Influences of high-heeled shoe parameters on gait cycle, center of pressure trajectory, and plantar pressure in young females during treadmill walking

Jiangyinzi Shang
Huashan Hospital Fudan University
Xiang Geng
Huashan Hospital Fudan University
Chen Wang
Huashan Hospital Fudan University
Li Chen
Huashan Hospital Fudan University
Chao Zhang
Huashan Hospital Fudan University
Jiazhang Huang
Huashan Hospital Fudan University
Xu Wang
Huashan Hospital Fudan University
Alan Yan
University of Pittsburgh Medical Center
xin ma (maxinshhs@126.com)
Huashan Hospital Fudan University https://orcid.org/0000-0002-8608-8642

Research article

Keywords: High-heeled shoe parameter, gait cycle, treadmill walking, plantar pressure

Posted Date: March 9th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-16287/v1

Version of Record: A version of this preprint was published at Journal of Orthopaedic Surgery on January 1st, 2020. See the published version at https://doi.org/10.1177/2309499020921978.

Abstract

Background Between 39% and 69% of women wear high-heeled shoes. Previous studies have shown that high heels can induce adverse biomechanical effects, but variables, such as walking speed, structure, style, and material of the shoes, have not been strictly controlled. The purpose of this study is to investigate the influences of high-heeled shoe parameters on gait cycle, center of pressure trajectory, and plantar pressure in young females. Methods Twenty healthy adult females were recruited to participate in this study. Subjects walked on a treadmill at a fixed speed (1 m/s). Overall, six pairs of high-heeled shoes were evaluated, which consisted of two heel types (thin and thick) and three different heel heights (low (3 cm), medium (6 cm), and high (8.2 cm)). Subjects also wore one pair of flat shoes (with 0.6 cm heel height) as the control group, while they walked on the treadmill at the same speed. Results and their significance were evaluated using a Heel Height × Heel Type Two way repeated ANOVA Test. Results The main parameters measured were the gait cycle, center of pressure parameters, peak pressure (PP), maximum force, contact area (CA), and the force time integral (impulse). The comparison of these parameters, conducted when the volunteers wore thick heel and flat shoes at different walking conditions, indicated that thin heels caused significant increases in the preswing parameter, CA, and PP exerted on the first toe and first metatarsus. Increased heel heights yielded smaller gait line lengths, single support lines, and smaller hindfoot areas. By contrast, increased anterior–posterior positions and plantar pressure parameter values were noted in the case of the forefoot. Conclusions Data analyses showed significant differences in plantar pressure distribution associated with the heel height and heel type at increased pressure in the central forefoot region and decreased pressure in the midfoot and heel sections, which consisted of the increased anterior shift. The implication of this study is to provide scientific advice to women for their choices of high heel shoes.

Background

Throughout history, high-heeled shoes (HHS) have been extensively used to increase the height and improve the profile of the wearer. According to the American Podiatric Medical Association, 39–69% of women wear HHS, while 40% of these women wear them daily [1–3]. However, wearing HHS may induce side effects on bones and the musculoskeletal system, and cause lower back discomfort, forefoot pain, and hallux valgus [4–7].

Moreover, several studies showed that high heels cause alterations in balance and are responsible for changes in the center of pressure (COP) and plantar pressure (PP) [8–10]. Previous literature indicated that the trajectory of COP had always been used to assess walking stability. Multiple COP parameters, such as the medial–lateral positions, anterior–posterior positions, and the average distance of COP from the mean position, were sensitive to deviations during extra inversion or eversion [9].

Previous studies have shown that the heel rise can induce adverse biomechanical effects, which may lead to an uneven distribution of plantar pressure. In turn, this would reduce the stress on the hindfoot and increase the stress to the forefoot [11]. Furthermore, these reported changes in forefoot pressure have been associated with the impacts of HHS on foot deformities, including the development of metatarsalgia, callus formation, increased rates of ulceration under the metatarsal heads, and the subsequent risk of painful bony deformities [12, 13].

Research on heel height and heel type of high heels has been carried out worldwide based on gait patterns on the ground or in other forms [14, 15]. However, to the best of our knowledge, this is the first time a treadmill was used in a survey of HHS. Additionally, as this paradigm needed a smaller space and allowed the use of harness support systems, it could be compared with more standardized conditions (e.g., constant walking speed) [16, 17]. Accordingly, treadmill gait analysis was an attractive alternative.

Furthermore, most shoes used for research are non-customized, not only in terms of the structure and style of the test shoes, but also in terms of the material of the shoe. These factors result in non-negligible errors and affect the accuracy of the research conclusions.

The shoes used in this study were customized, which reduced the human error and improved the accuracy of the research. By studying the influences of the differences in heel structure on the gait cycle, COP, and PP at a fixed walking speed, this study attempted to provide scientific advice to women for their high heel choices.

Methods

The survey participants included 20 female adult volunteers (mean age ± standard deviation: 21.22 ± 4.04 years, height: 162.0 ± 0.5 cm, weight: 55.80 ± 5.05 kg, and body-mass index (BMI): 20.73 ± 2.05 kg/m^2) with a foot size of 37 (European standard). Most of the participants wore HHS one to four times per week. All participants reported no foot-related disorders, skin lesions, or health-related problems. Signed written consent was obtained from all participants before the experiments. The study design was approved by the Ethics Committee of Huashan Hospital of Fudan University. The participants were examined while walking on treadmill at a fixed speed (1 m/s) at seven experimental conditions: (A1) thick HHS with 3 cm heels, (A2) thick HHS with 6 cm heels, (A3) thick HHS with 8.2 cm heels, (B1) thin HHS with 3 cm heels, (B2) thin HHS with 6 cm heels, (B3) thin HHS with 8.2 cm heels, and (C) flat shoes (Fig. 1a). All of the shoes were made at the Shanghai Second Leather Shoe Factory with the same type of material.

The EBRIS® gait analysis system and Noraxon myoPRESSURE™ module were operated with the treadmill system (Noraxon USA, Inc.) at a frequency of 100 Hz. The treadmill speed was set to 1 m/s. During the experiments, the participants were given several minutes to become accustomed to the HHS and were required to gradually walk along a track twice with each pair of shoes. Each session lasted approximately 10 s. MyoPRESSURE™ presented a comprehensive analysis of standard gait parameters and the COP. Associated average curves were generated. Plantar pressure measurements were recorded using the Tekscan® F-Scan® system (Tekscan Inc., South Boston, MA, USA) simultaneously. This system consisted of a wireless transmitter and two sensors. These sensors were approximately 0.15 mm thick and comprised 960 sensing elements, distributed in four sensors/area (cm^2). A sampling rate of 500 Hz was utilized for all the trials. All data were collected and processed using the Tekscan® F-Scan® research software (version 7).

All analyses were performed for the right foot (dominant side) [18]. In order to analyze the influences of heel height and heel type on gait parameters, A two-way repeated ANOVA was performed to determine which variables were affected by heel type and which were affected by heel height or a combination of both. For each statistical test, the significance was set at 0.05. When the tests were significant, the least significant difference criterion was adopted for post hoc comparisons. Statistical analyses were performed with the built-in functions of SPSS 21 (IBM Corp., Armonk, NY, USA).

Results

Normality information about this study we used the KS-test(Kolmogorov-Smirnov test)for the participants' body weight and height, the P value are 0.761 and 0.522, both were in normal distribution.

Gait phase parameters

The results of all gait phase parameters, for two heel types (thin and thick) and three different conditions (low: 3 cm, medium: 6 cm, and high: 8.2 cm), with a pair of flat shoes as the control group, are listed in Table 1. The stance phase was separated into three subphases: loading response (LR), midstance (MS), and preswing (PS).

The Heel Height × Heel Type two-way repeated ANOVA showed that the interaction factor and main effect heel height were not statistically different for the selected conditions. Meanwhile, the heel type only showed significant differences in the PS parameter. The post-hoc results showed significant differences between the control group and thin-heeled group, and also between the thick-heeled group and thin-heeled group.

COP parameters

The results of COP parameters, including the gait line length, medial–lateral position, anterior–posterior position, and single support line for two heel types (thin and thick), and three different conditions (low: 3 cm, medium: 6 cm, and high: 8.2 cm), with a pair of flat shoes as the control group are reported in Table 1.

The Heel Height × Heel Type two-way repeated ANOVA showed that neither the interaction factor nor the heel height and heel type was statistically different for the medial–lateral position.

Conversely, the main effect heel height and the interaction factor showed significant differences for the following parameters: gait line length, single support line, and anterior–posterior position. Regarding COP parameters, the post-hoc analysis revealed significant differences in the gait line length and single support line. However, the results for the anterior–posterior position yielded statistically significant differences between the control and high-heeled groups, low-heeled and medium-heeled groups, low-heeled and high-heeled groups, and between the medium-heeled and high-heeled groups.

Table 1
Gait phase parameters and COP parameters (n = 20, P = 0.05)

	Thick heel group Mean (SD)			**Thin heel group Mean (SD)**			**Flat shoe Mean (SD)**	**Main effect Heel type p-value**	**Main effect Heel heigh p-value**
	3cm	**6cm**	**8.2 cm**	**3cm**	**6cm**	**8.2 cm**			
Stance phase,%	67.01(1.40)	67.28(1.43)	67.04(1.45)	66.33(1.55)	66.82(1.40)	67.06(1.36)	66.44(1.49)	0.099	0.272
Load responce,%	16.91(1.24)	17.06(1.57)	16.95(1.45)	16.48(1.58)	16.70(1.53)	16.86(1.47)	16.37(1.52)	0.192	0.706
Mid stance,%	32.92(1.73)	32.96(1.69)	33.22(1.52)	33.58(1.44)	33.43(1.57)	33.28(1.56)	33.80(1.55)	0.098	0.971
Pre-swing,%	16.27(1.37)	16.69(1.36)	16.95(1.29)	16.88(1.50)	17.18(1.64)	17.28(1.47)	16.28(1.44)	0.031 b c	0.128
Swing phase,%	32.98(1.40)	32.72(1.43)	32.96(1.45)	33.67(1.55)	33.18(1.40)	32.94(1.36)	33.56(1.73)	0.096	0.282
Double phase,%	34.08(2.59)	34.35(2.87)	33.83(2.64)	32.74(2.62)	33.40(2.65)	33.79(2.57)	32.64(2.75)	0.058	0.605
Length of gait line,mm	224.00(6.51)	211.31(8.62)	194.88(9.47)	215.67(5.570	214.65(7.23)	203.72(6.56)	239.44(7.09)	0.254	0.000 &*#%§¥
Single support line,mm	83.98(20.99)	67.22(16.71)	45.18(12.54)	83.38(17.29)	62.50(14.54)	41.16(11.52)	102.71(15.86)	0.198	0.000 &*#%§¥
Medial-lateral position,mm	−1.21(6.71)	0.05(5.97)	−2.27(8.12)	−1.75(4.48)	−1.72(3.25)	−1.78(5.92)	−1.37(3.70)	0.486	0.531
Anterior-posterior position,mm	143.24(14.40)	145.07(15.10)	145.66(13.13)	131.84(8.54)	144.74(11.25)	153.22(10.58)	141.10(10.03)	0.489	0.000*#&

§Statistically significant difference between control group and low heeled group.

¥ Statistically significant difference between control group and medium heeled group.

& Statistically significant difference between control group and high heeled group.

* Statistically significant difference between low heeled group and medium heeled group.

Statistically significant difference between low heeled group and high heeled group.

% Statistically significant difference between medium heeled group and high heeled group.

b Statistically significant difference between control group and thin heeled group.

c Statistically significant difference between thick heeled group and thin heeled group.

Plantar pressure parameters

The plantar surface was divided into eight anatomical regions, including great toe (T1), lesser toes (T2–5), first metatarsal (M1), central forefoot (M23), lateral forefoot (M45), midfoot (MF), medial heel (MH), and lateral heel (LH) (Fig. 1b).

The heel height changed the maximum force over the entire foot region (Table 2). The heel height increased the maximum force over the T1, T2–5, M1, and M23, whereas a smaller force acted on the MF and MH regions. As shown in Table 3, the force–time integral exhibited patterns similar to those of the maximum force, i.e., lower force–time integral values in MH regions and higher in T1, T2–5, M1, and M23 regions.

As shown in Table 4, the contact area (CA) was larger in T1 and T2–5 with increased heel height. Moreover, the main effect of the heel type yielded significant differences in the T1 and M1 regions, while the post-hoc analysis results showed significant differences between the control and thin-heeled groups, the thick-heeled and thin-heeled groups, and between the thick heeled and thin heeled groups. Furthermore, the CA for the T1 was larger in the thick-heel group, while less CA was observed for M1 in the thin-heel group.

Table 5 shows the peak pressure (PP) results for eight anatomical regions. The PPs were larger in the T1, T2–5, M1, and M23 regions, and smaller in the MF, MH, and LH regions in high-heeled walking compared with the lower-heel height walking cases. The main effect of heel type yielded significant differences in the T1 and T2–5 regions, the post–hoc analysis results showed significant differences between the control and thin-heeled groups, the thick-heeled and thin-heeled groups, and also between the thick-heeled and thin-heeled groups. Additionally, both the PP for the T1 and T2–5 area were bigger in the thin-heel group than in the thick-heel group.

Maximum force(N)	Thick heel group Mean (SD)			Thin heel group Mean (SD)			Flat shoe Mean (SD)	Main effect Heel type p-value	Main effect Heel height p-value	I t (p
	3cm	6cm	8.2 cm	3cm	6cm	8.2 cm				
T1	44.96(21.80)	66.23(27.57)	65.95(19.37)	39.45(23.77)	50.11(19.29)	66.43(25.01)	17.42(14.51)	0.145	0.000 §¥ &*#	(
T2–5	43.14(31.01)	75.56(37.32)	88.21(34.64)	34.86(24.01)	61.88(20.35)	81.31(29.38)	17.09(11.66)	0.121	0.000 §¥ &*#	(
M1	61.63(33.73)	80.56(34.33)	102.63(46.56)	64.77(29.72)	92.31(34.87)	116.39(36.37)	52.85(33.30)	0.226	0.000 ¥ &*#%	(
M23	80.95(45.03)	102.40(37.57)	105.33(52.22)	72.70(36.52)	105.71(36.73)	120.61(52.96)	59.92(41.06)	0.718	0.007 ¥ &*#	(
M45	45.37(31.61)	47.85(32.35)	44.13(18.97)	44.53(20.89)	55.74(27.29)	52.60(28.27)	35.32(22.55)	0.372	0.627	(
MF	82.77(47.12)	53.35(36.67)	42.53(26.69)	101.60(59.47)	62.23(45.41)	38.85(23.01)	126.62(79.54)	0.455	0.001 §¥ &*#	(
MH	247.74(96.64)	181.15(62.47)	139.87(36.33)	254.03(85.23)	168.88(48.32)	125.60(53.29)	247.26(91.18)	0.664	0.000 ¥ &*#%	(
LH	108.33(35.68)	86.10(34.60)	86.58(21.18)	106.32(33.46)	92.28(17.51)	82.81(26.10)	150.25(99.22)	0.989	0.157	(

§Statistically significant difference between control group and low heeled group.

Table 2 Maximum force (n = 20, P = 0.05)

¥ Statistically significant difference between control group and medium heeled group.

& Statistically significant difference between control group and high heeled group.

* Statistically significant difference between low heeled group and medium heeled group.

Statistically significant difference between low heeled group and high heeled group.

% Statistically significant difference between medium heeled group and high heeled group.

Table 3
Force time integral (n = 20, P = 0.05)

Force time integral (N.S)	Thick heel group Mean (SD)			Thin heel group Mean (SD)			Flat shoe Mean (SD)	Main effect Heel type p-value	Main effect Heel height p-value	Mixed anova test (type*height) p-value
	3cm	6cm	8.2 cm	3cm	6cm	8.2 cm				
T1	0.90(0.25)	1.23(0.44)	1.32(0.39)	0.79(0.26)	1.00(0.39)	1.33(0.30)	0.35(0.11)	0.158	0.000 §* #%	0.457
T2–5	0.86(0.62)	1.51(0.75)	1.76(0.69)	0.70(0.48)	1.24(0.41)	1.63(0.59)	0.34(0.23)	0.121	0.000 §¥ &*#%	0.893
M1	1.23(0.67)	1.61(0.69)	2.05(0.93)	1.30(0.59)	1.85(0.70)	2.33(0.73)	1.06(0.67)	0.226	0.000 ¥ &*#%	0.842
M23	1.34(0.62)	2.05(0.75)	2.11(1.04)	1.45(0.73)	2.11(0.73)	2.41(1.06)	1.20(0.82)	0.718	0.007 ¥ &*#	0.603
M45	1.34(0.62)	2.05(0.75)	2.11(1.04)	1.45(0.73)	2.11(0.73)	2.41(1.06)	1.20(0.82)	0.372	0.627	0.762
MF	1.66(0.94)	1.07(0.73)	0.85(0.53)	2.03(1.19)	1.24(0.91)	0.68(0.30)	2.53(1.59)	0.310	0.546	0.704
MH	4.95(1.93)	3.62(1.25)	2.80(0.73)	5.08(1.70)	3.38(0.97)	2.73(0.80)	4.95(1.82)	0.842	0.000 §¥ *#	0.884
LH	2.17(0.71)	1.72(0.69)	1.73(0.42)	2.13(0.67)	1.85(0.35)	1.66(0.52)	3.00(1.98)	0.989	0.157	0.911

§Statistically significant difference between control group and low heeled group.

¥ Statistically significant difference between control group and medium heeled group.

& Statistically significant difference between control group and high heeled group.

* Statistically significant difference between low heeled group and medium heeled group.

Statistically significant difference between low heeled group and high heeled group.

% Statistically significant difference between medium heeled group and high heeled group.

Table 4
Force time integral (n = 20, P = 0.05)

Contact area (cm2)	Thick heel group Mean (SD)			Thin heel group Mean (SD)			Flat shoe Mean (SD)	Main effect Heel type p-value	Main effect Heel height p-value	Mixed anova test (type*height) p-value
	3cm	6cm	8.2 cm	3cm	6cm	8.2 cm				
T1	3.88(1.34)	5.08(1.07)	5.78(0.98)	3.21(1.40)	4.62(0.91)	5.37(1.02)	1.90(1.36)	0.040 abc	0.000 §¥ &*#%	0.937
T2–5	5.46(3.05)	8.01(3.18)	8.82(2.59)	4.80(2.80)	7.17(1.62)	7.96(2.18)	2.25(1.72)	0.157	0.000 §¥ &*#	0.987
M1	5.37(1.97)	5.78(1.76)	6.60(1.58)	6.27(2.05)	6.97(1.77)	7.21(1.10)	4.28(2.14)	0.029 abc	0.104	0.844
M23	6.40(2.08)	6.54(1.77)	6.71(1.70)	6.27(2.80)	7.31(1.36)	6.62(1.25)	6.77(3.90)	0.722	0.629	0.712
M45	5.31(2.85)	5.33(3.20)	5.42(2.27)	5.42(2.75)	6.15(2.62)	6.39(2.28)	4.76(3.09)	0.301	0.759	0.830
MF	9.84(4.20)	8.12(5.06)	7.20(3.79)	12.15(5.11)	9.30(4.74)	6.26(2.91)	13.47(6.67)	0.416	0.005 ¥&#	0.438
MH	13.94(2.06)	13.62(2.64)	13.32(1.75)	13.71(1.59)	13.57(0.80)	12.85(2.34)	13.83(2.25)	0.579	0.376	0.929
LH	9.16(1.51)	9.16(2.06)	9.92(1.73)	9.14(1.69)	9.79(1.51)	9.43(2.08)	10.33(4.06)	0.940	0.685	0.648

§Statistically significant difference between control group and low heeled group.

¥ Statistically significant difference between control group and medium heeled group.

& Statistically significant difference between control group and high heeled group.

* Statistically significant difference between low heeled group and medium heeled group.

Statistically significant difference between low heeled group and high heeled group.

% Statistically significant difference between medium heeled group and high heeled group.

a Statistically significant difference between control group and thick heeled group.

b Statistically significant difference between control group and thin heeled group.

c Statistically significant difference between thick heeled group and thin heeled group.

Table 5
Peak pressure (n = 20, P = 0.05)

Peak pressure(KPa)	Thick heel group Mean (SD)			Thin heel group Mean (SD)			Flat shoe Mean (SD)	Main effect Heel type p-value	Main effect Heel height p-value	Mixed anova test (type*height) p-value
	3cm	6cm	8.2 cm	3cm	6cm	8.2 cm				
T1	10.12(2.63)	11.02(1.82)	12.32(1.66)	11.69(2.43)	12.49(2.92)	13.79(3.21)	7.80(2.41)	0.010 abc	0.011 §¥& #	0.996
T2–5	7.24(1.17)	8.81(1.49)	9.64(1.44)	8.02(1.75)	9.27(1.58)	10.60(2.05)	5.61(1.43)	0.034 abc	0.000 §¥&* #%	0.737
M1	10.45(3.37)	13.14(2.42)	14.16(2.98)	10.13(2.62)	13.12(3.22)	17.27(2.77)	9.40(2.43)	0.141	0.000 ¥&*#%	0.050
M23	12.34(5.02)	15.56(4.32)	15.46(5.44)	11.50(3.58)	14.38(3.99)	18.09(6.24)	9.13(2.80)	0.837	0.001 ¥&*#	0.238
M45	8.32(2.45)	9.08(2.04)	8.20(1.58)	8.89(2.63)	8.75(1.96)	9.59(2.56)	7.8(2.4)	0.274	0.851	0.364
MF	8.02(1.24)	6.64(1.58)	5.68(0.99)	8.35(2.13)	6.19(1.19)	6.09(0.86)	9.16(1.68)	0.790	0.000 ¥ &* #	0.538
MH	17.27(4.3)	13.39(2.85)	10.43(1.72)	18.59(4.4)	12.27(2.6)	10.42(2.3)	18.48(3.84)	0.820	0.000 ¥&*#	0.603
LH	11.69(2.98)	9.47(3.05)	8.76(1.68)	11.78(3.49)	9.58(1.94)	8.79(1.97)	13.6(4.46)	0.820	0.000 ¥&*#%	0.603

§Statistically significant difference between control group and low heeled group.

¥ Statistically significant difference between control group and medium heeled group.

& Statistically significant difference between control group and high heeled group.

* Statistically significant difference between low heeled group and medium heeled group.

Statistically significant difference between low heeled group and high heeled group.

% Statistically significant difference between medium heeled group and high heeled group.

a Statistically significant difference between control group and thick heeled group.

b Statistically significant difference between control group and thin heeled group.

c Statistically significant difference between thick heeled group and thin heeled group.

Discussion

In this study, the effects of the heel type and heel height of HHS, gait cycle measurement, COP parameters, and plantar pressure were investigated. Heel type and heel height significantly influenced the trajectories of the COP and plantar pressure, and thus changed the walking stability during gait on a treadmill.

According to previous studies, the comfortable speed for high heels ranged from 122–140 cm/s when the heel height ranged from 1–6 cm [3, 19]. In this experiment, a maximum height of 8.2 cm was considered. Moreover, higher heel heights contributed to slower self-selected walking speeds [20]. Finally, the speed of 100 cm/s was used.

Previous kinematic studies state that walking in HHS led to a variation in lower-extremity joint kinetics, which began in the early stance phase [3, 21]. In agreement with these results, the results of our study suggested that the PS time increased as a function of the heel height, although no statistical difference was observed. However, for the heel type, the PS time for the thin-heeled group increased compared with both the control and thick-heeled groups. This indicated that thin-heeled shoes may contribute to muscular fatigue [22].

Regarding the COP parameters, both the gait line length and single support line decreased as the heel height increased, regardless of the heel type. However, a large increase in the anterior–posterior position was evident when the heel height increased. The novel finding of this study is the fact that the range of COP deviations in the anterior–posterior directions significantly increased for higher heels, while the anterior–posterior positions of the COP were parallel to the direction of progression. There were no statistical differences in the ML directions, partly owing to the slower speeds [8], because the medial–lateral positions of the COP were described relative to the line of progression that bisected the line of motion of the COM during the gait cycle. The COP deviations in the anterior–posterior directions were correlated with the results from another study that indicated that in HHS, anterior, medial shifts of forces occurred within the foot, whereby forefoot forces increased, and the force concentration was enhanced [20].

In this study, the primary kinetic differences with respect to the normalized distribution of plantar pressure at different heel height and heel-type conditions were observed for eight anatomical regions. In general, the maximum force, impulse, PP, and CA in the forefoot increased when the heel height increased, while the same indices decreased in the cases of the MF and heel when higher heel heights were used. Moreover, for both T1 and T2–5, the order of PP was: control group thick-heeled group thin-heeled group. For T1, the CA order for the heel region was: control group thin-heeled group thick-heeled group. For M1, the order of CA for the heel region was: control group thick-heeled group thin-heeled group. These results are consistent with those reported in previous studies [23]. More importantly, for heel regions, all the plantar pressures were almost at the same level (between those related to the pressured developed in flat heel and 3 cm heel height cases). This implied that there was a threshold for the flat–heel-height difference. Both the impact force and loading rate decreased when the heel height ranged from 7.6 cm to 8.5 cm. This outcome was similar to that observed in our experiment. This was attributed to the prevention strategy employed for high-heeled heights [24].

In our previous study on the impact of HHS on the ankle complex during walking in young women, it was shown that HHS mainly affected the rotational motion of the ankle complex during walking. The spatial position of the talocrural joint was abnormal, and the subtalar joint's range of motion decreased during high-heeled gait [25]. Moreover, the plantar flexions of the ankle joints increased as the heel height increased, which contributed to the increased pressure on the forefoot. These changes in force distribution have been linked to forefoot deformities, such as hallux valgus, metatarsalgia, and callus formation [20, 26].

Conclusions

Gait cycle, center of pressure parameters, PP, maximum force, contact area (CA), and the force time integral (impulse) were measured. The comparison of these parameters, conducted when the volunteers wore thick heel and flat shoes at different walking conditions, indicated that thin heels caused significant increases in the PS parameter, CA, and PP exerted on the first toe and first metatarsus. Increased heel heights yielded smaller gait line lengths, single support lines, and smaller hindfoot areas. In contrast, increased anterior–posterior positions and plantar pressure parameter values were noted in the forefoot. Data analyses showed significant differences in plantar pressure distribution associated with the heel height and heel type at increased pressure in the central forefoot region and decreased pressure in the midfoot and heel sections, which consisted of the increased anterior shift. The range of COP deviations in the anterior–posterior directions significantly increased for higher heels, while the anterior–posterior positions of the COP were parallel to the direction of progression. Future research will investigate walking at different velocities and the use of finite element analysis instruments to quantify the internal pressures, which will further assist women in their choices of high heel shoes.

List Of Abbreviations

BMI: body-mass index

CA: contact area

COP: center of pressure

HHS: high-heeled shoes

LH: lateral heel

LR: loading response

LSD: least significant difference

M1: first metatarsal

M23: central forefoot

M45: lateral forefoot

MF: midfoot

MH: medial heel

MS: midstance

PP: peak pressure

PS: preswing

T1: great toe

T2–5: lesser toes

Declarations

Ethics approval and consent to participate

The study design was approved by the Ethics Committee of Huashan Hospital. Signed and written consent was obtained from all participants before the experiments.

Consent for publication

Signed and written consent was obtained from all participants before the experiments.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests

Funding

This project was supported by the National Natural Science Foundation of China (Grant No. 81171670 and Grant No. 81472037) .

Authors' contributions

Data curation, jiangyinzi shang,Li Chen; Formal analysis, Xiang Geng,Chen Wang; Methodology, xin ma,Chao Zhang;

Writing – review & editing,   alan yan,Jiazhang Huang,Xu Wang.

References

[1] J.Y. Yoon, D.H. An, W.G. Yoo, Y.R. Kwon, Differences in activities of the lower extremity muscles with and without heel contact during stair ascent by young women wearing high-heeled shoes, J Orthop Sci 14(4) (2009) 418-22. https://www.ncbi.nlm.nih.gov/pubmed/19662476.

[2] M.R. Titchenal, J.L. Asay, J. Favre, T.P. Andriacchi, C.R. Chu, Effects of high heel wear and increased weight on the knee during walking, J Orthop Res 33(3) (2015) 405-11. https://www.ncbi.nlm.nih.gov/pubmed/25532875.

[3] M. Esenyel, K. Walsh, J.G. Walden, A. Gitter, Kinetics of high-heeled gait, J Am Podiatr Med Assoc 93(1) (2003) 27-32. https://www.ncbi.nlm.nih.gov/pubmed/12533553.

[4] C. Frey, Foot health and shoewear for women, Clin Orthop Relat Res (372) (2000) 32-44. https://www.ncbi.nlm.nih.gov/pubmed/10738412.

[5] S.S. Al-Abdulwahab, R.D. Al-Dosry, Hallux valgus and preferred shoe types among young healthy Saudi Arabian females, Ann Saudi Med 20(3-4) (2000) 319-321. <Go to ISI>://WOS:000168341600039.

[6] M.S. Barnish, J. Barnish, High-heeled shoes and musculoskeletal injuries: a narrative systematic review, BMJ Open 6(1) (2016) e010053. https://www.ncbi.nlm.nih.gov/pubmed/26769789.

[7] H.B. Menz, M.E. Morris, Footwear characteristics and foot problems in older people, Gerontology 51(5) (2005) 346-51. https://www.ncbi.nlm.nih.gov/pubmed/16110238.

[8] A. Mika, L. Oleksy, R. Kielnar, M. Swierczek, The influence of high- and low-heeled shoes on balance in young women, Acta Bioeng Biomech 18(3) (2016) 97-103. https://www.ncbi.nlm.nih.gov/pubmed/27840442.

[9] H.L. Chien, T.W. Lu, M.W. Liu, Effects of long-term wearing of high-heeled shoes on the control of the body's center of mass motion in relation to the center of pressure during walking, Gait Posture 39(4) (2014) 1045-50. https://www.ncbi.nlm.nih.gov/pubmed/24508016.

[10] L. Yung-Hui, H. Wei-Hsien, Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking, Appl Ergon 36(3) (2005) 355-62. https://www.ncbi.nlm.nih.gov/pubmed/15854579.

[11] Y. Cong, J.T. Cheung, A.K. Leung, M. Zhang, Effect of heel height on in-shoe localized triaxial stresses, J Biomech 44(12) (2011) 2267-72. https://www.ncbi.nlm.nih.gov/pubmed/21705002.

[12] P.H. Ko, T.Y. Hsiao, J.H. Kang, T.G. Wang, Y.W. Shau, C.L. Wang, Relationship between plantar pressure and soft tissue strain under metatarsal heads with different heel heights, Foot Ankle Int 30(11) (2009) 1111-6. https://www.ncbi.nlm.nih.gov/pubmed/19912724.

[13] C.M. Yin, X.H. Pan, Y.X. Sun, Z.B. Chen, Effects of duration of wearing high-heeled shoes on plantar pressure, Hum Mov Sci 49 (2016) 196-205. https://www.ncbi.nlm.nih.gov/pubmed/27428595.

[14] R. Csapo, C.N. Maganaris, O.R. Seynnes, M.V. Narici, On muscle, tendon and high heels, J Exp Biol 213(Pt 15) (2010) 2582-8. https://www.ncbi.nlm.nih.gov/pubmed/20639419.

[15] M. Roerdink, B.H. Coolen, B.H. Clairbois, C.J. Lamoth, P.J. Beek, Online gait event detection using a large force platform embedded in a treadmill, J Biomech 41(12) (2008) 2628-32. https://www.ncbi.nlm.nih.gov/pubmed/18657816.

[16] Parvataneni K, Ploeg L, Olney SJ, Brouwer B. Kinematic, kinetic and metabolic parameters of treadmill versus overground walking in healthy older adults. Clinical Biomechanics (Bristol Avon) 2009;24(1):95–100.

[17] Riley PO, Paolini G, Della Croce U, Paylo KW, Kerrigan DC. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. Gait and Posture 2007;26(1):17–24.

[18] M.H. B, Two feet□ or one person? Problems associated with statistical analysis of paired data in foot and ankle medicine, The Foot 14(1) (2004) 2 □ 5.

[19] S. Winiarski, A. Rutkowska-Kucharska, P. Zostawa, N. Uscinowicz-Zostawa, S. Klich, Foot mechanics in young women are altered after walking in high-heeled shoes, Acta Bioeng Biomech 19(3) (2017) 107-113. https://www.ncbi.nlm.nih.gov/pubmed/29205209.

[20] N.J. Cronin, The effects of high heeled shoes on female gait: a review, J Electromyogr Kinesiol 24(2) (2014) 258-63. https://www.ncbi.nlm.nih.gov/pubmed/24508305.

[21] E. Di Sipio, G. Piccinini, C. Pecchioli, M. Germanotta, C. Iacovelli, C. Simbolotti, et al., Walking variations in healthy women wearing high-heeled shoes: Shoe size and heel height effects, Gait Posture 63 (2018) 195-201. https://www.ncbi.nlm.nih.gov/pubmed/29772495.

[22] A. Gefen, M. Megido-Ravid, Y. Itzchak, M. Arcan, Analysis of muscular fatigue and foot stability during high-heeled gait, Gait Posture 15(1) (2002) 56-63. https://www.ncbi.nlm.nih.gov/pubmed/11809581.

[23] X. Zhang, B. Li, Influence of in-shoe heel lifts on plantar pressure and center of pressure in the medial-lateral direction during walking, Gait Posture 39(4) (2014) 1012-6. https://www.ncbi.nlm.nih.gov/pubmed/24440428.

[24] L.D.V. AS, Biomechanical aspects of high heel gait. , J Biomech 20(9) (1987) 909.

[25] C. Wang, X. Geng, S. Wang, X. Ma, X. Wang, J. Huang, et al., The impact of high-heeled shoes on ankle complex during walking in young women-In vivo kinematic study based on 3D to 2D registration technique, J Electromyogr Kinesiol 28 (2016) 7-16. https://www.ncbi.nlm.nih.gov/pubmed/26970876.

[26] G.E. Borchgrevink, A.T. Viset, E. Witso, B. Schei, O.A. Foss, Does the use of high-heeled shoes lead to fore-foot pathology? A controlled cohort study comprising 197 women, Foot Ankle Surg 22(4) (2016) 239-243. <Go to ISI>://WOS:000392721800007.

Figures

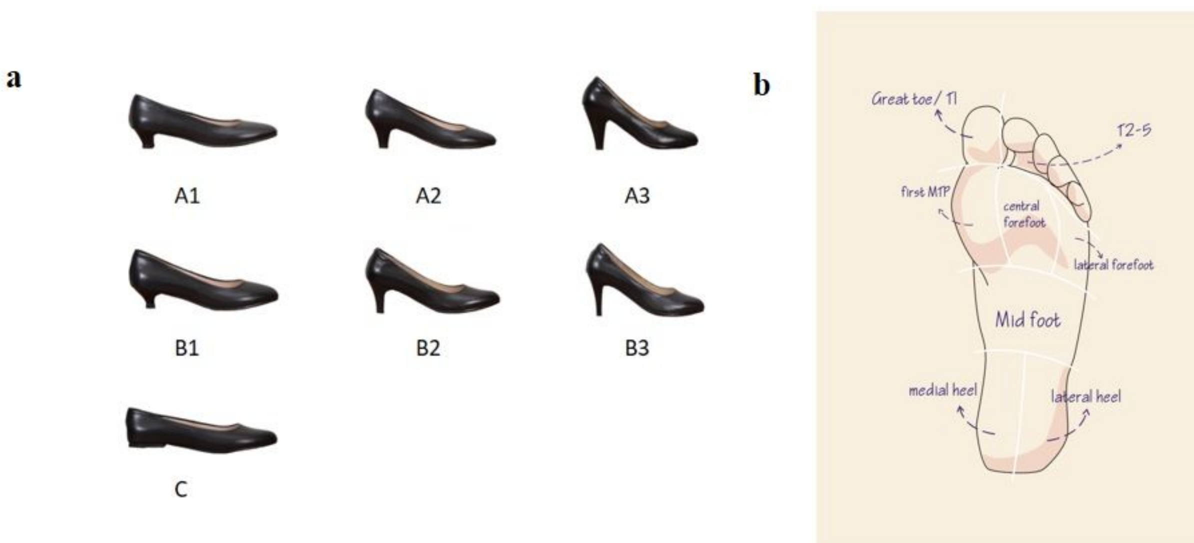

Figure 1

a:experimental conditions: (A1) thick heel HHS with 3-cm heels, (A2) thick heel HHS with 6-cm heels, (A3) thick heel HHS with 8.2-cm heels, (B1) thin heel HHS with 3-cm heels, (B2) thin heel HHS with 6-cm heels, (B3) thin heel HHS with 8.2-cm heels, and (C) flat shoes. b:The plantar surface was divided into eight anatomical regions, including great toe (T1), lesser toes (T2–5), first metatarsal (M1), central forefoot (M23), lateral forefoot (M45), midfoot (MF), medial heel (MH), and lateral heel (LH)