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The Effect of Shoe Heel Types and Gait Speeds on Knee Joint Angle in Healthy Young Women - A Preliminary Study

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ABSTRACT

The consequences of wearing high heels can be different according to the heel height, gait speed, shoe design, heel base area, and shoe size. This study aimed to focus on the knee extension and flexion range of motion (ROM) during gait, which were challenged by wearing five different shoe heel types and two different self-selected gait speeds (comfortable and fast) as experimental conditions. Measurement standards of knee extension and flexion ROM were individually calibrated at the time of heel strike, mid-stance, toe-off, and stance phase based on the 2-minute video recordings of each gait condition. Seven healthy young women (20.7 ± 0.8 years) participated and they were asked to walk on a treadmill wearing the five given shoes at a self-selected comfortable speed (average of 2.4 ± 0.3 km/h) and a fast speed (average of 5.1 ± 0.2 km/h) in a random order. All of the shoes were in size 23.5 cm. Three of the given shoes were 9.0 cm in height, the other two were flat shoes and sneakers. A motion capture software (Kinovea 0.8.27) was used to measure the kinematic data; changes in the knee angles during each gait. During fast speed gait, the knee extension angles at heel strike and mid-stance were significantly decreased in all of the 3 high heels ($p<0.05$). The results revealed that fast gait speed causes knee flexion angle to significantly increase at toe-off in all five types of shoes. However, there was a significant difference in both the knee flexion and extension angles when the gait in stiletto heels and flat shoes were compared in fast gait condition ($p<0.05$). This showed that walking fast in high heels leads to abnormal knee ROM and thus can cause damages to the knee joints. The findings in this preliminary study can be a basis for future studies on the kinematic changes in the lower extremity during gait and for the analysis of causes and preventive methods for musculoskeletal injuries related to wearing high heels.

☞ keyword : High heels, Outsole, Gait, Knee joint angle

1. Introduction

The consequences of wearing high heels can be different according to the heel height, gait speed, shoe design, heel base area, and shoe size. Wiedemeijer et al. (2018) defined the shoes with a heel height of 5.0 cm or higher are high heels [1]. Broega et al. (2017) categorized the topology of shoes corresponding to the height of the heels into four groups: flat heel (up to 2.0 cm), low heel (up to 4.0 cm), medium heel (up to 6.0 cm), and high heels (more than 7.0 cm) [2]. As the variety of footwear design expanded, so did the related studies on musculoskeletal injuries including sprains, hallux valgus, foot pain, and muscle spasm in the lower legs and the results showed that most of high-heeled shoes can be the cause [3].

The rise in high heel study has been done in different aspects; increase in heel height, gait speed, shoe base area [4] [5], type of high heel [6], and shoe size [7] to indicate the adverse effects across high heel usage. To observe the influence of the height increase in the heel, Chien et al. (2013) researched the center of mass (COM) motions in human body during high-heeled gait. They found that an altered rate change inclination angle (RCIA) was highlighted when heel height increased with a narrower heel base and this identified the difficulty in maintaining overall balance in the body and stability in the foot. The difficulty in retaining

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the balance control and normal movement pattern in the lower limb including the hip, knee, and ankle joints could be caused by wearing high heels, and it was noted to be more prominent with shortened step length during gait in heels [1].

Landreneau et al. (2014) performed a study on lower limb muscle activation during running and compared the mean ankle range of motion (ROM) at the time of rearfoot strike and forefoot strike in the sagittal plane. They noted that the pain and injury in the ankle might have relied on the modification of the ankle ROM [8]. Another study also reported that at heel strike in a comfortable gait speed while wearing high heels, the knee flexion was increased, but ankle eversion was decreased [4]. A repetitive abnormal movements in the knee and ankle joints during high-heeled gait can lead to limited range of motion from the the initial contact phase. This was notified in the work of Mika et al. (2012), which emphasized the musculoskeletal abnormality during walking movements. Using high heels for fast gait is well reported to contribute in changing the biomechanics of the knee movements including knee joint angle changes [1] [4], knee flexion peak [7], imbalanced muscle activation around the knee [9], decreased position senses in the knee, and balancing abilities during gait [10].

Jang et al. (2016) observed the position of the knee joint and balance, which were affected by an increase heel heights and various walking speeds [10]. They found out that wearing high heels increase the sway amplitudes for dynamic balance control and reduce position senses of the knee joint as gait speed was increased. This result exhibited of possible injuries that can be seen in weaker position senses of the knee.

Heel height and shoe design are considered as one of the key elements that change gait patterns. Researchers studied the effects of shoes on gait. The significant changes during gait were found in joint movements [1] and foot pressure distribution, which determines pathologies related to gait pattern [11]. Faisal et al. (2019) defined knee joint angle as one of the three key parameters of joint monitoring [12]. For lower limb joint monitoring, understanding the effects of the shoes is necessary. The influence of changing the outsole structure leads to fluctuating the function of metatarsophalangeal joint and other mechanics of lower limb joints [13]. Di Sipio et al. (2018) studied healthy women with the age range of 20 to 35 years and described abnormal kinematic changes in the knee flexion and extension peak during high-heel gait [7]. Other studies reported that wearing high heels for a prolonged time was found to cause pain in the knee and the foot area and have the possibility of leading to osteoarthritis in the knee [14].

Although there have been various studies on womens' gait and high-heeled shoes, not many studies have defined the correlation between different outsole designs and their effects on knee joint angle during gait in different gait speeds. Therefore, this study aimed to analyze the knee ROM changes affected by wearing five different shoe heel types in two self-selected gait speeds.

2. Methods

2.1 Subjects

Seven young, healthy women were recruited for this research. The participants had an average age of 20.7 ± 0.8 years, height of 157.7 ± 4.4 cm, weight of 50.4 ± 2.2 kg, and body mass index (BMI) of 20.3 ± 2.2 kg/m^2. Inclusion criteria for subjects were non-regular high heel wearers, non-regular gym user for intensive physical training, no history of surgery or injury in the leg and foot, and no structural deformity in the foot area. The participants were to experience walking in high heels and using a treadmill for running before they were finally included for our study. Anyone with flat foot, pain in the leg and foot area, general muscle pain, or acute spasm during the experiment was excluded from the study.

2.2 Experiment protocol

Before starting the experiment, we informed the main objective and the experimental protocol of our study clearly to all participants. For the subjects to get familiar with the testing environment, each participant was instructed to start walking on the treadmill at the same time to self-select the comfortable and fast gait speed. For this study, a total of 10 experimental conditions were performed by each participant; shoe 1: flat (S1), shoe 2: sneakers (S2), shoe 3: chunky heel (S3), shoe 4: classic pump heel (S4), shoe 5: stiletto heel

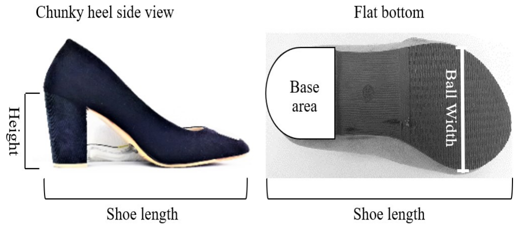
(S5), gait 1: at a comfortable speed (C), and gait 2: at a fast speed (F). The 10 conditions included wearing 5 different shoes for each of the 2 different gait speeds. The order of experimental conditions to be performed by each subject was randomized by a software on the computer. For each type of the shoe, two separate 2-minute walks were performed with a 5-minute break in between. The five types of shoes (S1 to S5) used in this study are described in Table 1, Figures 1 and 2.

The kinematic data of the knee joint angle was measured throughout the experiment. A reflective marker was to mark the lateral side of the hip, knee, and ankle joints. A smartphone was used to record the video of each subject walking during each test condition. The smartphone (camera) was fixed on a tripod 1.0 meter above from the ground (height) and 2.5 meters away from the center of the treadmill (distance) [15]. The video of each subject walking was recorded with a frame rate of 30 Hz. USB cable was used to transfer the data from the camera to the computer for further calibration.

(Table 1) Characteristics of the testing shoes

Shoe type	Heel height (cm)	Shoe length (cm)	Ball width (cm)	Heel base (cm^2)
S1	1.0	23.5	8.0	28.5
S2	3.0	23.5	9.5	55.3
S3	9.0	23.5	7.5	11.9
S4	9.0	23.5	7.5	0.9
S5	9.0	23.5	8.0	0.9

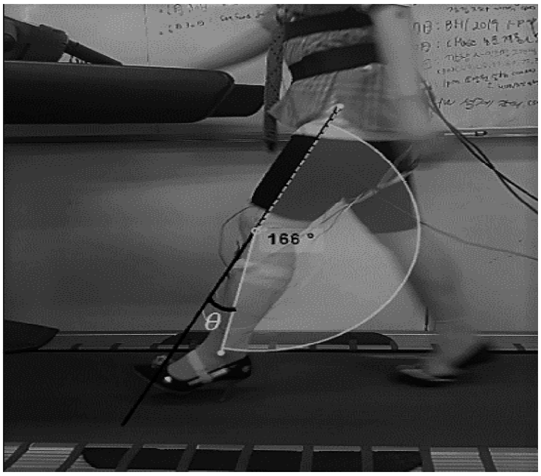
S1: flat, S2: sneakers, S3: chunky heel, S4: classic pump heel, S5: stiletto heel



(Figure 1) Example of the shoe heel design and size measurement standards

(Figure 2) Lateral view of the shoe types

2.3 Data processing and statistical analysis



(Figure 3) Sample image of knee flexion angle (θ) measurement at the time of heel strike

For data processing, a motion capture software Kinovea 0.8.27 (Open and Free Software Foundation, Inc., Boston, MA, USA) was used. For marking and measurement, the angle measurement tool in Kinovea was placed on the hip, knee, and ankle joints to auto-track the knee joint movements. The auto-tracker was set to start tracking the angular motion from the point where the posterior tip of the heel touched the ground (heel strike) to the final toe-off phase. MATLAB R2015b (MathWorks, Inc.Natick, MA, USA) was used to calibrate mid-1-minute data of the knee joint angle, which was exported from Kinovea in an excel file. The changes in the knee angle (θ) were computed by subtracting the angle measured by Kinovea from 180°, which is a full knee extension ROM (Figure 3) [16]. For every gait cycle, the knee flexion angle was measured from a heel strike to the next heel strike. Due to the unequal length of gait cycle data of each participant, we normalized the gait cycle data to 100 data points using the interpolation technique relied on interp1 in MATLAB's 1D function. This was based on a previous study, which reported that women aged between 18 to 49 years generate 98-138 steps per minute at a comfortable walking speed and that 49 to 69 gait cycles are present in 1-minute walking [17]. In this study, 35 gait cycles from the mid-1-minute data were extracted and a total of 245 gait cycles were acquired from the seven subjects for each experiment condition. We averaged the knee extension and flexion angles based on the normal gait pattern of 60% stance and 40% swing phase for heel strike, mid-stance, toe-off, and stance phase [18].

For statistical analysis, IBM SPSS Statistic 23 (SPSS Inc., Chicago, IL, USA) was used. One-way ANOVA was performed to identify the statistical difference between the shoe types. Paired t-test was implemented to compare the speed effect with a significance level of $p<0.05$.

3. Results

From all participants, we obtained the average walking speed of 2.4 ± 0.3 km/h and 5.1 ± 0.2 km/h for comfortable and fast gait speed, respectively.

The result from One-way ANOVA which applied for comparison between 5 shoes during comfortable gait walking, showed that there was no significant difference in the knee joint angles. However in fast gait walking, knee flexion angle was significantly increased in S3 (22.3 ± 7.3°), S4 (26.1 ± 7.1°), and S5 (25.4 ± 6.3°) compared to that of S1 (15.6 ± 8.0°) and S2 (15.6 ± 6.7°).

(Table 2) Result of knee ROM comparison between conditions (n = 7)

Gait Phase	Shoe Type	Comfortable gait (2.4 ± 0.3 km/h)	Fast gait (5.1 ± 0.2 km/h)	p-value
Heel Strike	S1	8.5 ± 1.8°	15.6 ± 8.0°	0.066
	S2	8.4 ± 3.1°	15.6 ± 6.7°	0.016 *
	S3	12.3 ± 6.8°	22.3 ± 7.3°	0.003 *
	S4	15.3 ± 6.2°	26.1 ± 7.1°	0.001 *
	S5	13.2 ± 6.3°	25.4 ± 6.3°	0.001 *
	p-value	0.080	0.015 **	
Mid-stance	S1	7.4 ± 1.9°	13.2 ± 7.9°	0.110
	S2	6.9 ± 3.3 °	12.8 ± 6.7°	0.049 *
	S3	11.2 ± 6.6°	19.9 ± 7.7 °	0.007 *
	S4	14.2 ± 6.3°	23.6 ± 7.2°	0.001 *
	S5	12.0 ± 6.2°	23.1 ± 6.8°	0.002 *
	p-value	0.064	0.016 **	
Toe-off	S1	61.0 ± 8.4°	70.9 ± 3.7°	0.015 *
	S2	57.0 ± 10.5°	70.6 ± 3.4°	0.005 *
	S3	52.9 ± 9.7°	65.0 ± 6.1°	0.003 *
	S4	54.9 ± 10.3°	64.8 ± 3.9°	0.022 *
	S5	52.9 ± 9.4°	64.1 ± 2.6°	0.009 *
	p-value	0.497	0.005 **	

*Statistically significant (comparison between speeds), **Significant (comparison between shoes), S1: flat, S2: sneakers, S3: chunky heel, S4: classic pump heel, S5: stiletto heel

(Table 3) Result of between-shoe comparison in fast speed condition (n = 7)

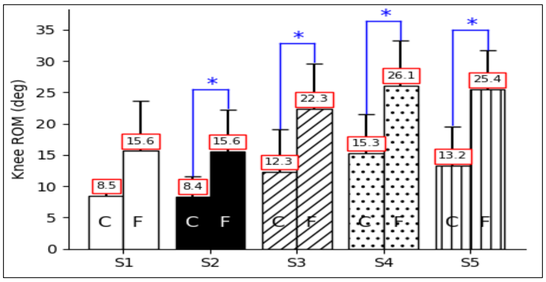
Shoe type (I)	Shoe type (J)	Knee flexion during stance			Knee flexion at toe-off		
		MD (I-J)	SE	p-value	MS (I-J)	SE	p-value
S1	S2	-1.5°	3.5°	1.000	0.2°	2.2°	1.000
	S3	-8.0°	3.5°	0.287	5.9°	2.2°	0.120
	S4	-9.6°	3.5°	0.097	6.1°	2.2°	0.098
	S5	-11.3°	3.5°	0.027 *	6.7°	2.2°	0.045 *
S2	S3	-6.5°	3.5°	0.702	5.7°	2.2°	0.150
	S4	-8.1°	3.5°	0.259	5.9°	2.2°	0.122
	S5	-9.9°	3.5°	0.079	6.5°	2.2°	0.057
S3	S4	-1.6°	3.5°	1.000	0.2°	2.2°	1.000
	S5	-3.4°	3.5°	1.000	0.9°	2.2°	1.000
S4	S5	-1.7°	3.5°	1.000	0.7°	2.2°	1.000

* Statistically significant, MD: mean difference, SE: standard deviation error, S1: flat, S2: sneakers, S3: chunky heel, S4: classic pump heel, S5: stiletto heel

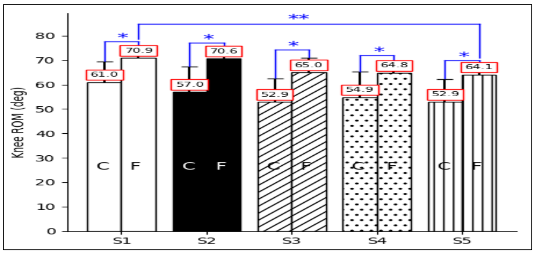
The result of knee joint angle flexion comparison between the experimental conditions is presented in Table 2. It emphasized knee flexion angle at the time of heel strike and mid-stance, showing a significant increase in the fast gait with $p<0.05$ for all three high heels (S3, S4, S5). Moreover, the knee flexion angle during toe-off was greater during fast gait than in the comfortable gait ($p<0.05$) (Table 2).

ANOVA was performed to analyze on the statistical difference of shoe types and Bonferroni Post hoc was used to reveal the affected knee flexion by each of the 5 shoes in fast gait. By comparing S5 to that of S1, knee flexion angle was significantly increased (11.3°) during the entire stance phase (60% of the gait cycle). During toe-off, knee flexion was significantly decreased (6.7°) when wearing S5 compared to that of wearing S1 (Table 3).

Figures 4 and 5 depicted the results of knee extension ROM at the time of heel strike and knee flexion ROM at toe-off, comparing the two gait speeds while wearing the same shoe. For all three high heels, knee extension angle was decreased at heel strike and knee flexion angle was detected lower at toe-off compared to wearing S1 and S2 in both gait speed. In our research for all three high heels, knee flexion angles during the stance phase were significantly greater than those of S1 and S2 at fast walking speed. At toe-off, both comfortable and fast gait speeds, knee flexion angles were consistently smaller in all three high heels compared to those in S1 and S2.



(Figure 4) Result of knee flexion at heel strike, *statistically significant between speeds, C: comfortable speed, F: fast speed, S1: flat, S2: sneaker, S3: chunky heel, S4: classic pump heel, S5: stiletto heel



(Figure 5) Result of knee flexion at toe-off, *statistically significant between speeds, **statistically significant between shoes, C: comfortable speed, F: fast speed, S1: flat, S2: sneakers, S3: chunky heel, S4: classic pump heel, S5: stiletto heel

4. Discussion

Our study aimed to observe the effects of five different shoe designs and two gait speeds on the knee joint angle during walking on a treadmill.

Fukuchi et al. (2019) marked that changing gait speed affects the spatiotemporal parameters such as joint kinematics and kinetics, which modify the gait pattern [19]. Wang et al. (2017) determined the influence of barefoot walking with a different walking speed of 1.1 m/s, 1.4 m/s, and 1.7 m/s, on the contact forces delivered on the knee and ankle. They found a significant increase in the knee joint angle at toe-off in the faster walking speed of 1.7 m/s compared to 1.1 m/s and 1.4 m/s [20]. The modification of gait speed may change the lower limb joint kinematics, which means it will be under greater impact while wearing high heels compared to barefoot gait.

In this study, no significant difference was found in the knee angle between the 5 shoes during comfortable gait. However, in fast gait speed, the difference was significant. This finding was similar to that of a study by Di Sipio et al. (2018), who investigated gait patterns in a heel height of 12.0 cm and barefoot with two different shoe sizes (European shoe size: 36-38 and 39-40) and compared their effects on knee flexion-extension peak during a comfortable gait speed. Their result showed a significantly increased knee flexion with high heels compared to barefoot gait during the stance phase [7]. Mika et al. (2012) also reported a significant increase in knee flexion during initial contact while wearing 10.0 cm-high heel compared to a gait without any shoe [4]. These findings were also similar to the results of our study. The fast gait may contribute more negative results to the knee joint.

Our observation of an increase in the knee flexion ROM in three different heel shoe design (S3, S4, S5) in the fast gait speed is also consistent with the work of Lythgo et al. [21]. Our data indicated that the heel height of 9.0 cm with different shoe designs and fast gait speed is the main factor in altering the flexion-extension angles in the knee joint during gait. At fast gait speed, we found all three high heels (S3, S4, S5) showing significantly decreased knee extension angle at the time of the heel strike. Cronin et al. (2012) reported that wearing high heels for walking leads to reduced knee extension angle at heel strike but increased ankle plantarflexion which is an opposite mechanism between knee and ankle joint angle activation [22]. Therefore, the findings in our study can infer the changes in ankle movements.

In this study, we also found out that the knee flexion angles during the stance phase and at toe-off were greater in fast gait speed compared to the comfortable speed. The findings of our research support the results of a study by Park et al. (2016), which observed the effects of changing heel heights and speeds to analyze the same factor as our study (knee ROM at stance phase) that could affect walking patterns [23]. Our study results showed that the knee flexion angle was significantly increased during the mid-stance phase when wearing S5 compared to that of wearing S1. During toe-off, knee flexion was significantly decreased when wearing S5 compared to that of wearing S1. However, the heel heights of S3, S4, and S5 were the same; different outsole designs caused different ground contact areas. Park et al. (2016) conducted a study on high heels with 9.0 cm, which has different heel base areas; narrow (0.9*0.9 cm), moderate (1.5*1.7 cm), wide (2.8*2.9 cm), wedge heels (one-piece of the sole and the heel), and two walking speeds of 1.0 m/s and 1.25 m/s to assess the utilized coefficient of friction (uCOF). They reported that wearing high heels with narrow base areas increases the peak of uCOF and decreases vertical ground reaction force (GRFv) compared to wide heels and wedge heel. They also noted that the walking speed of 1.25 m/s had higher peaks of uCOF and GRFv compared to the slow walking speed of 1.0 m/s during loading response [24]. High heels with a larger base area have less effect on heel strike during gait because they support lower limb with a better base of support (BOS), which refers to the stability [24].

Our result revealed that changing the gait speed from 2.4 km/h to 5.1 km/h increased knee flexion at heel strike but decreased knee flexion at toe-off (Figures 4 and 5). Moreover, wearing high heels of 9.0 cm also causes larger knee flexion at heel strike but decreases knee flexion at toe-off compared to flat shoes (heel height: 1.0 cm) and sneakers (heel height: 3.0 cm) (Figures 4 and 5). Our finding is consistent with the findings of Park el at. (2016), which investigated gait changes with the different heel height and gait speed. Their results indicated that changing heel heights from 1.0 cm to 9.8 cm and vary gait speed from 94 steps/min to 142 steps/min and increase knee flexion at the stance phase but decrease knee flexion at the swing phase. The high heel wearer should be more careful of musculoskeletal injuries at faster gait [23] since the knee joint angle adjustment alters enormously.

The rise of knee flexion in the fast gait condition was higher than the comfortable gait condition at the stance and swing phase. During the stance phase, the high heel wearer's knee flexion ROM was greater than that of wearing flat shoes and sneakers. However during the swing phase, the knee flexion of the high heel wearer was lower than that of the flat and sneaker-wearer. The other important finding on wearing stiletto's heel design with fast gait speed was a decreased knee flexion at the toe-off phase. Lyons el at. (2017) reported that when the lower extremity coordination function is decreased, the movement efficiency drops and can lead to injuries or musculoskeletal diseases [25]. Moreover, Sharma el at. (1997) also added that this is commonly seen in the individuals with knee joint osteoarthritis [26]. The knee joint plays an important role in the function of the movement of the lower extremity, which accurately adjusts movements for walking and balancing. Mandelbaum el at. (2005) determined the accurate proprioception is critical for proper injury prevention [27], which means that the awareness of the significant increase or decrease in the knee flexion caused by the type of shoe design and walking speed might be useful to prevent negative impact would happen to high heel wearer.

There were a few limitations in this work. First, the subjects wore different types of new shoes provided for the experiment which may have been uncomfortable to walk in. Due to this, their original gait characteristics may have altered. To minimize this effect, we gave the subjects plenty of time to practice walking in all five shoes on the treadmill to make them get familiar with the system. Second, we worked with only one camera (smartphone) which was placed at a fixed position. During fast gait, some subjects moved further to the front and back away from the center of the camera calibration angle. However, our camera placement distance from the treadmill was set based on the study of Himsham et al. (2017), which defined the optimum position of the camera to have the best possible video quality and field of view. In the same way, our limitation was minimized. Third, for Kinovea auto-tracking, some subjects didn't fixate their hand up as instructed while walking which made it difficult to detect the markers on the hip joint, but Kinovea is considered as a reliable software for dynamic gait analysis according to the study of Himsham et al. (2017), thus the aforementioned issue may have not severely impacted the findings of our study. Four, this study was conducted as a pilot test with a small number of participants, aiming to preliminarily examine how different types of high-heeled outersoles affect womens' gait, especially on the knee joint angle movements. The findings of this study can be the basis for our future study, which will be done with a larger number of subjects in different age groups and more types of footwear.

5. Conclusion

Our research observed the effect of five different shoes and two different gait speeds on the changes in knee extension and flexion range of motion. The results revealed that wearing high heels for faster gait speed decreases the knee extension at heel strike but increases the knee flexion at toe-off which leads to an altered gait pattern. Hence, increasing the gait speed and decreasing the base area of the heels could affect the kinematics in the knee and the gait patterns. The findings of our work can be used as a fundamental information for future studies which could identify the cause of injuries in the leg and the methods to injury prevention for high heel wearers.

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