

# Effect on the parameters of the high-heel shoe and transfer time of ground reaction force during level walking

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This study aimed to analyze an effect on the parameters of high-heel shoe and transfer time of ground reaction force during level walking and subjects participated were composed of adult female subjects ( $n=13$ ) of 20s with height of high heel (0 cm, 9 cm, respectively). Instrument used for the study was 1 set force plate (AMTI-OR9-7) and sampling rate for data collection of analysis parameters was set-up at 1,000 Hz. The revelation of required coefficient of friction (RCOF) maximum showed significant difference with more rapid than that of 1st peak vertical force (1 PVF). Transfer time of body weight showed significant difference with more delay at 9 cm than that of 0 cm. RCOF required more frictional force required because PVF showed significant difference

with larger value on 9 cm than that of 3 cm at 1 PVF. Both center of pressure (COP) x and COPy showed rather less displacement on 9 cm than that of 0 cm. In addition, level walking by high heel shoe did not control efficiently the ground reaction force due to restricted control capacity of coefficient of frictional force and therefore could suggest an inducement of muscle fatigue, heightening a possibility of sliding and falling due to decrease of frictional force.

**Keywords:** High-heel shoes, Walking, Required coefficient of friction, Ground reaction force, Torque

## INTRODUCTION

Center of mass (COM) was accelerated forwardly by three-dimensional external force during bipedal walking. Then the foot overloaded by body weight primarily absorbs and transfers ground reaction force (GRF) to whole body.

Foot segment structured with complex and rigid anatomical skeleton (Leardini et al., 1999) keep up the function of flexibility, stiffness and stability etc. (Rodgers, 1995). The above functions can absorb and counteract biomechanical disparity within proper range during locomotion (Gerber et al., 2012), but reduce their functions in case of over-work range (Csapo et al., 2010). For the above reasons, function of shoe wearing must be satisfied to protect and utilize effectively of inherent function of foot during lo-

comotion and other activities, and then can provide each user with static and dynamic stability (Nigg et al., 2006).

But high-heel shoe wearing frequently by young female among various types of shoes cause injurious side-effects and show tendency of more plantar flexion effect than that of bare-walking on sagittal plane (Hyun and Ryew, 2014a) due to instability in anterior-posterior direction with increase of moment of inertia of body relatively (Ryu, 2010).

Walking cycle can be divided into braking, supporting and propulsive phase, of which braking phase can be defined as phase of initial touch of heel to ground, then the higher heel, the more vertical reaction force and braking force linearly (Stefanyshyn et al., 2000). Impact force can cause amplitude wave of high impact and transfer to the other joint of body through various muscu-

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larskeletal system and then an impact amplitude cumulated can increase dynamic-load to body (Voloshin and Loy, 1994). Ryu (2009) designed the time coordination system used with max generating-time mechanism to analyze cause of Knee flexion, inward-rotation of tibia, abduction of foot in functions of lower leg and reported that higher heel showed proper time-coordination mechanism due to low max generating-time mechanism than that of lower heel.

Gerber et al. (2012) regarded lateral ( $M_x$ ), anterior-posterior ( $M_y$ ) rotation of GRF components as oscillation, and then various injuries can be generated during movement of foot segment, which can damage the function of center of pressure (COP). That is, higher heel height, the more function of cognitive sensory of vertical height at touch-down of next 1 step can be deteriorated (Hyun and Ryew, 2014c).

Overloaded COP distribution of midpost foot due to structural shape for part of fore part of shoe (Corrigan et al., 1993; Mandato and Nester, 1999; Morag and Cavanagh, 1999) could cause discomfort and plantar fasciitis and suggested possibility generating potential injuries as falling and sprain.

Like the former, In spite of problems of wearing of high heel, young female continuously prefer to wear due to not only more align closely to vertical direction of center of gravity of body but also provide longer length of lower leg viewing from frontal plane. Therefore considering the above, this study necessary to analyze the quantitative difference of transfer time between max peak amplitude for variable; peak vertical force (PVF), loading rate, free torque ( $T_z$ ), required coefficient of friction (RCOF) inducing sliding and falling related with COP displacement and provide basic materials for optimum height of heel shoes and dynamic stability during female's level walking.

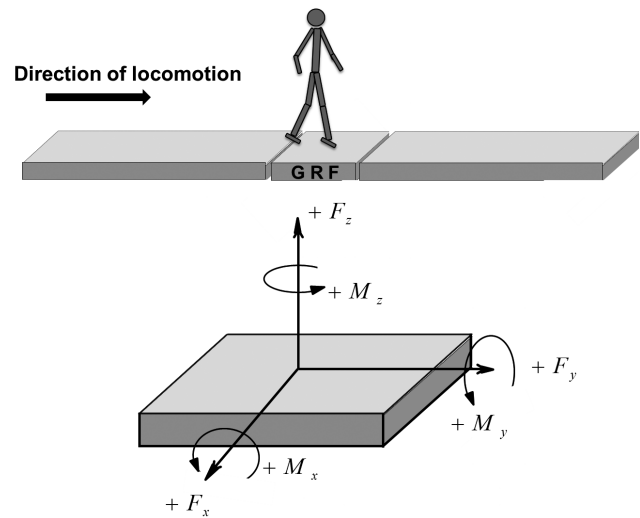
## MATERIALS AND METHODS

### Subject

Subjects participated were composed of adult female subjects ( $n = 13$ ; mean age,  $24.15 \pm 2.54$  years; mean height,  $166.41 \pm 2.28$  cm; mean body weight,  $58.75 \pm 8.36$  kg) of 20s with height of high heel (0 cm, 9 cm, respectively) and had habit of nonwearing over heel height of 3 cm.

### Experimental procedure

Height of 9 cm (shoe) and 0 cm (bare foot) were selected to analyze kinetic variables according to wearing of high heel shoe during level walking. All subjects were prohibited from wearing



**Fig. 1.** Coordinates of the ground reaction force (GRF) measurement system ( $M_x$ ,  $M_y$ , and  $M_z$ , moment about the vertical axis).

of socks to prevent errors data and coefficient of frictional force. Force plate (AMTI-OR9-7, AMTI, Watertown, MA, USA) was aligned with walking pathway after fixation and setting on the same level. When each subject was practiced repeatedly with high heel (9 cm) to keep eye's aiming of  $45^\circ$  forwardly during walking, experiment data was collected for 10 sec. Each experiment was performed walking of 2 times on the force plate with sampling ratio of 1,000 Hz. Coordinate setting-up of force direction of force plate and experiment set-up was the same with (Fig. 1).

### Analysis and process of data

PVF was normalized by subject's body weight and loading rate of impact was calculated with normalized PVF (Munro et al., 1987). That is, loading rate was calculated by vertical reaction force over 50 N minus 1 PVF/time applied after touch-down on force plate right foot during walking.

$$\text{Loading rate} = \frac{1 \text{ PVF} - F_{50}^+}{\Delta t}$$

RCOF was defined as value of medial-lateral GRF (ML GRF) and anterior-posterior GRF (AP GRF) divided by PVF, RCOF in ML direction and RCOF in AP direction was in the same line with (Asaka et al., 2002; Burnfield and Powers, 2007; Cooper et al., 2008).

$$\text{RCOF} = \frac{\sqrt{(\text{ML GRF})^2 + (\text{AP GRF})^2}}{\text{PVF}}$$

First of all,  $\text{COP}_x$  and  $\text{COP}_y$  of COP for  $T_z$  was calculated and

followed  $COP_x = -M_y - F_x \times d_z / F_z$  for COP location in ML,  $COP_y = -M_x - F_y \times d_z / F_z$  for COP location in AP. Then, after fixing (reference point) the location of COP generated at angle of initial touch-down, displacement of location during supporting phase was calculated with absolute value.

$$T_z = M_z + (F_x \times COP_y) - (F_y \times COP_x)$$

$d_z$ : vertically downward location ( $Z=0$ ) from origin point of force plate

First, mean  $\pm$  standard deviation for all variance calculated with PASW Statistics ver. 18.0 (SPSS Inc., Chicago, IL, USA), second, paired  $t$ -test was processed according to heel height (0 cm [bare foot], 9 cm [shoes]) and third, transfer time for GRF was interpreted with 2-way analysis of variance of parameters of GRF  $\times$  heel height. *Post hoc* test (Duncan) was treated in case of showing significant difference at  $P < 0.05$ .

## RESULTS

### Change of transfer time

Analysis variables were as with the transfer time between GRF parameters, 1 PVE, 2 PVE, RCOFmax, elapsed time during supporting phase respectively (Table 1).

Transfer time showed significant difference with the more delay in 9 cm than that of 3-cm heel height ( $F = 12.320$ ,  $P < 0.001$ ) and also transfer time between parameters in GRF showed significant difference. Result of post hoc test, appearance of RCOFmax showed significant with the shortest of all parameters ( $F = 891.134$ ,  $P < 0.001$ ).

### Change of GRF parameters according to heel height

Parameters from GRF during supporting phase of gait were as with the 1 PVE, 2 PVE, and average value of parameters (Table 2). PVF showed significant difference with the more in 9 cm than

**Table 1.** Variance analysis on occurrence time during stance phase between 0 cm bare foot and 9 cm (unit: sec)

Section	Heel height		Total average	Source	F	P-value	Post hoc
	0 cm (bare foot)	9 cm (shoe)					
1st PVF	0.155 $\pm$ 0.04	0.161 $\pm$ 0.03	0.158 $\pm$ 0.04	H	12.320	<0.001***	9 cm > 0 cm
2nd PVF	0.496 $\pm$ 0.03	0.546 $\pm$ 0.05	0.521 $\pm$ 0.05				
Stance phase	0.650 $\pm$ 0.06	0.693 $\pm$ 0.07	0.661 $\pm$ 0.07	T	891.134	<0.001***	RCOF > Fz1 > Fz2 > stance time
RCOFmax	0.042 $\pm$ 0.01	0.079 $\pm$ 0.01	0.671 $\pm$ 0.02				
Total average	0.336 $\pm$ 0.25	0.370 $\pm$ 0.26	0.353 $\pm$ 0.25	H $\times$ T	0.974	0.408	-

Values are presented as mean  $\pm$  standard deviation.

PVF, peak vertical force; RCOFmax, required coefficient of friction maximum; H, heel heights of the main effect; T, time of the main effect; H  $\times$  T, interaction 0 cm and 9 cm in gait. \*\*\* $P < 0.001$ .

**Table 2.** Ground reaction force parameters during stance phase between 0 cm and 9 cm

Section	Parameter	Heel height		t	P-value
		0 cm (bare foot)	9 cm (shoe)		
RCOFmax	RCOF	0.25 $\pm$ 0.06	0.29 $\pm$ 0.06	1.611	0.120
1 PVF	PVF (N/BW)	1.05 $\pm$ 0.08	1.21 $\pm$ 0.13	3.847	<0.001***
	Loading rate (N/BW/sec)	7.42 $\pm$ 2.61	8.38 $\pm$ 4.31	0.689	0.497
	RCOF	0.13 $\pm$ 0.05	0.16 $\pm$ 0.04	1.993	0.058
	Free Torque (N-m)	-0.38 $\pm$ 1.22	-0.78 $\pm$ 1.21	0.832	0.414
2 PVF	PVF (N/BW)	1.10 $\pm$ 0.07	1.12 $\pm$ 0.10	0.556	0.583
	RCOF	0.14 $\pm$ 0.03	0.17 $\pm$ 0.03	2.132	0.043*
	Free Torque (N-m)	2.14 $\pm$ 1.32	1.36 $\pm$ 0.79	1.814	0.082
Average	RCOF	0.14 $\pm$ 0.02	0.13 $\pm$ 0.02	0.668	0.510
	Medial-lateral COP ABS (cm)	1.91 $\pm$ 1.32	1.29 $\pm$ 0.98	1.364	0.185
	Anterior-posterior COP ABS (cm)	7.97 $\pm$ 3.18	6.65 $\pm$ 3.80	0.959	0.347

Values are presented as mean  $\pm$  standard deviation.

RCOF, required coefficient of friction; RCOFmax, RCOF maximum; PVF, peak vertical force; BW, body weight; COP, center of pressure; ABS, absolute value.

\* $P < 0.05$ . \*\*\* $P < 0.001$ .

that of 0 cm of heel height ( $P < 0.001$ ), but did not show in loading rate, RCOF,  $T_z$  at 1 PVF. PVF and torque did not show but RCOF showed significant difference with the more value in 9 cm than that of 0 cm during supporting phase of gait ( $P < 0.05$ ).

$T_z$  showed significant difference with the more rotational force at 0 cm than that of 9 cm, but did not show in parameters of RCOF, COPx, COPy, respectively.

## DISCUSSION

The duration which can be minimize stresses acting on foot and its musculoskeletal system is supporting phase among all phases of gait cycle (Gefen et al., 2001). But in case of wearing high heel shoe, excessive impact on ankle due to cognition error of exact touch-down distance to ground at heel touch-down by hyper-plantar flexion of ankle joint can be generated (Hyun and Ryew, 2014c).

PVF and load rate in this study showed the greater in 9 cm than that 0 cm, and particularly total time elapsed showed 0.650 sec in 0 cm and 0.693 sec in 9 cm respectively, but, transfer time for 1 PVF showed similar result. Therefore it was considered that gait wore high heel of 9 cm generated the greater load rate. While  $T_z$  at 1 PVF showed -0.38 N-m of 0 cm, and -0.78 N-m of 9 cm, showed 2.14 N-m of 0 cm and 1.36 N-m of 9 cm at 2 PVF respectively.

Inward rotation of tibia to longitudinal axis can be generated when ankle joint was pronated to the subtalar joint during locomotion (Ryu, 2010). But because pronation and inward rotation of tibia according to increase of heel height can be generated concurrently, the greater movement of high heel shoe in lower leg showed than that of not (Gajdosik et al., 1999). On the basis of the above view, it was considered to compensate on the instability of locomotion when inward and outward rotation of tibia resulted from inversion and eversion can cause an interaction effect influencing on knee joint due to hyper-plantar flexion of ankle joint during gait with high heel shoe (Lundberg et al., 1989).

COP variable of this study analyzed only during supporting phase, and calculated absolute mean value of change of displacement from touch down to take off of COP after propulsive phase. The result did not show significant difference according to heel height, but showed less change of displacement on 9 cm than that of 0 cm in both COPx and COPy. Proper change in displacement of COP could not only reduce and control the velocity of COP but also induced efficient gait during propulsive phase (Hyun and Ryew, 2014b), but relative minute range of displacement at high

heel of 9 cm suggested a failure of function on the posture control during gait.

That is, it may say that muscle fatigue could be cumulated as with increase of instability by the loss of control function in locomotion velocity (Ebbeling et al., 1994; Gefen et al., 2002; Valentini et al., 2009).

Calculation of RCOF was divided with vertical components of ML GRF and AP GRF, and RCOF showed greater value on high heel of 9 cm than that of 0 cm during both 1 PVF and 2 PVF due to increase of ML GRF and AP GRF in case of 9 cm. The above result can be explained with an interaction of material and environmental factor, friction coefficient of floor and sensory of neuromuscular function which may cause injuries of sliding and falling etc. (Hanson et al., 1999; Redfern and Dipasquale, 1997; Strandberg and Lanshammar, 1981; Tang and Woollacott, 1998).

Gait by high heel shoe divided as environmental factor can be regarded as important factor of frictional coefficient for structural problem of shoes, and also ratio of falling injury can be high due to more narrow area of touch down relative to gait of touch down by the sole of a foot to ground by arch type of midsole in case of bare foot.

Also transfer time showed faster at RCOFmax than in case of 1 PVF, and showed the shorter time in the transfer time than that of absorption time of impact to the body. Therefore gait of high heel shoe could not control efficiently the GRF and then increased the possibility of injuries of sliding and falling, and muscle fatigue due to decrease of the control ability of frictional coefficient.

When considering the above, It is important to select proper height of heel in female walking, but rather more to consider design of shoes of material and shape in course of manufacturing.

## CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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