Acta of Bioengineering and Biomechanics
Vol. 19, No. 3, 2017

Original paper
DOI: 10.5277/ABB-00671-2016-04

Foot mechanics in young women are altered after walking in high-heeled shoes

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Purpose: Nowadays, fashion has caused that many young women are wearing high-heeled shoes. Therefore, the aim of this study was to examine the effects of long-term walking in high-heeled shoes on the foot mechanics during barefoot gait. *Methods*: Forty-three young women (22 ± 2.1 years) divided into two groups participated in this retrospective cohort study. The first group was composed of women who frequently wear high-heeled footwear. The second, infrequent wearers group, consisted of women who preferred flat-heeled shoes. Measurements of gait parameters were recorded for barefoot gait. A motion analysis system and two force plates were used in order to evaluate the lower-limb rocker mechanism, transverse foot arch height and parameters of ground reaction force. *Results*: Walking in high-heeled shoes modified barefoot foot mechanics, which manifested itself in a shorter duration (by ca. 4%) of the first and second rocker and a significantly longer duration (by 5%) of the third rocker phase as well as a substantial reduction in height of the transverse foot arch (by around 50%) in women habitually walking in high-heeled shoes. A significantly shorter relative duration of the third rocker (44.3% of cycle time) and greater value of the vertical component of ground reaction force (114.7% BW) in the third rocker phase were found in the group of women habitually walking in high-heeled shoes. *Conclusions*: The mechanism of foot rolling, with flattened foot arch, and significantly higher values of the vertical component of ground reaction force and shorter time might lead to overload in lower-limb joints in young women.

Key words: *gait analysis, high-heeled shoes, ground reaction forces, foot rockers, foot deformities*

1. Introduction

Wearing high-heeled shoes may change body posture and the distribution of plantar pressure, which might lead to the risk of soft tissue problems. Wearing high-heeled shoes for a long time may cause forefoot pain, hallux valgus or calluses [1]. Wearing high-heeled shoes often also decreases the lumbar flexion angle, and creates a more unstable posture (because of the increased height of the centre of mass) and additional compressive forces in the lower lumbar spine [2]. Moreover, it often leads to a compensatory increase in erector spinae activity, which leads to muscle fatigue and consequently to back pain [2], [3].

Another negative effect of walking in high-heeled shoes is increased peak pressure and shear stress shifted from the lateral to the medial forefoot, which could be a contributing factor to hallux deformity [4]. Wearing high-heeled shoes has long been considered a risk factor for the development of patellofemoral pain in women [5]. Wearing high-heeled shoes for walking generates a force spike upon the initial ground contact. It may also lead to overuse injuries of soft tissues, which may result in leg and back pain. The significance of the problem in investigating the negative effect of walking in high-heeled shoes is

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Received: June 15th, 2016
Accepted for publication: November 7th, 2016

emphasized by the fact that foot posture, foot range of motion, foot deformation and lesions, lesser toe deformities, tactile sensitivity and strength change with the age of a person. Older people exhibit flatter feet, reduced range of motion, tactile sensation and strength, and a higher prevalence of foot deformity [6]. Studies have found that younger women walking in high-heeled shoes showed more adjustments in forces and torques at the knee and hip in frontal and transverse planes [7]. Along with a few significant changes in joint forces and torques, the older group demonstrated longer cycle duration and double stance phase, larger trunk side flexion and hip internal rotation, and less hip adduction [7]. The interaction between the heel height and age showed that the influences of heel height on trunk rotation, hip abduction/adduction, and knee and hip forces and torques in the frontal plane depended on age. This means that the load on the feet during walking in high-heeled shoes is substantially greater in older than in younger women [8]. Studies have demonstrated that the negative effects of walking in high-heeled shoes can be reduced. The use of a heel cup insert, for example, reduces the pressure and impact force exerted on heels and an arch support insert reduces the medial forefoot pressure, while both improve footwear comfort [9].

The analysis of references shows that the focus of the investigations of many authors is on the effect of the height of heels on the kinematic, kinetic and electromyographic parameters of walking in shoes with various heel heights. These studies have compared gait parameters when women walk in shoes with different heel heights. The aim of present study was to examine the effects of long-term walking in high-heeled shoes on the foot mechanics during barefoot gait of young women. We presume that walking in high-heeled shoes might lead to permanent changes in foot mechanics, which can be evaluated also through analysis of barefoot gait. Furthermore, we expect that changes in gait pattern in terms of both temporal parameters and values of ground reaction forces might occur in women walking in high-heeled shoes. Analysis of literature shows that various authors have limited their studies to maximum values over the gait cycle or limited the number of gait phases. Since we assume that walking in very high-heeled shoes might lead to changes in foot mechanics during barefoot gait, the focus of our study is on the analysis of detailed foot mechanics. Analysis of foot mechanics for all gait phases with respect to specific durations of rockers should indicate the gait phases where the greatest overload might occur in the lower limbs of young women.

2. Materials and methods

Forty-three women aged 19 to 25 years were examined in the study. The first, *frequent wearers* group (n = 21, 22.5 ± 2.5 years, 58.7 ± 8.2 kg, 165.8 ± 4.0 m) comprised the women who walked in high-heeled shoes on a regular basis (minimum of two years, at least three times a week and at least five hours a day). The second, *infrequent wearers* group (n = 22, 22.1 ± 1.9 years, 59.3 ± 7.2 kg, 164.5 ± 4.0 m) comprised women who did not use high-heeled shoes or used them less often than once a week. There was no statistical difference between groups in age, body mass and height. None of the subjects had complained about injuries or pain discomfort over the previous six months. All the participants took part voluntarily in the experiment and signed a written consent form. The study was conducted according to the principles expressed in the Declaration of Helsinki and received the approval of the Senate Ethics Committee of our university.

The motion analysis system BTS Smart-E (BTS Bioengineering, Italy), which comprised six infrared digital cameras (1.1 μm IR, 120 fps in 768 × 576 px resolution), two cameras operating within visible range and two piezoelectric force plates (Kistler 9286A), was used for measurements. Eight photo-reflective markers were attached to the lower limb. The locations of the markers were chosen using a simplified foot model verified in terms of reliability and repeatability [10], [11]. The lower limb in the model used comprised three segments: (1) lower leg – marked with the caput fibulae, lateral malleolus and marker located on the midpoint between the lateral head of the fibula and the lateral malleolus on the shank, (2) tarsal and metatarsal bones – marked with the lateral malleolus, tuber calcanei and I and V metatarsal heads, and (3) forefoot – marked with I and V metatarsal heads and the distal phalanx of the hallux. An additional marker was used between II and III metatarsal head (Fig. 1) in order to measure transverse arch height. Transverse arch height [12] was defined as the length of the orthogonal projection of the location of the II/III metatarsal head on the support base.

The barefoot women were asked to perform two tasks: (I) a static balance test: three repetitions of standing on both feet for 20 seconds with eyes open, and (II) a gait assessment: walking on flat ground at the velocity preferred by the subjects; each woman performed 3 walks over a section of 5 metres, which enabled the recording from 8 to 10 gait cycles for each woman.

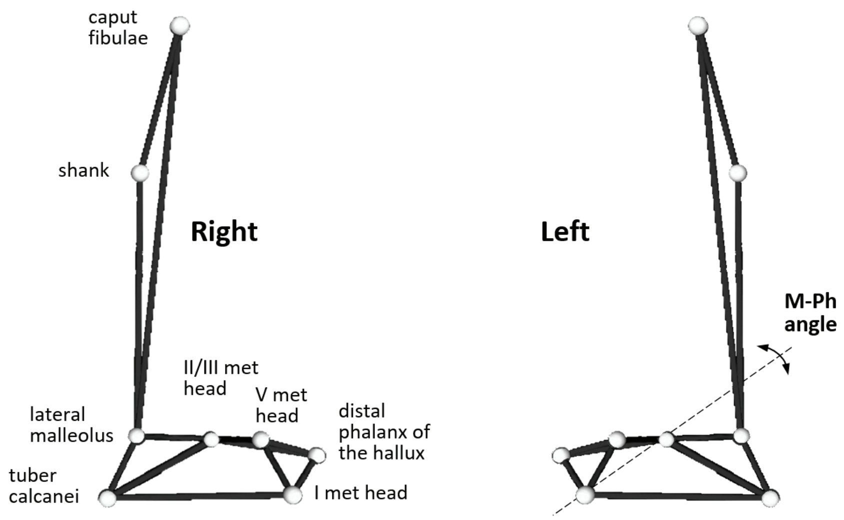

Fig. 1. Location of markers according to the modified filming protocol during quiet standing.
The lower limb was divided into three segments: the shank, the rear and middle part of the foot and the forefoot

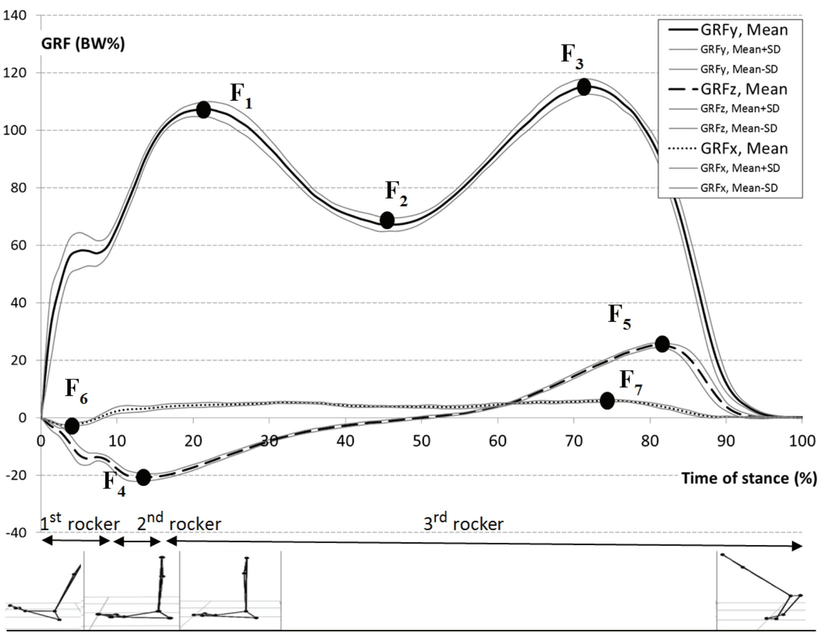

Fig. 2. The definition of parameters characterizing main components of the ground reaction force (GRF) vector as measured against the time of stance and time of the rockers. Mean value (thick line) and ± standard deviation (thin lines around mean value) based on 12 gait cycles. GRFy – vertical component, GRFz – fore-aft component, GRFx – mediolateral component

In order to describe foot mechanics, the duration of individual gait phases, values of ground reaction forces in three planes and transverse arch height were determined. Gait cycle was divided into the phases of 1st heel rocker, 2nd ankle rocker and 3rd forefoot rocker [13]. Transverse arch height was recorded during quiet standing (P0) (Fig. 1) and during gait at the moment of contact of the heel with the ground (P1), contact of the metatarsal heads with the ground (P2), contact of the big toe with the ground (P3) and when detaching the distal phalanx of the big toe from the ground (P4) (Fig. 2).

The following parameters were compared between test groups:

- temporal variables – total *cycle time*, time of contact of the metatarsal bone heads with the ground (P2 time) and 1st rocker duration, time of contact of the big toe with the ground (P3 time) and 2nd rocker duration, time of toe off (P4 time, identical with stance time) and time of the 3rd rocker duration expressed in seconds and with respect to the duration of the cycle time;

- transverse arch height in standing (P0), at contact of the heel with the ground (P1), contact of metatarsal bone heads (P2), contact of the big toe (P3), at toe off (P4) and averaged value in the whole stance phase (*Arch height Av*) expressed in millimetres;
- variables for three components of the ground reaction force expressed in absolute values [N] and in percentage of the gait cycle time [%]. For the vertical component: F1 – the maximal force during overload in the initial weight acceptance phase, F2 – the minimum force during unloading at middle stance associated with downward acceleration of the centre of gravity (CoG), F3 – the maximal force during overload at terminal stance related to the upward acceleration of the CoG. For the anterior-posterior component: F4 – maximal posterior braking force at initial stance, and F5 – maximal anterior push-off force at terminal stance. For the mediolateral component: F6 – the maximal lateral force in the initial weight acceptance phase, F7 – the maximal medial force during the single support phase (see Fig. 2). The time of occurrence of maximum values of ground reaction force in [s] and the *loading rate* in [BW/s], which is the rate of change of the F1 variable.

All the measurements were carried out in the biomechanical analysis laboratory of our university (PN-EN ISO 9001:2001).

The descriptive statistics were based on the values of mean, standard deviation and coefficient of variability (CV) for the parameters measured. Analysis of mean values in both groups was carried out based on one-way analysis of variance (ANOVA) and the Mann–Whitney U test. The statistical significance was set at $p < 0.05$. All the statistical calculations were carried out using Statistica 12 software (StatSoft, Inc., Tulsa, USA).

3. Results

Table 1 contains the means, standard deviations and coefficient of variability (CV) for variables that characterize transverse arch height during foot rolling and parameters of ground reaction forces for women walking in high-heeled shoes on a regular basis (FW – frequent wearers) and women who wear high-heeled shoes sporadically (InFW – infrequent wearers).

No substantial differences were observed between the groups studied during individual phases and rocker durations. Only the absolute duration of the stance phase (0.59 s) and the relative duration of the third rocker (44.3%) turned out to be significantly shorter for women frequently walking in high-heeled shoes than for women from the InFW group (0.62 s and 46.9%, respectively). The relative duration of the 1st heel rocker was ca. 8%, whereas for the 2nd ankle rocker it was around 3.5%, and the duration of the 3rd forefoot rocker was ca. 45% of the gait cycle. The relative durations of the stance phase (57%) and swing phase (43%) did not differ statistically between the groups within low variability.

Transverse arch height was found to be highest during free standing (ca. 23 mm) and was similar for both groups of women. The average arch height during gait was reduced, with a significant difference of 4.7 mm for the FW group and 8.0 mm for the InFW group. A significantly lower arch height was found for women in the FW group than in the InFW group during heel contact (4.3 and 10.2 mm, respectively), contact of metatarsal bone heads (3.9 and 9.5 mm), contact of the big toe (3.4 and 8.1 mm) and toe off (4.7 and 7.9 mm). Interindividual variation in the measurement of transverse arch height was insignificant (below 30%).

Differences between women walking in high-heeled shoes and those walking in flats were also noticeable in components of ground reaction force. The relative value of the component of ground reaction force in the middle stance phase (F2) was significantly lower in the FW group (67.6%BW) than in the InFW group (70.6%BW) and significantly higher at the moment of propulsion (F3), with 114.7% and 112.8% body weight, respectively. The duration of maximal ground reaction force also differed significantly (tF3). It was shorter for the first group than the second group, but this could have been caused by a relatively shorter duration of the whole gait cycle. The relative value of ground reaction force (F1) and time of this force occurring (tF1) were similar in both groups analysed. No differences were found in the loading rate either, which was ca. 7.8 BW/s in both groups. The relative value of ground reaction force (F4) for anterior-posterior ground reaction force (GRF) and its duration (tF4) was very similar in both groups, whereas the value of this force during the propulsion phase (F5) was substantially lower for the first group (26.0% BW) than the second are (26.9% BW). No significant differences in the duration of this force (tF5) were demonstrated between

Table 1. Mean value, standard deviation (SD) and coefficient of variance (CV) for the time parameters, the height of the transversal arch and for ground reaction force parameters for women walking in high-heeled shoes (Frequent wearers) and using a flat-soled shoes (Infrequent wearers) while quiet standing (P0), walking at heel contact (P1), at contact of the metatarsal heads (P2), at contact of the hallux (P3), at toe-off (P4) and the average height for the support phase. The *p*-value is given in brackets

	Frequent wearers			Infrequent wearers		
	Mean	SD	CV (%)	Mean	SD	CV (%)
Time parameters						
Cycle time (s)	1.04	0.05	4.6	1.07	0.06	5.8
P2 time (s)	0.08	0.02	28.0	0.09	0.02	26.3
P3 time (s)	0.13	0.05	39.3	0.13	0.04	31.4
P4 time / Stance time (s)	0.59 (0.04)	0.05	9.0	0.62	0.03	5.4
1st rocker time duration (s)	0.08	0.02	29.4	0.08	0.02	25.3
2nd rocker time duration (s)	0.03	0.02	48.9	0.04	0.02	55.6
3rd rocker time duration (s)	0.49	0.05	10.1	0.50	0.05	9.9
1st rocker time duration (%)	7.9	2.2	28.0	8.2	2.1	25.6
2nd rocker time duration (%)	3.3	1.7	50.6	3.7	2.0	54.5
3rd rocker time duration (%)	44.3 (0.04)	7.6	17.2	46.9	5.1	10.8
Stance time (%)	56.9	4.2	7.4	58.1	2.0	3.4
Swing time (s)	0.43	0.04	9.6	0.45	0.04	8.8
Swing time (%)	43.1	4.2	9.8	41.9	2.0	4.7
Transversal arch height						
Arch height at P0 (mm)	22.8	1.6	7.1	22.9	3.6	15.8
Arch height at P1 (mm)	4.3 (0.05)	1.2	27.2	10.2	3.5	34.7
Arch height at P2 (mm)	3.9 (0.04)	1.2	30.8	9.5	3.2	33.9
Arch height at P3 (mm)	3.4 (0.03)	1.1	32.2	8.1	2.4	29.3
Arch height at P4 (mm)	4.7	1.2	25.8	7.9	2.3	29.1
Arch height Av (mm)	4.7	1.2	25.7	8.0	2.2	27.6
Ground reaction force parameters						
F1 (% BW)	107.9	4.2	3.9	106.0	4.7	4.4
tF1 (s)	0.14	0.01	7.8	0.14	0.02	11.3
LR (B W/s)	7.7	0.5	5.9	7.8	0.8	10.8
F2 (% BW)	67.6 (0.05)	4.1	7.1	70.6	4.9	7.8
tF2 (s)	0.31	0.01	3.7	0.31	0.01	4.0
F3 (% BW)	114.7 (0.03)	4.8	4.2	112.8	5.9	5.2
tF3 (s)	0.48 (0.05)	0.01	2.2	0.49	0.02	3.9
F4 (% BW)	–21.2	2.1	9.8	–21.1	2.3	11.1
tF4 (s)	0.09	0.01	13.0	0.08	0.01	15.0
F5 (% BW)	26.0 (0.04)	1.1	4.1	26.6	1.1	4.0
tF5 (s)	0.55	0.01	2.0	0.55	0.01	2.2
F6 (% BW)	–3.5	0.5	15.4	–3.6	0.6	17.7
tF6 (s)	0.02	0.01	19.7	0.03	0.01	23.1
F7 (% BW)	6.2	0.5	8.4	6.3	0.7	11.1
tF7 (s)	0.49 (0.05)	0.03	6.6	0.51	0.03	6.8

the groups. Furthermore, the parameters for the mediolateral component did not differ significantly either between the groups. The variability of the parameters that characterize the components of ground reaction force was at a low level (below 20%).

4. Discussion

With the fashion for women wearing very high-heeled shoes, the interest in changes in the female motion system during gait has been increasing. Many authors have suggested that walking in high-heeled shoes for a longer time might increase the risk of injuries [2], [4], [14]. In order for the dynamic foot transition to occur properly, the activity and co-activity of the lower leg and foot muscles have to occur at the right time, which guarantees that the work of the foot rolling mechanism is economical [15]. This mechanism might be disturbed if changes in the foot mechanism occur.

In our study, the total duration of the gait cycle did not differ significantly between the groups studied and was consistent with the values demonstrated by other authors [16], [17]. The duration of the first rocker accounted for around 8% and that of the second rocker for around 3.5% of the duration of the gait cycle and was consistent with the temporal gait model [18]. Statistical differences occurred in the durations of the third rocker. The duration of the third rocker of 44.3% for the frequent wearers group was shorter by 5% than for the infrequent wearers group (46.9%). This shortening of the stance phase, found in the frequent wearer group, is typical in young and uncommon in older women [19]. Previous studies of walking in high-heeled shoes demonstrated instead elongation of the stance phase. These studies found unusual activity of the ankle joint muscles (m. gastrocnemius and m. tibialis anterior) for greater heel heights [20]. Occurrence of the disturbance during the stance phase of barefoot gait might suggest the establishment of unusual muscle activity [21].

The extrinsic structure of the foot is formed by a system of longitudinal and transverse arches, which stretch under load and return to baseline upon relieving [22]. Under normal weight-bearing conditions, the medial and longitudinal arch lowers on the level of the navicular bone by 15–20 mm, and the foot lengthens. In order to evaluate the foot arch, the photogrammetric method, based on moiré projection, is typically employed, using, for example, Clarke's angle and the Wejsflog index [23]. Since these methods are static, they cannot be used for evaluation of the foot arch during gait. Furthermore, the dynamic methods for evaluating the distribution of ground pressure force during gait have not dealt with the parameter being of interest to us [24]. The use of the gait cycle phase model based on rocker phases helped identify the time of occurrence of disturbance in the height of the transverse arch during gait. Women walking in high-heeled shoes exhibit substantially reduced transverse arch height compared to women walking in flats. The most substantial changes are observed during the first and second rockers, i.e., in the loading response phase when flattening of the foot occurs as a reaction to the impact of body weight. The weight shifts to the support leg and moves the foot rapidly into pronation, often causing a characteristic sound of foot slap.

Ground reaction force is caused by the pressure of the foot rolling over the surface following a sequence of individual steps [16]. The results obtained during our study of gait dynamics are consistent with the findings of other authors [25], [26]. In our study, during gait at preferred velocity, the relative values for the vertical component of ground reaction force were: ca. 102–115%BW for F1 and F3, 65–80%BW for F2; for the mediolateral component these values were 10–30% BW for F4 and F5; for the anterior-posterior component they were 2–5%BW for F6 and 5–10% BW for F7. Insignificant differences in the middle stance and terminal stance phases were found between the mean values recorded in the group of women walking frequently in high-heeled shoes and those from the control group. Women frequently wearing high heels were characterized by significantly lower values of F2 force (for middle stance) and significantly greater F3 and F5 forces (typical of the propulsion phase), which might suggest changes found in foot mechanics as a result of permanent foot overload. Furthermore, no significant differences were found in the extreme values of ground reaction force parameters. The absolute length of the gait cycle was slightly greater in women from the control group, which might have had an effect on the insignificant elongation of the times recorded.

5. Conclusions

The study analysed the risk of overload as an effect of foot injuries in women walking in high-heeled shoes under dynamic conditions. Elongation of duration and reduction in height of the transverse arch indicates that the greatest loads in gait are observed during the whole stance phase, which corresponds to the phases of the first, second and third rocker. The use of the gait cycle phase model based on rocker phases helped identify the time of occurrence of disturbance in the height of the transverse arch during gait. The disturbance in the mechanism of foot rolling with significantly higher values of the vertical component of ground reaction forces and loading rate might lead to overload in lower-limb joints. The changes found in gait dynamics in the middle and terminal stance phases might suggest permanent changes in foot structure (especially, in the metatarsal and forefoot regions) and disturbance of its function.

Wearing high heels may lead to a number of structural and morphological changes in the motor system, and thus poses a great health risk to young women.

Acknowledgements

We acknowledge the financial support from our department and help from our technical staff.

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