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Original articles

A Study on Changes in Lower Limb Joint Angles during Stair Walking with High Heel

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Purpose: The purpose of this study is to compare kinematics on lower limbs between stair walking with high heel and barefoot in healthy adult women.

Methods: 18 healthy adult women were recruited in this study. The subjects performed stair ascent and descent with high heels and barefoot. The experiment was conducted in random order and repeated three times for each stair walking with high heels and barefoot. The movements of lower limb joints were measured and analyzed using a three-dimensional analysis system.

Results: The ankle, knee, and hip flexion angles on the sagittal plane exhibited statistically significant differences between stair ascent and descent with high heels and barefoot. The pelvic forward tilt angles showed statistically significant differences only during stair ascent. The ankle inversion, hip abduction and pelvic lateral tilt angles on the frontal plane showed statistically significant differences between stair walking with high heels and barefoot. On the transverse plane, the hip rotation angles showed statistically significant differences between the high-heeled and barefoot gait during stair ascent and descent. However, the pelvic rotation angles showed no statistically significant differences.

Conclusion: Therefore, wearing high-heeled shoes during stair walking in daily life is considered to influence lower limb kinematics due to the high heel, and thus poses the risks of pain, and low stability and joint damage caused by changes in the movement of lower limb joints.

Key Words: Stair ascent, Stair descent, Barefoot, High-heeled shoes, Lower limb joints

Ⅰ. Introduction

In daily life, stair walking is the most common movement next to walking on the ground.[1] It not only comprises our daily activities, but also is a part of rehabilitation treatment.[2] Stair walking is similar to walking on the ground as both motions are largely divided into the stance and swing phases. However, during stair walking, the lower limbs generate different characteristics depending on the stair height and slope.[1] During stair ascent, the body should move forward to maintain physical balance during the single-limb support phase.[3] It involves horizontal and vertical ascents, and thus requires larger lower limb joint moments, range of motion (ROM), muscular strength and the ability to control.[4,5,6] During stair descent, people often fall by tripping over the edge or surface of stairs.[7,8] A major cause of falling is known as an inappropriate space between the foot and the stair.[9] Therefore, shoes can become a predictor for falling on stairs.[10,11]

While walking, shoes protect the walker's foot, which is the direct contact point between the body and the external environment, from outside impacts. Shoes also play the role

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of absorbing shocks and providing foot stability.[12,13,14] For normal walking, ideal shoes should have a larger area contacting the ground, low heels, and soft and flexible materials.[15] In the past, shoes were primarily worn for walking and convenience. However, in modern society, the materials and types of shoes are diversifying, including fashion-oriented shoes, sneakers for exercise,[16] microcurrent shoes for medical intervention,[17] shoe inserts,[18] and aids.[19]

In recent years, young women who pursue bold fashion styles prefer high heels and walk in such shoes in daily life.[20] Walking in high heels changes the locations of spines and lower limb joints.[21] In particular, it can have negative impacts on walking and balance functions, such as increases in plantar flexion, which is a movement of the ankle joint, and changes in physical alignment. These negative changes are pronounced in the ankle joint.[21,22] The movements of lower limb joints are connected by close kinetic chains.[23] Therefore, such kinetic changes in the ankle joint during gait influence the movements of hip and knee joints. This subsequently increases the knee flexion, pelvic anterior dislocation, and trunk extension angles,[22,24] which result in various musculoskeletal problems.[20]

While studies on wearing high heels have been frequently conducted, most of them have been focused on walking on the ground.[15,21,25,26] On the other hand, few studies have been conducted on stair walking, which is the second most common type of walking. In addition, previous studies on stair walking with high heels include those on healthy adults,[3,27,28] anterior cruciate ligament (ACL) patients' barefoot gait,[29] and the width of stairs.[30] However, studies on stair walking with high heels remain inadequate. Moreover, a study on stair walking and slope ways reported that a three-dimensional analysis should be performed by incorporating all movements that occur in the front and rear, and left and right surfaces.[31] Existing studies on stair walking with high heels by employing a three-dimensional analysis of lower limb joint movements have mainly dealt with the kinematics and kinetic mechanism of lower limb joints according to the height of heels.[11] However, these studies were focused on the motion of stair ascent, whereas studies covering stair descent still remain inadequate. Therefore, this study aimed to identify the effects of stair walking with high heels by comparing stair walking with high heels and barefoot for healthy adult women.

II. Method

1. Subject and research period

18 healthy adult women were recruited from the student population of the University of OOOOO participated in this study. It excluded those who had had orthopedic problems, neurological diseases, dizziness, or visual impairment over the previous year.[11] All subjects had to be right-footed and confirmed weather they prefer to use the right leg or not when they are kicking.[32] Prior to the experiment, the subjects received a full explanation of the experiment's procedures and submitted a written consent.

2. Experiment method

1) Measuring instrument

(1) Kinematic measurement of lower limb joints

The three-dimensional motion analysis device (Motion Analysis Corp, Santarosa, CA, US) used in this study consisted of eight infrared cameras to capture the three-dimensional trajectory data of markers attached to each lower limb of the subject. During stair walkingat a camera frame rate of 120Hz using the motion capture software Cortex 1.1.4.386, the subject's pelvic, hip, knee, and ankle movements were measured. The markers of the three-dimensional motional analysis device were attached using the Helen-Hayes market set. 21 markers were used in total while being attached to each side of the body except the sacrum. The attachment areas included the ASIS, PSIS, sacral, thigh, medial knee, lateral knee, shank, medial malleolus, lateral malleolus, heel, and the region between the second and third toes. The markers for the heel and the region between the second and third toes were attached above the shoe surface.[11]

(2) Shoes for the experiment

This study used high-heeled shoes (HH) with a 9 cm heel, which reveal the top of the foot (Figure 1). All subjects were tested under the same conditions.

(3) Control instrument per motion

This study used stairs as an instrument to control each motion. The stairs for the motion of stair walking were wooden and 22cm in height, which is higher than that of typical stairs.

2) Experiment procedures

The subjects received a full explanation of the experiment before starting it, and then, were measured in terms of age, height, weight, foot length, and foot width. The subjects rehearsed stair ascent and descent before the experiment, and then performed the same motions in high heels and barefoot three times. The subjects performed the motions in random order. A break was given between the motions for three minutes or until the subjects no longer feel tired.

3) Stair walking

The subject's arms were crossed on the trunk and the stairs were placed in the same location for all subjects. During stair walking, the subject had each foot take turns while first moving the right foot forward when stair ascent and first moving the left foot forward when stair descent. The subject added a few more steps before and after each set of motions.[29]

4) Terminology

The following abbreviations were used for the experimental conditions of stair walking.

(1) BF: barefoot

(2) HH: shoes with a 9cm heel (high-heeled shoes)

5) Data collection

This study collected the kinematic data of lower limb joints at the following events among the gait phases. Stair ascent was measured during the right foot-flat and left toe-off phases. Stair descent was measured during the left foot-flat and right toe-off phases. The collected kinematic data about the lower limb joints were processed to produce average angles.

3. Statistical analysis

Average angles of the lower limb joints were analyzed using SIMM Biomechanics Software 6.0.2. PASW 18.0 was employed for statistical processing. General characteristics of the subjects were analyzed using a frequency analysis of descriptive statistics. To compare the lower limb joint angles before and after wearing HH during stair walking, paired t-tests were employed. The statistical significance level was set at α =0.05.

III. Results

1. General characteristics of the subjects

Eighteen women participating in this study were, on average, 22.7 years old, 160.4cm in height, and 50.0kg in weight, 23.5cm in foot length, and 9.0cm in foot width.

2. Changes in lower limb joint angles during stair ascent

1) Kinematic changes on the sagittal plane

During stair ascent, the ankle flexion angles showed statistically significant differences between the HH and BF gait ($p<0.05$). The knee flexion angles exhibited statistically significant differences between the HH and BF gait ($p<0.05$). The hip flexion angles showed statistically significant differences between the HH and BF gait ($p<0.05$). The pelvic forward tilt angles also revealed statistically significant differences between the HH and BF gait ($p<0.05$)(Table 1).

2) Kinematic changes on the frontal plane

During stair ascent, the ankle inversion angles showed statistically significant differences between the HH and BF gait ($p<0.05$). The hip abduction angles exhibited statistically significant differences between the HH and BF gait ($p<0.05$). The pelvic lateral tilt angles yielded statistically significant differences between the HH and BF gait ($p<0.05$)(Table 1).

3) Kinematic changes on the transverse plane

During stair ascent, the hip rotation angles showed statistically significant differences between the HH and BF gait ($p<0.05$). However, the pelvic rotation angles exhibited no statistically significant differences between the HH and BF gait (Table 1).

Table 1. Stair walking of lower limb joints angle (stair ascent)

Stair walking (ascent)	BF	HH	p
Ankle flexion	11.98 ± 4.20	-11.45 ± 3.25	0.000*
Ankle inversion	-16.00 ± 3.89	-14.16 ± 5.45	0.001*
Knee flexion	53.39 ± 5.61	63.45 ± 5.71	0.000*
Hip flexion	51.06 ± 5.85	58.84 ± 6.26	0.000*
Hip adduction	10.17 ± 2.79	7.49 ± 2.89	0.000*
Hip rotation	-5.56 ± 3.10	-10.38 ± 2.98	0.000*
Pelvic forward tilt	20.88 ± 3.06	20.10 ± 2.82	0.000*
Pelvic lateral tilt	5.82 ± 1.96	6.75 ± 2.32	0.000*
Pelvic rotation	0.69 ± 3.33	0.79 ± 2.45	0.728

Values are mean ± SD.
*P<0.05
BF: Barefoot condition
HH: High-heeled shoes condition

3. Changes in lower limb joint angles during stair descent

1) Kinematic changes on the sagittal plane

During stair descent, the ankle flexion angles showed statistically significant differences between the HH and BF gait ($p<0.05$). The knee flexion angles exhibited statistically significant differences between the HH and BF gait ($p<0.05$). The hip flexion angles yielded statistically significant differences between the HH and BF gait ($p<0.05$). However, the pelvic forward tilt angles showed no statistically significant differences between the HH and BF gait (Table 2).

2) Kinematic changes on the frontal plane

During stair descent, the ankle inversion angles showed statistically significant differences between the HH and BF gait ($p<0.05$). The hip abduction angles exhibited statistically significant differences between the HH and BF gait ($p<0.05$). The pelvic lateral tilt angles yielded statistically significant differences between the HH and BF gait ($p<0.05$)(Table 2).

3) Kinematic changes on the transverse plane

During stair descent, the hip rotation angles showed statistically significant differences between the HH and BF gait ($p<0.05$). However, the pelvic rotation angles exhibited no statistically significant differences between the HH and BF gait (Table 2).

IV. Disccusion

This study intended to collected lower limb joint angles while healthy adult women were stair walking with high heels, using a three-dimensional motion analysis system, thereby identifying the effects of high heels on the movements of lower limb joints in terms of physical kinematics. Lower limb joints bear weight, and thus are subject to substantial loads in terms of kinematic dynamics. Even a small problem with physical alignment can cause abnormal symptoms. Therefore, an accurate evaluation of lower limb alignment is required.[33] During stair walking, different characteristics are exhibited regarding the force generated by the lower limb joints depending on the slope,[30] and larger lower limb joint moments and ROM are required compared to walking on the flat ground.[4,5] Such lower limb joint movements are connected by closed kinetic chains. Therefore, changes in the movement of the ankle joint during gait affect the movements of hip and knee joints,[23] and various types of shoes lead to changes in the movement of the ankle joint.[22,34] In particular, high-heeled shoes such as high heels cause an excessive flexion of the sole in the ankle joint,[25] and alter the ankle's normal functions. This subsequently gives rise to a compensatory action in the hip and knee joints to maintain stability during gait.[26] In this respect, this study intended

Table 2. Stair walking of lower limb joints angle (stair descent)

Stair walking (descent)	BF	HH	p
Ankle flexion	6.18 ± 3.27	-14.78 ± 4.92	0.000*
Ankle inversion	-12.01 ± 5.34	-5.35 ± 7.83	0.000*
Knee flexion	22.84 ± 3.77	34.93 ± 8.03	0.000*
Hip flexion	18.93 ± 5.37	26.97 ± 5.22	0.000*
Hip adduction	4.46 ± 2.86	2.55 ± 3.22	0.000*
Hip rotation	-5.29 ± 4.27	-11.86 ± 5.62	0.000*
Pelvic forward tilt	14.93 ± 3.10	14.97 ± 3.18	0.787
Pelvic lateral tilt	-0.89 ± 1.68	-2.87 ± 2.29	0.000*
Pelvic rotation	-5.51 ± 4.65	-5.27 ± 4.79	0.430

Values are mean ± SD.
*$P<0.05$
BF: Barefoot condition
HH: High-heeled shoes condition

to understand lower limb joint movements along the flat surface while performing a set of motions while walking stairs in high heels.

During stair ascent and descent, the ankle plantar flexion angles increased when wearing HH. This coincides with a previous study that suggested that high heels increase sole flexion.[22] During stair ascent and descent, the knee and hip flexion angles increased when wearing HH. The shape of a high heel may have caused changes in the movement of ankle, knee, and hip joints on the sagittal plane. Moreover, in terms of the comparison of stair ascent and descent, the knee and hip flexion angles revealed greater changes during stair ascent. This is also in line with a previous study.[27] Kim et al[28] suggested that the knee joint was flexed as much as the height of a stair during stair ascent. Yoon et al[35] reported that a leg's lifting the body weight to move to a next stair increases the distance between the center-line of gravity applied to the body and the knee joint, thereby visibly increasing the knee flexion moment. This study also exhibited greater movements in the knee joint than in the hip joint during stair ascent with HH. Therefore, the knee joint is considered to generate larger flexion moments. In previous studies, the knee, hip, and ankle joints showed different degrees of flexion during stair descent. These movements were reported to have resulted from the effort to absorb the shock while landing.[36] Likewise, this study observed a different level of movement for each joint during stair descent. In addition, given that greater movements were generated while stair walking with high heel and the knee joint showed a larger flexion angle than the hip joint, the movement of the knee joint is likely to have a greater impact on absorbing shocks. Pelvic forward tilt angles were exhibited in both conditions of stair ascent and descent, whereas the pelvic forward tilt angles showed statistically significant differences only during stair ascent ($p<0.05$). This result can be explained in terms that stair ascent leads the pelvis to move further forward than stair descent and accords with the result of a previous study.[28]

During stair ascent and descent, the ankle eversion angles on the frontal plane decreased when wearing HH. A study noted that the most common mechanism for injuries in the ankle joint is excessive inversion.[37] In addition, an increase in heel height increases inversion due to a decline in maximum eversion during stair walking,[11] and a decline in eversion will reduce the ability to absorb the weight load when the heel touches the surface. The study also reported that soft tissues are more likely to be damaged by absorbing direct shocks.[38] Based on the results of this study, stair walking with high heels may increase the loss of the ability to absorb weight loads. During stair ascent and descent, the hip abduction angles decreased when wearing HH. The pelvic lateral tilt angles showed statistically significant differences between the HH and BF gait during stair ascent and descent ($p<0.05$). Opposite movements were exhibited between stair ascent and descent, which may have resulted from performing the motions with the legs crossed. Lower limb joint movements on the frontal plane during gait are a greatly important element in exhibiting physical balance.[39] The movement changes caused by wearing HH in this study are likely to influence physical balance.

A previous study on hip rotation angles on the transverse plane reported that an increase in the slope of an ascending slope way resulted in a corresponding decrease in internal rotation.[31] In present study, the hip external rotation angle increased when wearing HH. Moreover, the previous study mostly reported internal rotations during stair descent.[36] Contrarily, the present study showed external rotations were mostly exhibited in both conditions, and stair descent with HH resulted in larger external rotation angles. These results were contrary to those of the previous study, and may have resulted from various factors such as the timing for collecting lower limb motions, the use of a slope way, and different types of stairs.

During stair walking with high heels, limited ankle joint movements due to the high heel resulted in movement changes in the ankle, knee, and hip joints, and the pelvis. Changed movements in the lower limb joints generate an excessive force in a single joint, and can be accompanied by various types of joint disorder.[11,40] Therefore, they pose the risks of pain, low stability, and joint damage during stair walking.

Regarding stair walking in daily life or undergoing the training of stair walking as a rehabilitation process, this study will provide basic kinematic data about the relationship between postural changes in the ankle joint and movements in other lower limb joints. However, this study was conducted only from a kinematic perspective on lower limbs, and therefore, had difficulty drawing a conclusion about the effects of heel shape on lower limb joints. Moreover, the subjects were limited to a small number of healthy women in their 20s. Therefore, a future study is planned to suggest the effects of shoes on the kinematics and kinematic dynamics of lower limbs while performing functional activities including stair walking by employing a larger number of subjects and shoes with more diverse heel shapes.

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