoe Construction on Pressure Distribution

Foot pressure at toe off for athletic, canvas, and midfoot walking shoes was in front of the second and third toes. This area of pressure does not correspond to any anatomical structure on the foot. This demonstrated that foot pressure corresponds with not only the anatomy of the foot but also with the shape of the shoes.

Ⅴ. Conclusions

Although barefoot walking and five toed shoes had similar COP trajectory, excursion angle, and pressure distribution, these results were different from padded shoes. Differing construction and configuration of padded shoes altered the foot's point of contact, center of pressure trajectory, and pressure distribution. Most notably padded shoes caused lateral heel contact and a "medial wobble" during the first moments of double leg support. This "medial wobble" could lead to rearfoot pronation and forefoot valgus. This movement could lead to foot deformities, pain, and dysfunction. With forefoot excursion the toes are used to generate propulsive force. Since shoes act as a brace that keeps individual foot segments(especially the toes) from moving independently, most shoe wearers are unable to perform excursion. Thus shoe wearers don't use their toes to generate propulsive force, resulting in a loss of both range of motion, and muscle activation, which, in turn, can lead to forefoot muscle degeneration. High heels were excluded from the study because the concentrated heel pressure from the spiked heel could damage the EMED-AT 25/D(Novel, Germany) pressure measurement system. Future studies will investigate the effects of high heel shoes, and anti-pronation/anti-supination design(such as inner arch support, variable padding) on gait variables.

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