Maximum force and the center of pressure trajectory length according to foot angles during stair walking

JEON HYEONG LEE, PT, PhD(1), MYOUNG HEE LEE, PT, PhD(2)*, SANG YEOL LEE, PT, PhD(3)

1) Department of Physical Therapy, Daegu Health College, Republic of Korea
2) Department of Physical Therapy, Human Service College, Uiduk University: 261 Donghaedaero, Gangdong, Gyeongju 780-713, Republic of Korea
3) Department of Physical Therapy, College of Science, Kyungsung University, Republic of Korea

Abstract. [Purpose] Walking with the feet turned inward or outward often causes issues for the people with these walking patterns. The purpose of this study was to examine the influence of in-toeing and out-toeing on maximum force and the center of pressure (COP) trajectory length during stair walking. [Subjects and Methods] The subjects were 30 female university students without orthopedic diseases of the foot. The foot angle was divided into three types: in-toeing, normal, and out-toeing. A plantar pressure measurement instrument was used, and the maximum force was obtained by dividing the foot into six regions covering the anterior medial-lateral, middle medial-lateral, and posterior medial-lateral regions. The COP trajectory length was statistically calculated by measuring the medio-lateral, anterior-posterior, and total travel distances. [Results] During stair climbing, the maximum force was significantly different in the anterior lateral region. During stair descending, the maximum force was significantly different in the anterior lateral, middle medial, middle lateral, posterior medial, and posterior lateral regions. The COP trajectory length showed a statistically significant difference in the medio-lateral travel distance. [Conclusion] Walking with abnormal foot angles causes deformed foot structures and can result in musculoskeletal disabilities in the long term. Therefore, therapeutic intervention is required to maintain normal foot angles.

Key words: Foot angle, Stair walking, Maximum force

INTRODUCTION

Walking refers to alternating anterior movements of the trunk and legs in a simultaneous and continuous manner while maintaining stability in the stance phase. This is the most fundamental movement of the human body, and it is realized through interactions between the musculoskeletal and nervous systems. Stairs area circumstance that individuals are frequently exposed to in daily life during walking. In stair walking, each step starts on the toes and the ball of the foot rather than the heel. In addition, the vertical upward movement of body weight requires external forces, while the vertical downward movement of body weight requires control of falling. Stair walking differs from horizontal walking in terms of the changes in characteristics of the force generated in the lower-extremity segments according to the angle of inclination. In addition, as stair walking progresses, the body is lifted at the same time as it is moved horizontally. Stair walking also reduces stability by increasing head and neck movements. Therefore, stair walking requires more frequent muscle activities and a higher level of balance control than just walking on the ground.

The foot angle describes the location of the foot in relation to its moving direction during walking and refers to the angle between the foot’s baseline (the line that connects the heel’s center and the third metatarsus) and the foot’s moving direction. In general, when a foot lands on the ground during walking, the foot’s end turns outward in relation to the moving direction. In-toeing or out-toeing can be influenced by factors such as the movement of the hip joint, the degree of distortion in the tibia and malleolus, and adduction or abduction of the talus in relation to the foot. In-toeing and out-toeing also affect the movement of thigh muscles during open kinetic chain exercises. Given the structure of the human body, a normal foot angle is around 15°; angles smaller than this are defined as in-toeing and angles larger than this as out-toeing.

Plantar foot pressure is the pressure applied to the entire foot as well as specific regions of the foot. It measures and reflects the status of balance and walking of the human body. The measurement of plantar foot pressure is clinically useful, as it helps to identify anatomical foot deformities and diagnose and treat walking disorders and...
impairments in walking ability\(^{11}\)). Plantar foot pressure is usually measured using a force plate, pressure plate, or in-shoe sensor. However, the methods that use force or pressure plates cannot fully measure pressure on each region of the foot. The method that measures plantar foot pressure using in-shoe sensors is useful for obtaining various types of information on changes in plantar foot pressure\(^{12}\).

A number of existing studies have researched plantar foot pressure on the ground and stairs according to age group and disease type, and many of these performed kinetic analyse of plantar foot pressure on the ground according to foot angle. However, studies that have compared plantar foot pressure according to foot angle in various environments are few. Therefore, the purpose of this study was to compare plantar foot pressure and the center of pressure (COP) trajectory length according to in-toeing, out-toeing, and a normal foot angle using an F-scan system, which enables the observation of the distribution of plantar foot pressure, during ascent and descent of stairs.

**SUBJECTS AND METHODS**

The subjects of this study were free of orthopedic diseases, open wounds, or diseases of the foot or lower extremities. Before the experiment, the purpose of this study was explained to the subjects, and their consent to participation was obtained. This study was approved by the Institutional Review Board of the Local Ethics Committee in accordance with the ethical principles of the Declaration of Helsinki. The general characteristics (mean±SD) of the subjects were: an age of 21 ± 2.16 years a foot size of 235 ± 7.24 mm, a height of 158 ± 4.17 cm tall, and a weight of 45 ± 8.22 kg.

The plantar foot pressure measuring system F-scan (Tekscan Inc., USA) was used to measure plantar foot pressure and the COP trajectory length. This system consists of an insole-type sensor that can be tailored to measure plantar foot pressure, conversion devices that can be attached to the legs, cables that connect the conversion devices to a computer, a computer, and software for the analysis of plantar foot pressure. The insole-type sensor is thin (0.18 mm thick), inflexible, and consists of 960 pressure sensors evenly distributed in a grid pattern with a spacing of 0.2 inches. The insole sensor was cut to fit the foot size of each subject and then installed in his/her shoe. The input signals were delivered to a computer via a 10-meter cable connected to the computer interface attached to the waist. The subjects were instructed to insert the insole-type sensors that had been cut to fit the size of their shoes inside each shoe and then walk. The distribution of plantar foot pressure data was collected at a rate of 60 Hz using Tekscan’s commercial program. In this study, the foot was divided into six regions: anterior-medial, anterior-lateral, medio-medial, medio-lateral, posterior-medial, and posterior-lateral. Subjects’ plantar foot pressures were recorded using Tekscan Pressure Measurement System Version 5.23. The COP trajectory length was analyzed by dividing it into the anterior-posterior, medial-lateral, and total trajectory lengths. SPSS 12.0 for Windows was used for the statistical processing of the collected data. One-way ANOVA was performed to compare plantar foot pressure and the COP trajectory length according to foot angles during stair walking. In addition, Fisher’s least significant difference (LSD) test was performed as a posthoc test. The statistical significance level was choosen as \( \alpha = 0.05 \).

**RESULTS**

In stair walking, the maximum pressure showed statistically significant differences in the anterior-lateral region. The results of the posthoc test showed there were statistically significant differences between normal and out-toeing, normal and in-toeing, and in-toeing and out-toeing walking (\( p < 0.05 \)) (Table 1).

The COP trajectory did not show statistically significant differences in the anterior-posterior, medial-lateral, and total trajectory lengths (\( p > 0.05 \)) (Table 2).

In stair descending, the maximum pressure showed statistically significant differences in the anterior-lateral and medio-medial regions between in-toeing and out-toeing walking, as well as statistically significant differences in the medio-lateral region between normal and in-toeing walking and in-toeing and out-toeing walking. The posterior-medial

| Table 1. Comparison of maximum force on the stair up (Unit: kPa) |
|---------------------------------------------------------------|
|                  | Anterior | Middle | Posterior |
|                  | Medial   | Lateral | Medial   | Lateral | Medial   | Lateral |
| Normal           | 12.8±1.4 | 13.8±1.5 | 4.3±0.9  | 8.3±1.6 | 8.1±1.1  | 7.9±0.8 |
| Out-toeing       | 10.2±1.1 | 13.4±1.4 | 4.5±0.8  | 6.9±1.4 | 9.1±1.1  | 8.9±0.9 |
| In-toeing        | 11.3±1.2 | 8.9±1.1  | 3.3±0.5  | 8.7±1.4 | 7.7±0.9  | 6.7±0.8 |

Values are Mean±SD, \(^* p<0.05\)  
\(^{a}\) significant difference between normal and out-toeing 
\(^{b}\) significant difference between normal and in-toeing 
\(^{c}\) significant difference between out-toeing and in-toeing

| Table 2. Comparison of COP on the stair up (Unit: cm) |
|-----------------------------------------------------|
|                  | AP       | ML       | Total    |
| Normal           | 13.8±0.5 | 1.8±0.2  | 13.9±0.5 |
| Out-toeing       | 14.6±0.4 | 2.0±0.1  | 14.8±0.4 |
| In-toeing        | 14.1±0.8 | 2.2±0.2  | 14.3±0.8 |

Values are Mean±SD, AP: anterior posterior, ML: medial lateral
and posterior-lateral regions revealed statistically significant differences between normal and out-toeing and in-toeing walking (p < 0.05) (Table 3).

The COP trajectory length showed statistically significant differences in the medial-lateral trajectory length. The post-hoc test exhibited statistically significant differences between normal and in-toeing and in-toeing and out-toeing walking (p < 0.05) (Table 4).

**DISCUSSION**

The purpose of this study was to perform a comparative analysis of plantar foot pressure and COP trajectory length during stair climbing and descending by subjects with in-toeing, normal, and out-toeing foot angles.

In this study, the maximum pressure during stair climbing showed statistically significant differences in the anterior-lateral region, whereas the COP trajectory length did not reveal statistically significant differences in the anterior-posterior, medial-lateral, and total trajectory lengths. In stair descending, the maximum pressure showed statistically significant differences in the anterior-lateral, medio-medial, medio-lateral, posterior-medial, and posterior-lateral regions. The COP trajectory length exhibited statistically significant differences in the medial-lateral trajectory length.

Han et al. researched plantar foot pressure during level walking, stair climbing, and slope climbing, and reported that, compared to level walking, stair walking yielded increases in pressure on the fourth and fifth toes and the fourth and fifth metatarsals, and decreases in pressure on the mid-foot and hindfoot [4]. Rao and Carter found increases in pressure on both the anterior-medial and anterior-lateral regions during stair climbing [4]. Of the results of these two studies regarding the pressure on the anterior-lateral region are in agreement with that of the present study. In addition, Han et al. compared the COP trajectory length of level and stair walking and discovered that the anterior-posterior and total trajectory lengths declined during stair walking. Again, these results are similar to those of the present study.

While many previous studies simply observed changes in plantar foot pressure on the ground according to foot angle, the present study measured foot plantar pressure during stair walking. This differentiates the present study from previous studies. The results of the present study are similar to those of previous studies that compared level and stair walking and reported pressure increases in the foot’s anterior-lateral region, and decreases in the hindfoot. During stair climbing, the maximum pressure on the anterior-lateral region decreased in in-toeing walking compared to out-toeing and normal walking, and the medial-lateral trajectory length increased in in-toeing walking. This shows that pressure was not properly supported in the lateral region, which led to increases in the medial-lateral movement. In addition, during stair descent, in the case of in-toeing walking, the maximum pressure on the anterior-lateral and posterior-lateral regions decreased, and the maximum pressure on the medio-lateral region increased. Moreover, the COP trajectory length showed increases in the mediolateral movement. In-toeing walking appears to increase the loads on the mid-foot and medial-lateral region. In-toeing hinders the even distribution of an individual’s weight and thus raises the risk of a fall. In other words, in-toeing and out-toeing cause anatomical changes in the location of the hip joint, which result in walking patterns that consume high levels of energy due to low stability [15, 16].

In conclusion, this study demonstrated that differences in foot angle influence plantar foot pressure and the COP trajectory length during walking. The concentration of pressure on a specific region of the foot due to abnormal foot angles can cause foot deformities and physical disabilities. In addition, it can have substantial effects on the forces required for inward and outward turns [2], thereby dispersing the force that moves the body forward [13]. Excessive pressure applied during consecutive motions such as walking is highly likely to impair the body’s actions to protect itself [5]. Therefore, continuous training is required to maintain normal foot angles.

The results of this study may help to provide basic data on plantar foot pressure and COP trajectory length in abnormal gait patterns. To better understand the effect of foot angle on muscles and the musculoskeletal system, in addition to

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**Table 3. Comparison of maximum force during stair descent (Unit: kPa)**

|         | Anterior | Middle | Posterior |
|---------|----------|--------|-----------|
|         | Medial\(^a\) | Lateral\(^a\) | Medial\(^b\) | Lateral\(^b\) | Medial\(^c\) | Lateral\(^c\) |
| Normal  | 9.9±1.0 | 9.6±1.1 | 3.8±0.7 | 5.9±0.9 | 4.8±0.8 | 4.8±0.6 |
| Out-toeing | 7.5±0.8 | 12.3±1.5 | 5.2±0.8 | 6.3±1.0 | 7.4±1.0 | 7.8±0.9 |
| In-toeing | 10.4±1.1 | 7.2±1.0 | 2.9±0.4 | 10.5±2.1 | 4.7±0.6 | 4.3±0.6 |

Values are Mean±SD, \(^a\) p<0.05
\(^b\) significant difference between normal and out-toeing
\(^c\) significant difference between normal and in-toeing

**Table 4. Comparison of COP during stair descent (Unit: cm)**

|         | AP | ML\(^b\) | Total |
|---------|----|---------|-------|
| Normal  | 14.8±0.5 | 2.4±0.2 | 15.0±0.5 |
| Out-toeing | 14.4±0.8 | 2.4±0.1 | 16.6±0.8 |
| In-toeing | 12.7±0.6 | 3.0±0.2 | 13.1±0.6 |

Values are Mean±SD, \(^a\) p<0.05, AP: anterior posterior, ML: medial lateral
\(^b\) significant difference between normal and out-toeing
\(^c\) significant difference between normal and in-toeing
\(^c\) significant difference between out-toeing and in-toeing
the types of foot angle, the effects of kinematic and kinetic variables related to joint angles and muscles on the lower extremities should be investigated. Moreover, additional studies should research changes in gait patterns according to relevant kinematic interventions.

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